Tactical Sciences for Biosecurity in Animal and Plant Systems

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The economics of plant and animal health protection influence country policies through rapidly evolving benefit-cost tradeoffs that are difficult to forecast. Increased threat of infestation by invasive species following novel trade pathways is one recent trend, being counteracted by advances in data analytics to target interventions on higher risk pathways. The availability of increasingly large, complicated datasets generated from daily enforcement of regulations are available to safeguarding analysts. These data resources used to monitor and evaluate pathways are increasingly available electronically with shorter time lags. But the efficacy of increased analytic capabilities requires a clear objective of what is optimal. Economic frameworks can help focus the analytics. For example, increased protection that costs more than the benefit generated is not efficient. Economic theory provides a systematic method with which to develop policy or to assess existing programs. This chapter provides basic economic concepts and examples relevant to biosecurity safeguarding.

The goal of biosecurity is to minimize the risk of introduction and transmission of infectious diseases to people, animals, and plants. This is achieved by accurately identifying pathogens and instituting appropriate methods to prevent their introduction, reemergence, and/or spread. However, disease is dynamic, and biosecurity needs to continually change to keep pace as pathogens evolve. As described in this chapter, a basic understanding of evolution is central in considering how genetic changes and their associated phenotypes can alter the disease presentation of pathogens. In addition, evolution leaves a trail of genetic information that can be leveraged to inform biosecurity because the spatiotemporal patterns of these past changes provide clues as to how the pathogen might be spreading. This chapter aims to provide insights into how various genetic alterations occur, the background on how these are informative for biosecurity, and illustrations of applications to real-world examples. Evolution underlies the abilities of pathogens to adapt, emerge, and to cause epidemics.

Chapter 3

Humans have always played an important role in dispersing plants, animals, and other organisms—either intentionally or inadvertently. Over the last several decades, rapid developments in infrastructure and transportation have led to dramatic increases in trade, travel, and mass migration; this in turn has accelerated the human-mediated spread of organisms across the globe. In their new environments, introduced species may thrive and cause severe economic and ecological impacts. Mitigating the entry, establishment, and spread of exotic pests and pathogens is crucial for protecting agriculture, ecosystems, and people. To do this, it is important to understand the pathways by which invasive species spread, assess the associated risks, and develop effective mitigation measures. This chapter describes the role of risk analysis for understanding human-mediated pathways of pest introduction and spread and provides case studies from both the plant and animal health arenas.

Chapter 4

Biosecurity, in the context of agriculture and natural ecosystems, refers to a strategic framework of policies and procedures intended to prevent the introduction or release of biological agents and materials that have the potential to threaten or compromise the agricultural sector in the form of invasive species, exotic pathogens, and foreign pests. Exchange of plants, animals, and agricultural products along with wood packaging material and dunnage that are transported through commerce and trade can lead to accidental introductions of foreign pathogens and pests unless sound biosecurity protocols are implemented to ensure the quality and safety of imported commodities at the local, transboundary, and global levels. Principal stakeholders at risk are those with interests in food, feed, fiber, oil, ornamental, and industrial crops; commercial forestry, natural ecosystems, and parks; and the livestock, poultry, aquaculture, fisheries, and apiculture industries.

Surveillance is one of the core activities of national organizations responsible for human, animal, or plant health, with the goal of demonstrating the absence of infection or infestation, determining the presence or distribution of infection or infestation, and/or detecting as early as possible exotic or emerging pests and pathogens that may be harmful to agriculture and the environment. Surveillance is a tool to establish absence of the pest or pathogen, monitor trends, facilitate the mitigation and control of infection or infestation, provide data for use in risk analysis, substantiate the rationale for sanitary measures, and provide assurances to trading partners, producers, and the public. The type of surveillance applied depends on the objectives of the surveillance, the available data sources, resources, and the outputs needed to support decision-making.

Surveillance is the collection, analysis, and dissemination of information to support prevention and mitigation of pest and pathogen impacts across natural and managed health systems. Surveillance provides an informational foundation for the risks posed by the organism, current status of the outbreak, directing limited resources, and effectiveness of management actions within the context of a response. Each response may have a series of management goals to accomplish over time and the information needs to support each goal will vary. Surveillance must be appropriately designed to align with the response goal and be well supported by risk assessment information on the biology of the invasive pest/pathogen, biology of the host or host system, pathways of introduction and spread, types and magnitude of impact, etc. This chapter proposes a generalized framework as a starting place for designing surveillance schemes using core design factors and how to effectively narrow parameterization of these factors within the context of a response goal.

Chapter 7

Diagnosis of disease is a process of hypothesis, investigation, and synthesis. Regardless of whether a human, animal, or plant is afflicted, the process of diagnosis is strikingly similar. Positioned on the biosecurity continuum between surveillance and response, early and accurate diagnosis is critical to effective mitigation and management of disease. Infectious diseases have the potential to spread among animal or plant populations, jump species barriers, and result in epidemics and global pandemics. Additionally, zoonotic infectious agents can also significantly impact human health on a mass scale. It is critical that infectious diseases be identified and detected in a timely fashion to prevent spread. This chapter will delve into the resources and supporting activities for that process, demonstrated via case studies from animal and plant systems, illuminating similarities and differences in the diagnostic process tools that can be mobilized and enhanced for biosecurity.

Chapter 8

This chapter focuses on emergency response following an initial detection of an invasive plant pest or foreign animal disease (FAD) as well as the regulatory authority utilized to initiate a response. Many emergency responses will be associated with crops and livestock on farms and ranches while others may involve nurseries, forests, wildlife, and exotic animals in various urban and rural locations. The incident command system framework is typically utilized to organize response efforts. Standard response preparedness and mobilization will be discussed with a consideration of the multitude of internal and external influences that can impact the strategy and tactics used during an outbreak. Sources of emergency funding and the critical need to manage public perception and information are also explained.

Chapter 9

The policy and resource infrastructure required to manage agricultural and environmental pest and pathogen incursions evolve and strengthen over time. Animal and plant health responses involve the highly coordinated efforts of various entities. Governments partner with state and territory officials, subject matter experts, and representatives of the commodity(ies) that are/may be impacted by the invasion. Short-, intermediate-, and long-term animal and plant health incident management tactics may change over time depending upon multiple conditions and externalities that will be described in this chapter. Results to response may range from fully successful eradication to learning to live with the pest and deregulation. Although the scope, timeframe, and consequences of events can vary, actions taken in response to the identification of an exotic plant or animal pest, disease, or condition are designed to minimize economic and environmental impacts, ensure trade and food security, assure business continuity, and avoid social unrest.

The secure and continuous production of agricultural commodities and food security are key to U.S. national security. The introduction of foreign-origin or emerging animal, plant, and human diseases by intentional acts of espionage, terrorism, biological warfare, or criminal activity can lead to severe consequences for domestic and international agricultural markets, the economic security of the agricultural community, food safety and food security, and the credibility of responsible state and federal agencies. Early public, animal, plant health, law enforcement, and intelligence assessments and investigations of suspected or confirmed intentional threats are critical additions to existing interagency prevention, response, and management protocols. Forensic microbiology, a multidisciplinary science, is essential to the nation's readiness for responding to a potentially criminal, intentional, or otherwise nefarious incident in the agricultural sector (plant or animal), and of eventual supporting attribution and the prosecution of the perpetrators.

Advances in technologies, increased globalization, impacts of changes in climate and land use on food production practices, and the expanding world population will continue to exert significant pressures on global biosecurity systems. The world must be prepared to face novel biosecurity threats, whether a consequence of natural pest and pathogen emergence or an intentional or unintentional release into a community. It is imperative that public and private sectors develop comprehensive and innovative strategies to mitigate these ever-evolving threats rapidly and effectively. This chapter reviews several opportunities that currently exist in global biosecurity of animal and plant systems with the hope that it will provide researchers, health experts, educators, and first responders with the awareness and impetus to adopt biosecurity tactics that enhance preparedness, reduce risk, and prevent catastrophic outcomes.

Chapter 5

Surveillance for Early Detection of High-Consequence Pests and Pathogens

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ABSTRACT

Surveillance is one of the core activities of national organizations responsible for human, animal, or plant health, with the goal of demonstrating the absence of infection or infestation, determining the presence or distribution of infection or infestation, and/or detecting as early as possible exotic or emerging pests and pathogens that may be harmful to agriculture and the environment. Surveillance is a tool to establish absence of the pest or pathogen, monitor trends, facilitate the mitigation and control of infection or infestation, provide data for use in risk analysis, substantiate the rationale for sanitary measures,

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and provide assurances to trading partners, producers, and the public. The type of surveillance applied depends on the objectives of the surveillance, the available data sources, resources, and the outputs needed to support decision-making.

INTRODUCTION

Introduced pests and pathogens require strategies for detection, identification, and prevention of spread. These strategies can be applied across regions, states, or international borders. Threats include known, high-consequence pests and pathogens, as well as emerging, unknown threats. Ideally, an integrated, strategic approach to intervention and mitigation is in place prior to introduction of the threat, however there are manifold threats and myriad pathways by which foreign or exotic pests and pathogens may enter a new area or region. This may occur through human-assisted transport of animals and plants, products made from animal or plant materials, contaminated food, migratory wild animals or insects, and even through shipping containers and airport luggage. However, natural spread of pests and pathogens also can occur. Given that weather patterns, especially hurricanes and typhoons, can move birds and insects, or dust and debris, across international borders, movement of pests and pathogens become almost inevitable.

With awareness of potential threats and routes of introduction, what strategies and tactical elements can be applied to detect an introduced pathogen or pest early and rapidly contain the invader? Critically, we need sound **surveillance** strategies, including guidelines for when to look, where to look, how to look, and for timely data analysis and sharing. These strategies include interoperable tactical sciences to look for, and identify, something unusual that could be indicative of some new organism that may pose an agricultural or environmental threat. A global surveillance system for crop diseases has been proposed that would allow sharing of information to facilitate detection of new threats to enable countries and regions to quickly respond to emerging disease outbreaks (Carvajal-Yepes et al., 2019). Global systems also exist to facilitate information sharing and threat detection for animal pathogens through a network of national and international organizations. The **Office International des Epizooties** (**World Organization for Animal Health** [OIE], 2021) coordinates efforts among more than 75 national and regional organizations.

The common analogy for the detection of foreign or exotic pathogens and pests in the United States (U.S.) is the 'needle in a haystack' reference. It is much more complex. The premise is that we only 'know what we know,' but we also must acknowledge that what we 'do not know is much more than what we do know.' Essentially, in many instances, the unknown universe of potential pest and pathogens is far greater than the relatively limited knowledge of those we know cause disease and/or economic damage to agricultural crops, livestock, landscape plants, forest and urban trees, and other aspects of the food and environmental landscape in which we live. What we do know, however, are the characteristics of the populations we are trying to protect. We know location, density, prevailing conditions of climate, operational norms, and opportunities for movement in and out of the area. This knowledge helps determine our strategies.

Design and implementation of an effective surveillance system is critical to early detection, identification, and containment. The goal of early detection is to find and identify pathogens and pests before they become established and cause widespread damage and economic harm to the agricultural, landscape, and environmental sectors (Reaser et al., 2020). The U.S. National Invasive Species Council's National Management Plan (2018) champions the concept that early detection, rapid assessment, and rapid response is a critical second line of defense and provides the greatest opportunity for eradication and cost-effective management. An effective early detection and rapid response program increases the likelihood that invasive species will be found, contained, and eradicated before they become widely established.

To do this, a variety of surveillance strategies have been developed and implemented. These can be categorized into two main strategies, **active (specific)** and **passive (general) surveillance**. There are advantages and disadvantages of both types of surveillance and the selection of active and/or passive surveillance approaches is dependent upon the assumed risk. Passive surveillance is effective because it casts a wide net and can be more easily conducted on an on-going basis and is usually less expensive. However, it may result in underreporting and/or incomplete data. If the risk and/or consequences are deemed low, then passive, lower cost, methods may be more appropriate. These might include use of less specifically targeted **surveys**, remote sensing technologies, or indirect methods such as **monitoring** social media to identify unusual events. Active surveillance should be used to investigate diseases and pests with a high risk to agriculture and the environment and to confidently declare absence of pests and pathogens. Data collected through active surveillance generally provides more accurate and complete information than passive surveillance, however, it can be resource intensive. If the entry risk and consequences of a pest or pathogen to agriculture and the environment are high, it follows that resources should be invested into active surveillance strategies. These may include regular sample collections and testing of specific sentinel populations, or targeted interrogation of first detector communities through surveys or reporting requirements. There is no definitive delineation between active and passive surveillance and some strategies use components of both. One strategy leads to the other, and vice versa, and it can be difficult in practice to distinguish a given approach as active or passive (Table 1). The effectiveness and efficiency of any surveillance strategy should be evaluated based on the probability of detection of the agent in a particular scheme, and the accuracy of guaranteeing detection, containment, and ultimate freedom from the disease or pest.

The data gathered by the surveillance system is ultimately subject to analysis to describe the pest or pathogen status, generate hypotheses about the risks, and model potential spatial and temporal spread (Figure 1). This information feeds back to inform decisions about how well the systems are working and how to effectively manage and mitigate the threat. These aspects, including risk assessment, are covered in other Chapters. This Chapter explores both animal and plant surveillance strategies, identifies complementary strategies, and shows where surveillance strategies may be specific to either the animal or plant world.

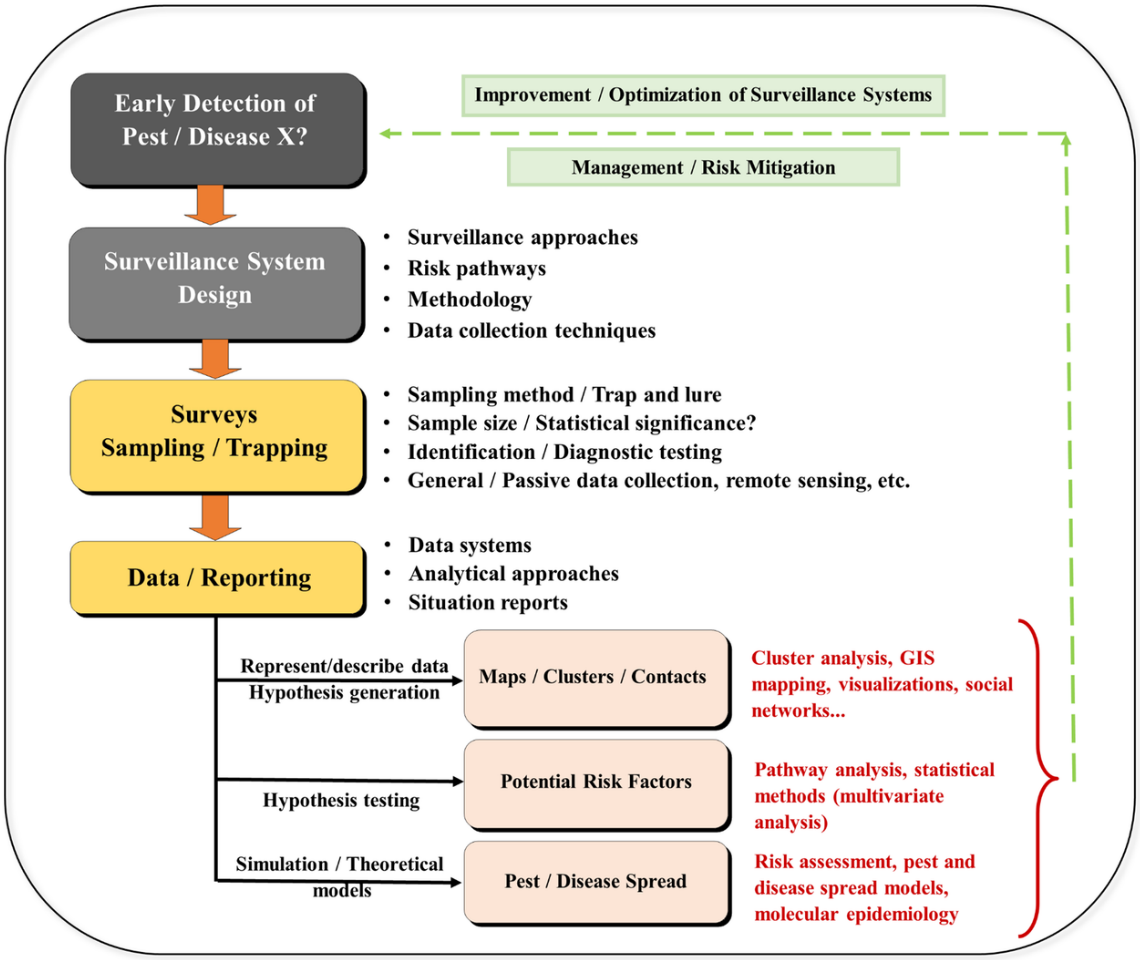
Surveillance results provide data on the:

- Detection of new pests and pathogens in an area,
- Distribution of a pest or pathogen,
- Establishment and maintenance of pest-free areas and pest-free production sites,
- Determination of the status of a pest in an area for reporting to other countries,
- Changes in a pest population,
- Delimitation of a pest population in an area,
- Eradication of a pest in an area, and
- Effectiveness of pest management in an area

Table 1. Various strategies to conduct surveillance

Surveillance Approach	Brief Description and Considerations	Advantages	Disadvantages	Examples Animal / Plant
Structured Interviews	• Use of closed or structured questionnaires and interviews for data collection • It is essential to know: a. what information is required b. how to capture that information c. how to structure that information so that it can be easily digitalized and analyzed	• Quick contact with large number of people • Easy to create, code, and interpret • Easy to standardize	• Fixed format; thus, difficult to examine complex epidemiological scenarios or risk factors	• Reports of NAHLN Laboratories • State Veterinarians • Local Veterinarians
				• Nursery Inspectors • Master Gardeners • Landscapers • Reports from NPDN labs
Sentinel Surveillance	• Health status of a population of animals or plants is periodically assessed • Sentinel animal population, crop field plot, or habitat (reporting unit) selected based on the high probability of detecting the target pathogens and/or pests	• Rapid • Economic	• Depends on the quality of the sentinels • May not be effective for rare diseases • Not population based	• Testing milk produced by a dairy for the presence of a pathogen
				• Defined areas in crop fields that are assessed for the presence of a target pathogen
Syndromic Surveillance	• An investigational approach where health indicators are monitored to detect outbreaks of disease or pests earlier than would otherwise be possible with traditional methods • Use of clinical, diagnostic, or health-related information that precedes confirmatory diagnosis of specific disease or pest conditions • Alternative approach focuses on detecting individual atypical cases, where a new disease or pest that shows symptoms or signs the clinician or diagnostician cannot link to a known pathogen or pest	• Easy • Economic • Sustainable	• Potential "false alarms" (low specificity) • Limited or no information on "negatives"	• Respiratory congestion, cough, or nasal discharge across multiple animals on a farm or some other reporting unit
				• Analyses of pathogen trends from results of multiple diagnostic laboratories • Reports of new symptoms in plants
Proxy or Indicator Surveillance	• Like syndromic surveillance, but uses other, non-health-related information (e.g., animal or crop productivity, human movement, social activity)	• Easy • Economic • Sustainable	• Potential "false alarms" (low specificity)	• Reduced weight • Reduced feed intake • Immobility
				• Reduced crop yield • Reduced commodity quality
Participatory Surveillance	• Stakeholders have a greater role in shaping animal and plant health surveillance programs • Uses the existing knowledge that people have about the animals they keep and plants they cultivate, and about the pests and pathogens that cause disease that impact their health and livelihoods • Uses semi-structured interviews, focus-group discussions, ranking/scoring, exercises, and diverse visualization techniques	• Low cost • Communities that are at risk engage with the surveillance process • Can lead to the development of disease control programs that are both acceptable and effective • Allows for "discovery" of new information	• Data generated can be difficult to code, interpret, and/or analyze without standardization	• University extension • Continuing education • State agencies • Commodity and grower associations • Industry groups
Post-harvest surveillance	• Sampling/surveys at the slaughterhouse and packinghouse level (usually for food safety purposes). May be just visual (e.g., clinical signs or fruit symptoms) or through tests or surveys. • Quality analysis of grains and fresh produce	• Easy • Relative low cost	• Data access • Potential difficulty tracing back to the farm of origin • Depends on inspector experience	• Monitoring for signs of infection or inflammation in lymph nodes, liver, spleen, kidneys
				• Commodity mills and packinghouse inspections
Risk-based surveillance	Sampling of high-risk groups: these risk groups might share risk factors or be geographically defined; for example, along border areas or in animal-dense areas.	• Cost-effectiveness • Same or increased sensitivity with smaller sample size	• Definition and quantification of risk • Sometimes complex design	• Transportation of animals between locations, especially when animals from more than one location are mixed
				• Pathways along transportation routes • Previous detections

Figure 1. Summary of some of the most important considerations when designing a surveillance program for post-border detection of high-consequence plant and animal pests and diseases



National and International Organizations Engaged in Surveillance for Introduced Pathogens and Pests

National Plant Protection Organizations (NPPOs) conducting surveillance to detect high-consequence plant pests and diseases follow international guidance and protocols as described in various **International Standards for Phytosanitary Measures** (Adopted Standards [ISPM], 2021). The **Standards** are developed by the Commission on Phytosanitary Measures (CPM, 2021), the governing body of the **International Plant Protection Convention** (IPPC, 2021), and published by the Food and Agriculture Organization of the United Nations (Food and Agriculture Organization [FAO], 2021). For surveillance of plant pests and pathogens, ISPM 6: Surveillance is the guiding international document (ISPM 6, 2019).

As an example, the United State participates in the International Plant Protection Convention (IPPC, 2021) through the North American Plant Protection Organization (NAPPO), which is the phytosanitary standard-setting organization for North America (North American Plant Protection Organization

[NAPPO], 2021). "NAPPO was created in 1976 as a regional organization in accordance to Article IX of the International Plant Protection Convention (IPPC). NAPPO provides a forum for public and private sectors in Canada, the United States and Mexico to collaborate in the regional protection of plant resources and the environment while facilitating safe trade" (NAPPO, 2021). Official Pest Reports and Emerging Pest Alerts are published via NAPPO's Phytosanitary Alert System (Phytosanitary Alert System [PAS], 2021). Official Pest Reports are provided by National Plant Protection Organizations within the NAPPO region. Emerging Pest Alerts are news items obtained from public sources and are not official communication from NAPPO. Emerging Pest Alerts are early warnings for emerging plant pests that are not present in the North American region.

As defined in ISPM 5: Glossary of Phytosanitary Terms (ISPM 5, 2019), surveillance is defined as "An official process which collects and records data on pest presence or absence by survey, monitoring or other procedures." Surveillance activities form the basis for regulatory decisions and the establishment and removal of federal and state quarantines on the intra- and interstate movement of goods, the facilitation of bi-lateral trade talks and subsequent requirements for pathogen and pest information with foreign trading partners, and agricultural/crop/animal and environmental/forest management decisions based on pest or pathogen presence, threshold, or absence. With pests and pathogens come costs in one form or another in terms of management or eradication. Surveillance results can reduce, manage, or eliminate these extra costs.

Similarly, general surveillance of pathogens and pests affecting animals involves the regular collection and reporting of observational and surveillance data and relies on the cooperation of many organizations and individuals, General surveillance often is the result of outreach programs that target veterinarians and others in the livestock industry. Often people or groups are directed to report what they see to state extension or regulatory officials, or report through various mobile applications that collect the information.

As in the practices for plant pests and pathogens, surveillance to detect high-consequence animal pests and diseases also follows international guidance and protocols. The Office International des Epizooties (OIE, 2021) is the intergovernmental organization responsible for improving animal health and welfare worldwide. The OIE, established in 1924, is made up of 182 Member Countries and is recognized as a reference organization by the World Trade Organization (World Trade Organization [WTO], 2021). In addition, the OIE has relationships and agreements with nearly 75 other international and regional organizations, including the Food and Agricultural Organization (FAO, 2021) and World Health Organization (World Health Organization [WHO], 2021) of the United Nations, and has offices on every continent. Working through a network of 246 OIE Collaborating Centers and Reference Laboratories across the world and recognized as the sole international reference organization for animal health, information on animal disease control is made available to improve disease control and eradication. An example of these collaborating centers is the Center for Food Security and Public Health (CFSPH) at Iowa State University (CFSPH, 2021). The OIE standards outlined in the **Terrestrial and Aquatic Animal Health Code** (OIE, 2019) are recognized by the World Trade Organization as reference international sanitary rules.

In direct collaboration with their respective Veterinary Services, the Member Countries of OIE agree to report listed animal diseases detected within their respective territories. There are over 100 OIE-listed terrestrial and aquatic animal diseases that carry a specific mandate for reporting whenever they are detected. This information is disseminated through the Disease Information and the World Animal Health Information System Interface (WAHIS, 2013), so countries can take necessary action. The OIE reporting also includes animal diseases transmissible to humans occurring both naturally through deliberate means.

The OIE has five Regional Commissions to address specific problems facing its Members in the different regions of the world. The United States is a member of the Regional Commission of the Americas. The United States actively participates in developing the OIE international animal health standards. Within the U.S. Department of Agriculture (USDA), Animal and Plant Health Inspection Service (APHIS), the Deputy Administrator of Veterinary Services (VS) (APHIS, 2020a), as the Chief Veterinary Officer (CVO), is charged with managing and coordinating U.S. animal health standard-setting activities related to the OIE.

In the United States, USDA, APHIS, VS is the agency responsible to protect animal health. Preventing, controlling, or eliminating animal diseases requires the ability to detect emerging foreign and domestic diseases, monitor trends, risks, and threats around the world, evaluate disease control and eradication programs, and disseminate animal health information to multiple audiences. The national reference laboratory for the United States is operated by the National Veterinary Services Laboratories (NVSL) (APHIS, 2021b) located at Ames, Iowa and the Foreign Animal Disease Diagnostic Laboratory at Plum Island, New York. Testing for certain types of diseases, such as OIE-listed diseases, must be performed at either the NVSL or other approved facilities such as laboratories in the National Animal Health Laboratory Network (NAHLN) (APHIS, 2020c) distributed across the United States.

General Surveillance

General surveillance involves the regular collection and reporting of surveillance or observational data and may rely on the cooperation of many organizations and individuals. Data and information sources may include federal, state, or local government offices, university research and extension, museums, scientific societies and their publications, trade journals, consultants, producers and their organizations, independent specialists and websites, and the public, among others. General surveillance often is the result of outreach programs that target the public for awareness (Crimmins et al., 2017), or specific groups like crop consultants, Master Gardeners, landscapers, or tree experts. Often people or groups are directed to report what they see to state extension, veterinarians, or regulatory officials, or report through various mobile applications that collect the information.

In addition to official notifications, the OIE conducts active search activity for non-official information and rumors relating to animal health and public health. This information is evaluated in the context of the animal health situation prevailing in the country or region concerned and, where appropriate, verified with the Member Country or Territory for the purposes of official confirmation and potential publication. This general surveillance begins with the search for non-official animal health information and rumors disseminated by the media, networks such as Health Canada's Global Public Health Intelligence Network (GPHIN, 2021) and ProMed (2021), and scientific journals and publications. Reports also are collected from OIE Reference Laboratories, which have a mandate to report any positive finding relating to an OIE-listed disease. The search is intended to identify specific health events, including the suspected disease, clinical signs (e.g., high **mortality**), geographical location, and the animal species affected. Further analysis determines relevance of the information and whether it relates to an exceptional event requiring immediate action, confirmatory investigation, and notifications. If the information relates to an animal disease that is already present or to human cases of a zoonotic disease, it is retained for comparison with future reports. Zoonotic diseases are diseases and infections naturally transmitted between vertebrate animals and humans. The U.S. Centers for Disease Control (CDC) One Health Office is an effort to track and prioritize zoonotic disease surveillance (CDC, 2021). If appropriate, notifications include the designated official of the Member Country or Territory who would officially notify the OIE if that had not already been done.

Another example of this type of effort is housed within the Center for Invasive Species and Ecosystem Health at the University of Georgia (Bugwood, 2021). The Early Detection & Distribution Mapping System (EDDMapS, n.d.) began as an effort to aggregate and normalize invasive species observation data among partners focused on different geographic scales, disciplines, institutions, taxonomic groups, and commodities. By not only aggregating the data but working with partners to ensure that the definitions used to describe different attributes of an observation aligned, it became possible to directly compare data sets without having to first resolve differences in terminology.

Once put online, partners working with EDDMapS wanted to be able to continue adding data by accepting reports from both their teams and the public. This led to development of a platform for citizen science reporting of invasive species and other agronomic pests. Reports received are routed to the local teams working on a given taxa. These teams communicate with the reporter, regulatory authorities, and related invasive species management areas. Once verified, they review the online records and take appropriate measures to protect the confidentiality of the locations and reporters. All partners have the option of signing up for alerts in their given areas of interest to keep them informed of ongoing detections. The data are made available for all partners to develop more effective management plans, conduct research to better predict new invasions and spread of existing species, and continue to give a near-real time update of invasive species distribution.

Success within the invasive species arena has led to further expansion to incorporate agronomic pests. While not all the pests currently are considered invasive, many were at one time newly introduced species, and after many years the goal of eradication or containment became untenable. This combined with efforts of the Integrated Pest Information Platform for Extension and Education (iPiPE, 2021, Isard, 2015) and its predecessor, ipmPIPE (Isard, 2006b), to provide an infrastructure with tools, information products, and expert commentary for the detection and management of pests that threaten U.S. crops.

Rather than attempting to be the one solution for all users, and having to deal with competition between different commercial platforms, EDDMapS forms the basis for a National Pest Observation Repository (NPOR, n.d.) Multiple platforms including FarmDog (2021) and myFields (n.d.), which are specifically aimed at crop consultants and growers, contribute data alongside platforms such as iNaturalist (n.d.). These partners unite with the tools provided by EDDMapS through AgPest Monitor (n.d.) to provide distinctly branded notifications to both invasive species and agriculturally focused audiences. Data products, models, and risk analysis tools are made available to all partners contributing data so they may improve their decision management process.

USDA, APHIS, VS, works with a national network to carry out surveillance activities in the United States, including the NAHLN laboratories, the National Animal Health Monitoring System (NAHMS) (APHIS, 2021a), and the National Animal Health Surveillance System (NAHSS) (APHIS, 2020e). NAHMS conducts national studies on the health and health management of United States domestic livestock populations. These studies are designed to meet the information needs of the industries associated with these commodities, as identified by people within those industries. NAHSS is a system created to detect events and trends related to animal health. Comprehensive and Integrated Surveillance (CIS) within the NAHSS is based on having an integrated and coordinated database for alerts and decision analysis. National plans for CIS for multiple high-impact pathogens of animal species in the United States and supporting resource documents are published by USDA, APHIS, VS (APHIS, 2020a).

In general surveillance of high-consequence animal diseases and pests, veterinary practitioners play a key role. Veterinarians interacting with owners of livestock or pets are often the first line of defense against emerging and exotic animal disease. It is the role of the veterinary practitioner to educate owners, to be aware of unusual clinical signs, to be aware of current disease outbreaks or threats, and to immediately report possible diseases of concern to both Federal and State Animal Health Officials. Veterinarians are required by law to immediately report to the APHIS Veterinarian-in-Charge (APHIS, 2020i) and the State Animal Health Official (USAHA, 2021) all diagnosed or suspected cases of a communicable animal disease for which APHIS has a control or eradication program, and all diagnosed or suspected cases of any animal disease not known to exist in the United States.

Similarly, for plant pests and pathogens, the National Plant Diagnostic Network (NPDN, 2021) is a network of plant health diagnostic laboratories in all 50 states and four territories with the goals to provide high quality diagnostics and to ensure effective and timely communications with regulatory partners, other diagnostic and regulatory labs, and the plant health communities they serve. The NPDN was established in the wake of the terrorist attacks on September 11, 2001, with USDA funding to "protect national plant health by quickly detecting and accurately identifying plant pests and pathogens and effectively communicating these diagnoses to stakeholders and clientele." The NPDN contributes to the safeguarding of U.S. agricultural and natural ecosystems by providing early detection and identification of plant pests and diseases, enhancing diagnostic and detection capabilities, improving communication among federal, state, and local agencies, and delivering educational programs regarding the threats posed by their introductions. As veterinary practitioners play a key role in animal health, plant diagnosticians play that same role for plant health as they are in a prime position to recognize an 'out of the ordinary' pest or pathogen in their State or Region and alert State and federal regulatory agencies to its occurrence. The NPDN labs also partner with state and federal survey efforts by performing validated diagnostic procedures for pests and pathogens of regulatory concern, thus adding capacity for survey efforts and national, state, and local responses to disease and pest outbreaks.

Specific Surveillance

Specific, or active, surveillance is a structured process where specific pests of concern are targeted in surveys over a defined area and period using standard methodology. Pest- or pathogen-specific information is collected to determine the characteristics of a population (size, density, range, etc.) or to determine if a species is present or absent in an area within the timeframe of the surveillance. As the case with both plant and animal pathogens, the disease caused by the pathogen often is the focus of the survey. Here we will refer to pathogen populations with the understanding that they also refer to populations of diseased individuals.

There are three types of specific surveillance activities: **detection**, **delimiting**, or **monitoring surveys** depending on the objectives of the specific surveillance program. These surveys may be developed for pests or pathogens in relation to one or more areas, sites, hosts, pathways, or commodities. This chapter deals specifically with surveillance for early detection when the pest or pathogen is either absent or very rare. A detection survey is conducted in an area over a specified time frame to determine if a pest or pathogen causing disease is present or absent. These surveys may target foreign pests and/or **endemic** pathogens not known to occur in an area, and invasive or established pests or pathogens not known to be present in an area. Often, the purpose of this type of surveillance is to document absence of a pest or disease caused by a pathogen for phytosanitary purposes that will facilitate market access, trade and the movement of crops, forest products, animal products, and other commodities and goods within a country or internationally. The overall goal is to document the status of a pest or pathogen as either present or absent.

An example of a specific surveillance program structured on the early detection strategy is the United States Department of Agriculture (USDA), Animal and Plant Health Inspection Service (APHIS), Cooperative Agricultural Pest Survey (CAPS) program (Cooperative Agricultural Pest Survey [CAPS], 2021b, Animal and Plant Health Inspection Service [APHIS], 2020g, Kalaris et al., 2014). Similar programs exist in just about every country, and although they may be structurally different, all attempt to adhere to the principles of surveillance in ISPM 6 (2019). The CAPS program is a federal and state partnership that conducts science-based national and state surveys targeted at specific exotic plant pests, diseases, and weeds identified as economic and environmental threats to U.S. agriculture and/or the environment and is an essential element in providing a continuum of checks from offshore preclearance programs, domestic port inspections, and surveys in rural and urban sites across the United States.

The goals of the CAPS program in the United States are to keep agriculture and natural resources safe and to satisfy other countries that the United States' agriculture is safe. To accomplish these goals, the program provides a survey profile of presence/absence data on exotic plant pests in the United States deemed to be of regulatory significance through early detection and surveillance activities. This documented information serves as the basis of APHIS' regulatory efforts and pest management programs that preserve economic opportunities for farmers (i.e., interstate commerce and international trade) and safeguard U.S. agricultural and natural resources. Refer to the CAPS Resource and Collaboration website for more detail on structure, function, and survey guidance (CAPS, 2021b).

The CAPS Program strengthens APHIS' emergency preparedness efforts through the early detection efforts aimed at discovering these pests before they spread and become pest emergencies. These activities are accomplished primarily under USDA funding that is provided through cooperative agreements with state departments of agriculture, universities, and other entities. Resulting survey data support the development and expansion of export markets by identifying pest-free regions that allow the continued export of commodities from different areas of the country.

Similarly, the USDA Forest Service also conducts early detection surveys through their Early Detection and Rapid Response (EDRR) program (Rabaglia, 2019). The goals of the program are to detect, delimit and monitor newly introduced exotic bark and **ambrosia beetles** at selected high-risk forest areas and quickly assess and respond to newly detected infestations. The introduction and establishment of non-native species through raw wood products, solid wood packaging material, or live plants has already had profound ecological effects on forests across the country. The EDRR team, consisting of Forest Service, APHIS, university, and state representatives, has developed a framework for implementing a national, interagency detection, monitoring, and response system for these insects within the forest environment, and complements APHIS and Invasive Species Counsel efforts in the agricultural, landscape, and aquatic environments.

For animals, Comprehensive Integrated Surveillance (CIS) plans (APHIS, 2020a) call for regular testing of specific populations and/or subpopulations of animals in a geographic area determined to be at-risk for a specific pathogen introduction. At-risk areas might be large concentrations of livestock that move in an out of the area or have opportunity for contact with wildlife. An example would be domestic swine operations with proximity to feral swine populations. Animal disease reporting systems can be supplemented with participatory methods, surveys, and specific sampling. Examples include inspection of animals at slaughterhouses/abattoirs; surveillance of sentinel units involving regular testing of one or more animals of known health or immune status in a specified geographical location; clinical observations of animals in the field; systematic analysis of health data, including **morbidity** and mortality rates, production records, and other parameters indicative of changes to the health of an animal population. These data can be supplemented with surveillance of wildlife populations including road-kills, wild animal meat markets, sanitary inspection of hunted animals, morbidity and mortality observations by the general public, wildlife rehabilitation centers, wildlife biologists and wildlife agency field personnel, farmers and other landholders, hunters, and conservationists. Analyses used in surveillance may arise from clinical observations, production records and rapid field and detailed laboratory assays. Various features of these methods are described in other Chapters, and specifics are based on the surveillance objectives, epidemiology, risk of introduction, etc., as listed in the OIE Terrestrial Animal Health Code (OIE, 2019). ISU_FLUture (2021) is an interactive web-based tool developed to provide diagnostic information on Influenza A Virus infection in swine. There is a database of test results, metadata collected from surveys submitted with diagnostic samples, and virus genome sequences collected at the Iowa State University Veterinary Diagnostic Laboratory. The goal is to find trends in the data that will allow for informed decisions regarding influenza and swine health.

Surveillance Strategies and Questions to Answer

A surveillance program, whether for plant or animal pests and pathogens should first consider the objectives of the surveillance, and then develop strategies to achieve those objectives. A system to detect any introduced pathogen or pest should consider all animal or plant species susceptible to the infection or infestation in the region of interest, including wildlife and weeds that may be pest and pathogen reservoirs. In cases where the aim is to detect a known pathogen, the surveillance strategy can be active and highly targeted. Detection of unknown or newly emerging pathogens may be more passive. Regardless of the overall surveillance strategy, multiple assessments and knowledge must be acquired and infrastructure put in place to conduct the surveillance. A multi-pronged approach may include:

- A structured, transparent assessment process to identify threats;
- An assessment of the biology and epidemiology of the pest or pathogen (e.g., pathogenesis, **vectors**, transmission pathways, seasonality, environmental factors);
- An assessment of the risk of introduction and spread;
- Knowledge of husbandry and crop practices, production systems, and disease prevention and control measures;
- Development of cost-effective, scientifically sound survey methods and protocols;
- Development and validation of diagnostic tests and identification methods;
- Providing approved, standardized survey materials (traps, lures, etc.);
- Conducting the actual surveys;
- Decisions on data collection methods;
- Timely reporting and compiling of pest or pathogen survey results through an approved database;
- Ensuring that the data collected are valid and of high quality; and
- Notification of significant pest detections through established protocols.

To carry out its mission and achieve its goals, a surveillance program must answer some fundamental questions with scientific answers that are common to most specific surveys. These are:

- What pests and pathogens to target and how to assess or prioritize their potential risk;
- Where to carry out surveillance activities, and when;
- How to survey and what methodology and tools to use;
- How to collect and record surveillance activities and results; and
- How and where to share the information obtained?

What Pests and Pathogens to Target

The first task to complete when contemplating a surveillance program is to determine which pests and/or pathogens to target. For early detection surveys, where the pest or pathogen is not known to occur domestically, one needs to look beyond one's borders for pests and pathogens that may be reported and/or on the move in different regions of the world. For plant pests and pathogens, the PestLens (PestLens, n.d.) and NAPPO's Phytosanitary Alert System (PAS, 2021) are components of that analysis, along with reports and communications from collaborators in other countries. For animal pests and pathogens, the World Animal Health Information System Interface (WAHIS, 2013) provides summary analysis of disease status in countries around the world. The USDA Animal and Plant Health Inspection Service provides analysis of present, future, and emerging animal health threats, including epidemiological and economic impact modeling.

Likewise, The Program for Monitoring Emerging Diseases (ProMED, 2021), a program of the International Society for Infectious Diseases (ISID, 2018), is an important and publicly available system conducting global reporting of infectious disease outbreaks. The goal of ProMED is to "identify unusual health events related to emerging and re-emerging infectious diseases and toxins affecting humans, animals, and plants." A multidisciplinary global team of subject matter experts produce reports and provide commentary in a variety of fields, which are then emailed to subscribers. Subscribers to these reports are often the first to be aware of disease outbreaks. For example, reports of outbreaks of **Severe Acute Respiratory Syndrome** (SARS), **Ebola**, and the early spread of **Zika** virus were first reported by ProMED.

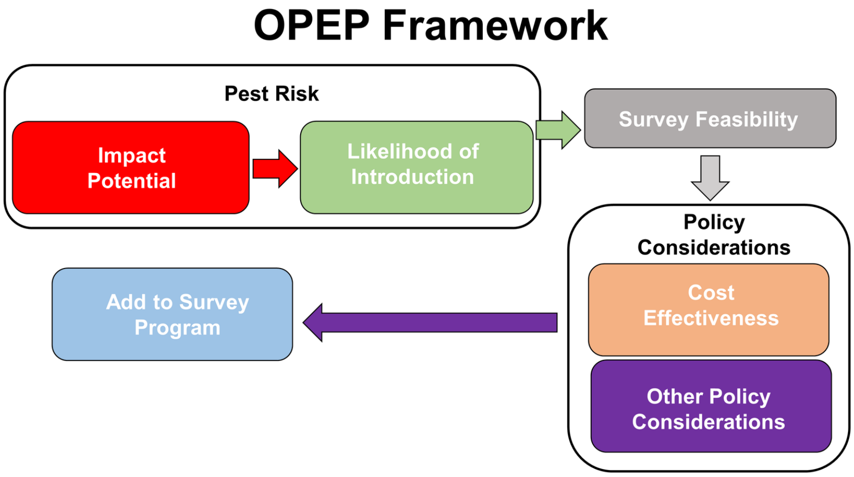
PestLens is an early-warning system that supports the analysis of which pests and/or pathogens to target by collecting and distributing new information on exotic plant pests and providing a web-based platform for documentation and reporting. A team of PestLens analysts with expertise in entomology, plant pathology, weed science, and technical communication systematically collects, evaluates, and summarizes relevant pest information, both from online sources and contributed by system users. When summarizing news items, the PestLens team places them into a plant health context and includes pertinent biological background information. A weekly e-mail notification is sent to PestLens subscribers that includes new distribution records, new host records, new pest descriptions/identifications, significant outbreaks, weed naturalization events, new pathogen/vector relationships, and research of regulatory or phytosanitary interest. Sensitive information is not distributed in the weekly notification. However, it is made available through the PestLens web system to designated USDA representatives via a login. While PestLens was developed for USDA, its audience now extends to a wide range of international plant protection officials.

How to Assess or Prioritize Potential Risk

There are a several internationally agreed-upon frameworks used to assess risk. Two examples of pest and pathogen risk assessment frameworks are outlined in the International Standards for Phytosanitary Measures No. 2, *Framework for pest risk analysis* (ISPM 2, 2019) and in the OIE, *Terrestrial Animal Health Code* (OIE, 2019). Even when potential pests or pathogens of importance have been identified, with limited resources and literally hundreds—if not thousands—of known threats, one of the most fundamental challenges countries face is deciding which of these pests and/or pathogens to target.

While risk analyses are covered in more detail in other Chapters, it is important to understand that different strategies may be employed under the same framework, and to support a strategy, the combination of biological, epidemiological, geographical, statistical, economic, and sometime political and policy sciences work together within a given approach to inform risk. One such example is the **Objective Prioritization of Exotic Pests** (OPEP) model. This model categorizes pest and pathogen threats based on the likelihood of causing serious impacts in the U.S., and the likelihood of being introduced (Figure 2). The process is evidence driven, comparable across different types of organisms, flexible in that it can be used to compare risk by region and host, and defendable in that it uses methods that have been tested and validated statistically.

Figure 2. Objective Prioritization of Exotic Pests (OPEP) Framework



One of the most important changes in how the U.S. prioritizes pests is the intentional focus on ensuring survey resources go towards the pests most likely to cause serious impacts. To this end, two models were developed, one for arthropods and one for plant pathogens, to determine the characteristics most predictive of impact. Each model was developed using the same process the USDA used to develop its Weed Risk Assessment model (APHIS, 2019; Caton et al.; 2018, Koop et al., 2012). A set of yes/no and multiple-choice questions were developed that may be predictive of impact.

Using the arthropod model as an example, the questions that were developed covered:

- Biology and natural history, including natural dispersal, reproduction mode (e.g., sexual, parthenogenic), number of generations, **oviposition**, **fecundity**, **diapause**, use of mating or aggregation **pheromones**, and phenotypic variability,
- Pest damage including whether the pest typically attacks healthy vs. stressed hosts, the ability to vector potential plant pathogens, type of damage (e.g., visible, internal changes, loss of vigor, reduced production, mortality), plant parts damaged, and what other species use the same resources (feeding guild).
- Research and management (e.g., evidence of controls, types of controls, amount of research conducted, magnitude of damage, types of host systems, efforts at eradication).

First, non-native arthropods and pathogens were identified *that were introduced* to the United States. Each pest on the list was then analyzed *as if it were <u>not</u> present* in the United States. In other words, each pest was evaluated using information from outside the United States. Question-specific guidance was developed to minimize variance among the analysts (all questions were approached from a similar standpoint).

A separate team of entomologists and economists classified each pest in terms of its *<u>observed</u>* impacts in the United States. Observed impacts were classified into five (5) groups: very high impacts, high impacts, medium impacts, low impacts, and very low impacts. Because the amount of damage was not available for every pest, especially those that have been present in the United States for a long time, also included were "level of management and control costs" and "amount of research" conducted on the pests as proxies for damage when that information was not available. Thus, the final criteria for observed impact class included:

- Severity of unmitigated damage
- Frequency of severe outbreaks
- Impact on production practices
- Environmental and social impacts
- Level of management and cost control
- Amount of research

A statistician compared results of the assessments to the actual observed impacts in the United States and tested how well each question predicted observed impact. Non-predictive questions were removed using the following methods:

- Entropy based techniques
- Maximized mutual information scores
- Non-parametric tests including Chi-square with contingency analysis and Kruskal-Wallis tests

The questions left in the model were weighed by their predictive power. Questions that were the most predictive received the largest weight. Additionally, the production practices in the United States, particularly control practices already in place for other pests, will greatly influence the additional impact a pest will have should it become established. Therefore, questions also were added that consider how effective the control methods and practices already in place for other pests would be at controlling the pest being evaluated. The model was *validated by assessing additional pests* established in the United States using the methods described above, and re-testing some questions that were not predictive.

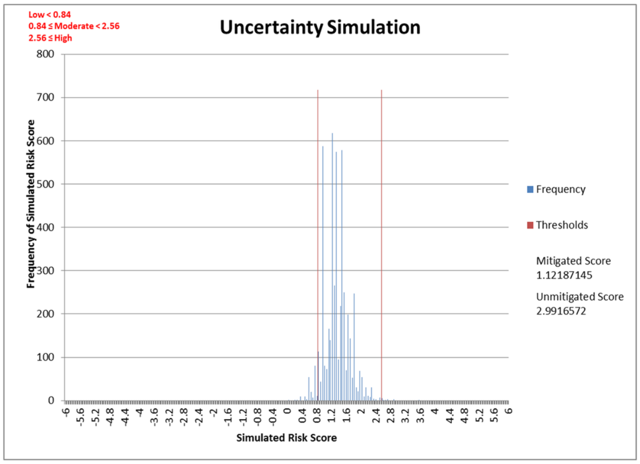
The current model is housed in Microsoft Excel. Ordinal logistic regression was selected based on model usability within the development platform (Excel). Results are provided as probabilities for a given pest being a high, moderate, or low impact pest (Figure 3A). Uncertainty was considered through a Monte Carlo simulation with 5000 iterations where alternate answers were used (Figure 3B).

Figure 3. OPEP model outputs. **A.** *Example output of the regression model in Excel. The risk score is determined based on how analysts answer the questions in the excel template. The percent probability a pest will have a low, moderate, and high impact are the results of the logistic regressions.* **B.** *Example output of a Monte Carlo simulation of uncertainty*

A

Risk Rating and Probabilities	
Biology and Natural History	13
Pest Damage	17
Research and Management	26
Raw score sum	56
Impact of Current US Conditions	-35
Zeta1 (Low | Medium)	0.588047
Zeta2 (Medium | High)	2.8025218
Coefficient	0.05342245
Risk Score - OLR fitting	1.121871
Logit1	-0.533824
Logit2	1.680650
Probability (Low)	36.9625408 %
Probability (Moderate)	47.3365221 %
Probability (High)	15.7009371 %
Sum	1
95% CI for the High Probability	11.359 ~ 31.595 %
Predicted Pest Category	**Moderate Impact Pest**

B



The result is a list of pests and pathogens grouped by risk score and uncertainty. Pests that have the greatest likelihood of causing serious impacts and of being introduced are given the highest priority for survey. Three categories with 10 Risk Groups have been developed to prioritize pests and pathogens. Regardless of the model used, arthropod or pathogen, the outcome of the analyses will place all pests into one of these Risk Groups (Table 2). Over time the list of pests and pathogens has the potential to become very large as more species are analyzed. It is up to the organization funding and conducting the surveys to determine the number of pests in the Risk Groups that will be the targets of the surveys. Some situations may call for a more restricted prioritized list based on resources and capacity.

The introduction of a pest or pathogen into a new area can be defined as the entry of that pest or pathogen and results in its establishment (ISPM 5, 2019). However, establishment requires the pest to find 1) a suitable host and climate and 2) a mate or host for reproduction (if necessary). Because of the difficulty of predicting likelihood of establishment, the United States has opted for a qualitative approach to evaluating likelihood of introduction. Only pests and pathogens with predicted high or moderate impacts are considered further because a low impact pest or pathogen that is highly likely to be introduced into

Table 2. OPEP model outputs place organisms into Risk Groups based on Predicted Impacts

Risk Group	Predicted Impacts
A	Predicted to be a high impact pest in the United States (low uncertainty)
B	Predicted to be a high impact pest in the US, but with a higher degree of uncertainty
C	Probability of being a high impact pest vs moderate impact pest is roughly equivalent (w/in 10 percentage points)
D	Predicted to be a moderate impact pest, but probability of being high impact is >20% (cause high impacts when environmental conditions are right)
E	Predicted to be a moderate pest, but with a high degree of uncertainty
F	Predicted to be a moderate pest
G	Probability of being a moderate vs. low impact pest is roughly equivalent (within 10%)
H	Predicted to be a low impact pest, but with high uncertainty
I	Predicted to be a low impact pest
J	Undetermined-- Cannot be evaluated through OPEP; Pest does not cause damage in its native range and has not been introduced outside of native range, or pest has not been introduced outside its native range and closely related species are high impact pests

the U.S. is not relevant for prioritizing survey resources. Pests and pathogens with a higher likelihood of being introduced are elevated in the overall prioritization, while pests and pathogens that are less likely to be introduced are given a lower priority.

A pest's priority is elevated due to likelihood of introduction when one or more of the following situations exist:

- The pest is present in Mexico, Canada, or the Caribbean and capable of natural spread into the United States.
- There is evidence in recent literature that demonstrates that a pest has recently been introduced to new areas and is spreading.
- Introduction and eradication of the pest has previously occurred in the United States.

A pest's priority is reduced based on likelihood of introduction if one or more of the following situations exist:

- Pest spread requires a vector that is not present in the United States
- Pest requires more than one host, and it seems unlikely that all will be present in an area where the pest would enter to allow for establishment.
- Pest establishment has not occurred outside of its native range.

As outlined in the OIE Terrestrial Animal Health Code (OIE, 2019) there are four components to import risk analysis, hazard identification, risk assessment, risk management and risk communication. The steps of risk assessment involve entry or release assessment, describing biological pathways for release of a threat agent and estimation of the probabilities of these under various relevant conditions; similar to plants, what is the likelihood of introduction and/or what is the likelihood of spread? Scenarios might include evaluation of animal species, types of veterinary services, and surveillance and control methods available. Exposure assessment describes the pathways necessary for exposure of humans/animals to the threat agents released and estimation of these probabilities. Factors to consider here include potential vectors of the pathogen, impacts of cultural or geographic characteristics. Consequence assessment is the description of the relationships between exposure to threat agents and consequences of those exposures in both biological and economic terms, such as impact on trade. The overall risk assessment, then, should be based on an iterative process of entry (or release) assessment, exposure assessment, and consequence assessment under current local conditions over time. It is important to note that risk can be estimated in different ways, such as using climate suitability models as outlined below to evaluate climate-based risk, a different but complementary approach.

Where to Carry Out Surveillance Activities

When an exotic species has been predicted to be a high impact pest if it were to become established, the next question to ask is *where* surveys should be conducted. Detection surveys are a key defense against new exotic pests and pathogens but are only applicable when the **prevalence** or abundance of the agent is low (or zero). This means that simple random sampling, in which each individual, trap, or area has an equal probability of being inspected, would have to proceed at exceptionally high levels to either reliably detect the presence or declare the absence of the agent. This issue can be overcome by preferentially sampling hosts known to be at a higher risk of containing the agent. Although the terminology describing such approaches varies both within and between disciplines, they are commonly termed "targeted" or "risk-based" approaches (Hoinville et al., 2013; ISPM 6, 2019). Whilst the central tenet of these surveillance activities is that not all hosts or geographical areas are equal when it comes to surveillance value, there are a wide variety of ways in which this is translated into practice. Sampling sites may be selected based on their spatial location, as has been commonplace for plant pests and pathogens for some time – generally manifesting as increased surveillance close to ports of entry or known infected areas (Bulman, 2008; Carter, 1989; Lance, 2003). In these cases, pathway models of trade movements are commonly used to quantify the incursion risk when planning such surveillance activities (Douma et al., 2016; Kalaris et al., 2014; Magarey et al., 2011), although recent approaches using large datasets of movements also have shown promise (Gottwald et al., 2019). Another approach is to consider selecting individuals based on the attributes of the hosts themselves (Stärk et al., 2006). This is commonly achieved by using statistical models to identify epidemiological "strata" within a population and quantify their relative risk of infection (Doherr & Audigé, 2001; Hadorn & Stärk, 2008; Martin et al., 2007). Approaches based upon methods such as this have been used to plan surveys to declare the absence of pests and pathogens of both animals (Calistri et al., 2018; EFSA, 2012) and plants (Lázaro et al., 2020).

Climatic Approach to Risk

When considering the spatial distribution in surveillance activities, modelling and mapping the potential distribution of threatening pests is used to quantify the risk of establishment in a new area (Lantschner et al., 2019; Srivastava et al., 2019). Identifying which regions are at highest risk of invasion can improve early detection and rapid response measures by providing information on where to concentrate surveillance resources and efforts to detect the pest or disease (Reaser et al., 2020). InterSpread Plus® (ISP) and the North American Animal Disease Spread Model/Animal Disease Spread Model (NAADSM/ADSM) are the most used applications to simulate animal disease spread and control (APHIS, 2020b).

Climate is typically the dominant variable for risk mapping because of its usefulness as a regional-scale indicator of environmental suitability for organisms (Sutherst, 2014). Spatialized temperature and precipitation data are freely available from databases such as WorldClim (Fick & Hijmans, 2017; WorldClim, 2020), CliMond (CliMond, n.d.; Kriticos et al. 2012), and PRISM (Parameter-elevation Relationships on Independent Slopes Model) (Daly et al., 2008; PRISM, 2021). Risk of establishment also may be influenced by anthropogenic factors (e.g., eradication efforts and assisted dispersal) and biotic factors (e.g., host availability, natural enemy limitations, and interspecific interactions (Lantschner et al., 2019). However, incorporating these factors into risk models is complicated by a lack of understanding of the mechanistic underpinnings of their effects, and how they may change in new environments (Lantschner et al., 2019; Srivastava et al., 2019).

Pest risk maps of modelled climate suitability may be generated via correlative or process-based approaches (reviewed in Lantschner et al., 2019; Srivastava et al., 2019). Process-based distribution models include parameters that describe how environmental factors directly influence the development and survival of a species, such as temperature thresholds and stress limits (Evans et al., 2016; Kearney & Porter, 2009). Conversely, correlative models involve statistically linking spatial environmental data to species distribution records, and do not require knowledge of the mechanistic links between climate and the biology of a target organism (Elith & Leathwick, 2009). While correlative models are more widely used than process-based models, they are thought to be less reliable in predicting a species' potential distribution in novel climates (Evans et al., 2016; Kearney & Porter, 2009).

As an example, the CLIMEX software (Hearne Scientific Software, Melbourne, Australia) is a widely used modeling tool for pest risk mapping (Lantschner et al., 2019). The CLIMEX model uses a process-based approach to give an overall measure of the suitability of a location for long-term persistence by a species (Sutherst, 2014; Kriticos et al., 2016). It considers multiple factors that either contribute to or limit growth and survival of a species, including heat and cold stress, wet and dry stress, and the minimum number of heat units (degree-days) that must accumulate to support reproduction (Kriticos et al., 2016). CLIMEX model parameters are fine-tuned, and the model is fitted using observations from the species' known geographical distribution, although laboratory collected data may help with parameterization (Sutherst 2014; Kriticos et al., 2016).

Pest risk maps of modelled climate suitability are typically based on **climate normals** because these data are available at global scales, whereas real-time (current) climate data are limited to certain countries or regions (e.g., PRISM data is generated solely for the continental United States, CONUS). This facilitates developing a model for a species whose current range may extend across several countries, and then predicting the potential distribution in a new region. However, biosecurity practitioners should consider that a model based on averages of historical climate may produce unrealistic predictions of present-day climatic suitability due to rapid climate change in recent years, and that climate averages may essentially erase signals of extreme weather events (e.g., hard freezes, heat waves) that may influence suitability. See for example, changes in distribution of important tick vectors of disease (Marques, et al., 2020; Saleh, et al., 2021).

Considering Epidemiology and Ecology When Planning Surveillance

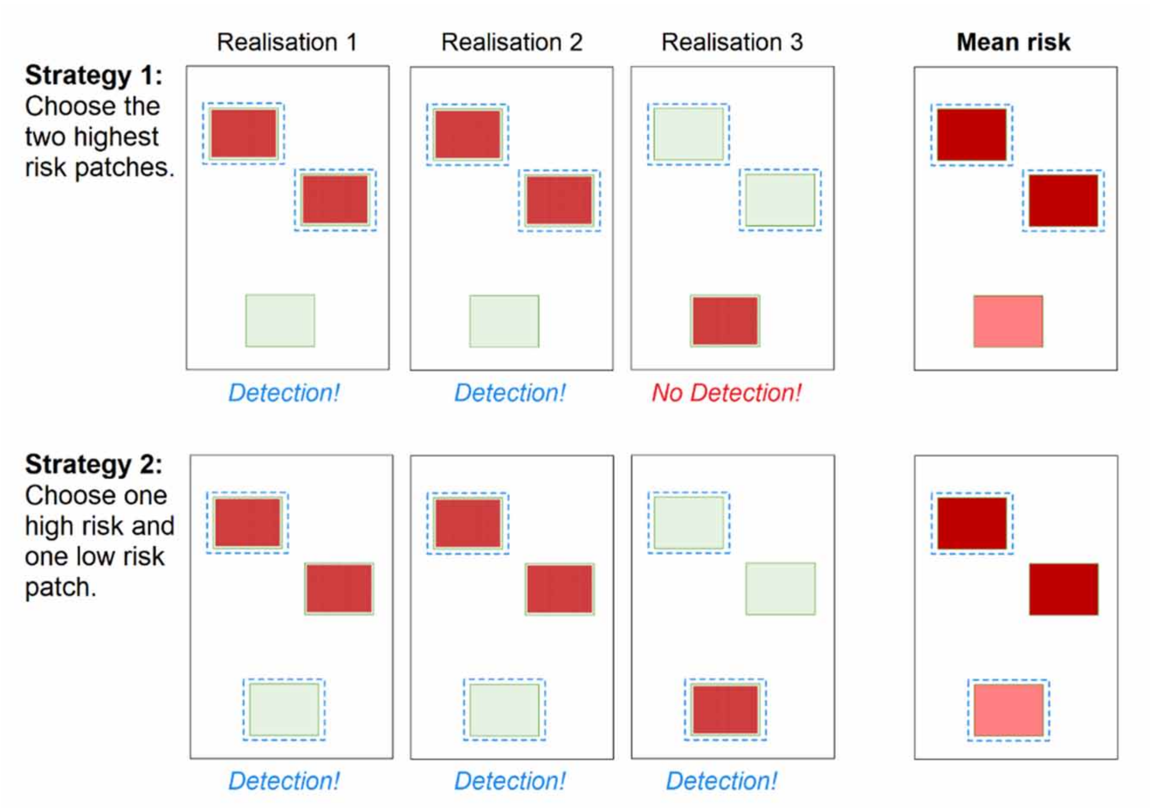
The entry and spread of pests and pathogens are dynamic processes, and as such the performance of surveillance activities is affected by the epidemiological and ecological factors underpinning these temporal and spatial dynamics. Considering these first in a nonspatial context, one characteristic of early stage spread of new pests and pathogens in areas with large numbers of susceptible hosts is exponential growth. This means that as the levels of the agent increase, the probability of detecting the agent for the first time would be expected to initially increase (as the pest becomes more widespread) and then decrease (as the probability of having failed to detect earlier decreases). This pattern allows one to predict the expected level of an agent at either the time of first detection or in the absence of any detections given knowledge of the initial exponential growth rate of the agent, the test performance (the diagnostic sensitivity and the duration of the lag period before detection is possible), and the intensity of sampling (Alonso Chavez et al., 2016; Bourhis et al., 2019; Mastin et al., 2019; Mastin et al., 2021b; Parnell et al., 2012, 2015). These same ideas also can be applied to heterogeneous systems in which the agent moves between different "strata", such as a vector-borne pathogen moving between a stratum of plant or animal hosts and a stratum of arthropod vectors. In these cases, a key additional requirement is an estimate of the relative prevalence in each stratum during early stage spread. This can be obtained from analysis of a compartmental model of pathogen spread between hosts and vectors – thereby relaxing the requirement for empirical estimates of the prevalence, which may be challenging to obtain for an exotic pets or pathogen (Mastin et al., 2017; Mastin et al., 2021b). These methods allow the estimation of the prevalence of infection in hosts at the time of first detection or in the absence of any detections for a given sampling effort amongst hosts, vectors, and therefore the sampling effort required to detect infection before a given host prevalence is reached. Interestingly, the total required sample size generally is minimized when a single stratum (the one with the highest prevalence of infection during early stage spread) is selected for surveillance (Ferguson et al., 2014; Mastin et al., 2017), and this stratum can be identified analytically from a relatively small number of epidemiological parameters (Mastin et al., 2017; Mastin, et al., 2021b).

As well as increasing in number following initial entry, new pests and pathogens also would be expected to spread spatially. A limitation of using potential establishment to target surveillance is that it does not account for the process of entry and onward spread. That a particular location is suitable for a pest does not mean that the pest has a high likelihood of arriving there. Conversely, that a particular location has a high risk of entry does not mean that establishment and spread will take place. These issues would be expected to be particularly pronounced for plant pathogens, where the distribution of susceptible hosts would be expected to have a considerable impact on pathogen spread, but also for many vector-borne pathogens for which spread patterns may be influenced by environmental heterogeneity. Wind-borne arthropods, mosquitoes, midges, and/or ticks can quickly spread high-threat animal pathogens including protozoal and viral pathogens (Yanase et al., 2020; Folly et al., 2020). Pest entry and spread models can be combined with data on host distribution and climatic suitability to predict where and when disease will occur, as well as provide estimates of how much surveillance is required to achieve early detection.

The risk of spatial spread to any given location will be influenced by agent dispersal patterns, the distribution of suitable hosts, and the environmental suitability, as well as the site of entry. These considerations have been captured in a risk-based sampling framework developed to identify where to target surveillance efforts for plant pathogens (Parnell et al., 2014). Under this approach, the region of interest is divided into grid cells, and for each the product of the probability of infection (determined by the dispersal characteristics of the pathogen and the landscape connectivity) and the predicted size of an epidemic if entry did occur (as captured by the basic reproduction number, R_0, which would be expected to be associated with the host density in the cell along with other pathogen-specific factors) is estimated. The use of this method was demonstrated for the economically important plant pathogen, *Candidatus* Liberibacter asiaticus (the cause of the citrus disease huanglongbing; HLB) in Florida (Parnell et al., 2014). Risk-based survey methodologies such as this have been used routinely in Florida since 2006, not only for HLB, but for a range of citrus pests and pathogens (Gottwald et al., 2007; Parnell et al., 2014, 2007). These approaches have been expanded and are currently conducted multiple times per year across the citrus acreage in all citrus producing states (Florida, Louisiana, Texas, Arizona, and California) (McRoberts et al., 2019).

A consideration when planning surveillance is how well a particular surveillance strategy performs in terms of achieving a given surveillance aim. Although methods based on host or site-specific "risk" provide a flexible and transparent methodology for the identification of where best to place surveillance efforts, they do not explicitly quantify how well surveillance performs. Additionally, effectively capturing "risk" can be challenging, since it could relate to a variety of processes, including the potential for establishment (such as climatic suitability or the host density), the probability that an agent actually enters and establishes (which also requires consideration of host connectivity and agent spatial spread

Figure 4. Impact of correlation in site status on detection probability
Only three patches are considered and represent patch status as a dichotomous variable (infected, shown in red (dark), or uninfected, shown in green (light)) rather than considering dynamic trends over time. Over the three simulated outcomes (realizations) considered, the top two patches become infected more frequently than the lower one and would therefore likely both be selected if site selection was based on infection risk (selected sites have a dotted outline). However, if we assume that infected patches will always be detected if visited, sampling these patches will consistently fail to detect infection in the 3rd outcome. Instead, selecting one of the top two patches and the lower patch maximizes the overall detection probability
Source: Mastin et al., 2020



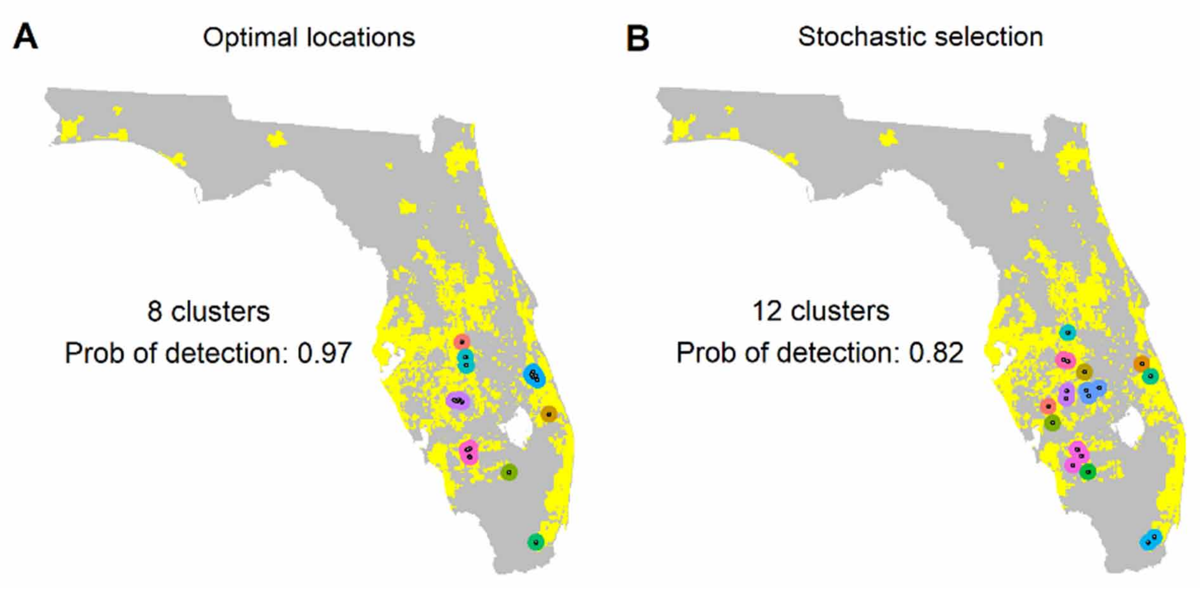
patterns), and the magnitude of the impact if the agent establishes. The question then arises whether an "optimal" arrangement of sites which achieves a given surveillance aim can be identified without quantifying risk. To do this, we need to consider both the performance of the detection method (which will affect the relative value of surveillance in any given site) and the **stochasticity** and variability in the entry and spatial spread of the agent (which will result in the status of certain sites being correlated with each other). As these will impact upon each other, they must be considered simultaneously. This is represented in Figure 4, which shows two different sites selection strategies – one in which sites are selected purely on risk (Strategy 1), and one in which sites are selected from distinct "risk clusters" which capture the correlation in infection status (Strategy 2). While Strategy 1 would be expected to maximize the mean number of detections per outcome, the mean probability of detection per outcome is lower than Strategy 2. While the above is true when the ability to detect infection in a selected site is high, Strategy 1 may give a higher detection probability than Strategy 2 when the ability to detect infection in a selected site is low as infected sites may be missed.

Stochastic spatial simulation models can be used to capture the degree of spatiotemporal correlation in site infection during early stage spread, allowing us to capture the concepts shown in Figure 4. These models can be parameterized using a relatively small number of variables relating to agent entry and spread, either based upon available data or adjusted to reproduce expected spatiotemporal spread dynamics and run up to a predefined maximum prevalence or abundance. The ability to detect infected sites can be estimated given some knowledge of the sampling effort per site and the performance of the detection method used (diagnostic sensitivity and detection lag). From these, the probability of detecting the agent in any given site over the course of early stage spread, and the probability of at least one detection for any given selection of sampling sites (i.e., a particular "survey arrangement") can be estimated. By running multiple simulations, the variability in the spread of the agent through the landscape, and by extension the variability in the detection probability for any given survey arrangement, can be captured. The mean of these outcome-specific detection probabilities provides a single metric – the "mean detection probability" – for each survey arrangement which captures both the expected correlation and variability in site status and the ability to detect a pest or pathogen.

While it is relatively easy to estimate the mean detection probability for any given survey arrangement, the question of what this arrangement should look like is more challenging. Due to the sheer number of potential locations in a typical landscape, the number of possible combinations of selected sites is likely far too high to consider enumerating all possible survey arrangements. Instead, a computational optimization routine to approximate the arrangement of sites which maximizes (or minimizes) a carefully chosen "objective function" can be used (Mastin et al., 2020). In the case of early detection surveillance, the mean detection probability provides a useful objective function, but alternatives could be used, according to the particular surveillance aim in question (Mastin et al., 2021a). As this method considers surveillance in isolation of any control strategies which would be required following detection, economic considerations associated with control are implicitly captured by selecting an economically acceptable maximum level of the pest or pathogen, although some economic considerations such as the estimated costs of moving between sites could be captured by adjusting the objective function used in the optimization step. Alternatively, other methods are available for the investigation (Rimbaud et al., 2019) or optimization (Bussell & Cunniffe, 2020; Epanchin-Niell et al., 2012; Mehta et al., 2007) of combined surveillance and subsequent control activities.

As well as offering valuable theoretical insights into surveillance strategy, such as the impact of the diagnostic test performance on the survey arrangement and the differences between optimal and conventional site selection methods, optimization-based surveillance planning has direct applied value. As the method quantifies spread in real-world landscapes and the performance of the detection method, optimal survey arrangements can be precisely targeted, and the impact of epidemiological uncertainties explored. Although not yet evaluated in the field, when using the example of HLB, the optimization method outperformed all other approaches based on quantification of "risk" within sites, such as probability of pathogen entry, host density, and the product of these, as represented in Figure 5 and was resilient to parameter misspecification. Indeed, many of the suggested surveillance sites correlated with sites found to be infected during the early stages of spread, suggesting that approaches such as this could have considerable value in planning and implementing surveillance strategies.

Figure 5. Performance of optimized sampling (A) in contrast to conventional site selection strategies (B). These plots show the distribution of 20 sites selected using the optimized approach assuming a diagnostic sensitivity of 0.5 (A) and selected with a probability proportional to the mean end prevalence. Clusters are defined as sites within 20 km of each other. Shaded areas represent citrus production.
Source: Mastin et al., 2020



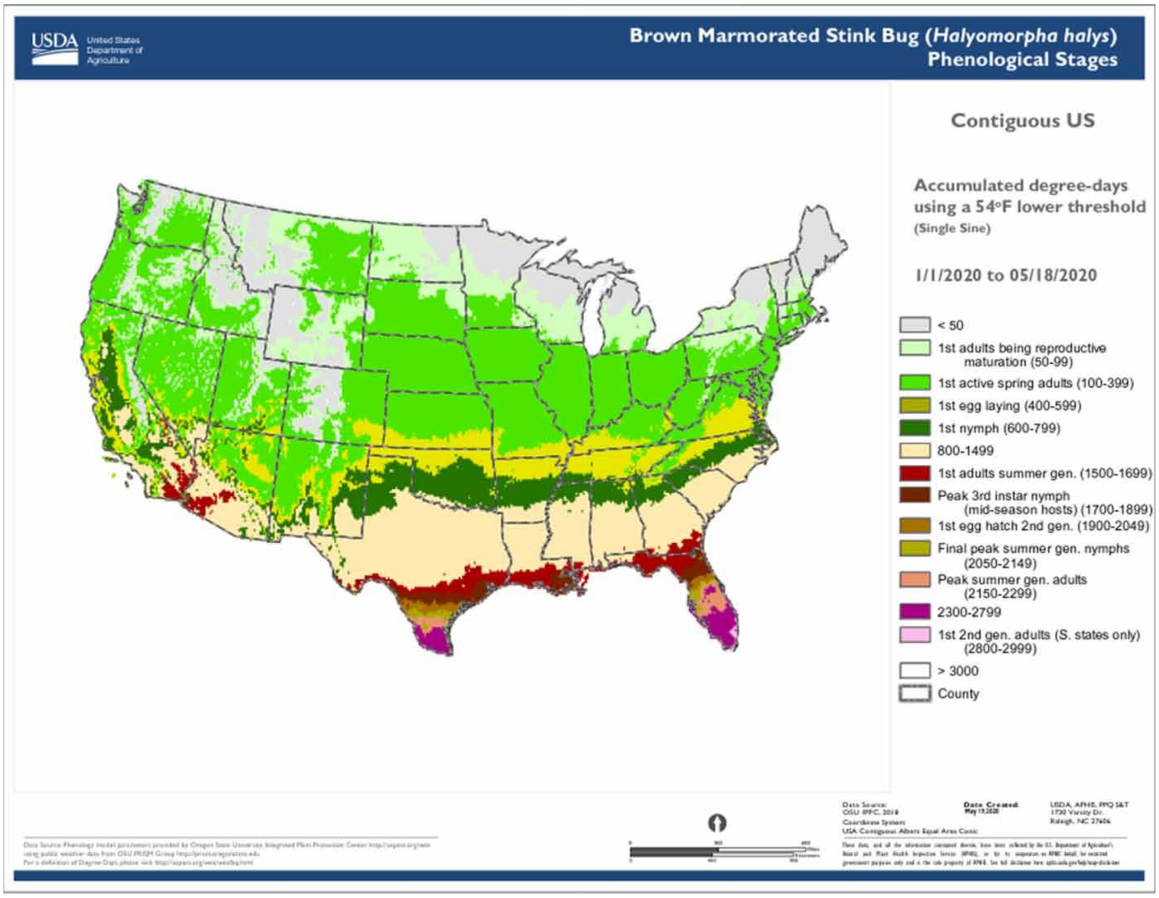
When is the Appropriate Time to Carry Out Surveillance Activities?

Following the question of *where* to conduct surveillance is *when* to conduct surveillance activities. Knowing when to deploy resources can improve the timing of surveillance, e.g., when to deploy traps or collect samples, and thus conduct surveillance activities in a more efficient and economic manner. The case study on **vesicular stomatitis** explores this concept in terms of animal health.

Modeling the **phenology** (seasonal activities) and life-cycle development of the target organism is a standard method used to improve the timing of surveillance. Classically, a two-dimensional (temperature and time) heat unit is the primary driver of phenology models. Most phenology models measure heat units as degree-days, which are calculated using daily minimum and maximum temperatures (T_{min} and T_{max}, respectively) and the lower (and sometimes upper) developmental threshold of a target species (Pruess, 1983; Wilson & Barnett, 1983). Degree-day accumulation is tracked over a daily time step to predict the timing of transitions to life stages and stage-specific events (e.g., first adult flight and first egg laying). The simplicity and ability of degree-day models to accommodate multiple species with varying life-histories have made them popular decision support tools for detecting and managing invasive pests (Coop & Barker, 2020; Crimmins et al., 2020).

A host of phenology modeling desktop software and web platforms have been developed to support decision-making related to preventing the establishment and spread of invasive pest species in the United States (reviewed in Coop & Barker, 2020). These offer users an opportunity to model the phenology of multiple species at single locations (site-based model) or across a certain area (spatialized model). Web-based phenological mapping platforms for pests include Michigan State University's Enviroweather (2021), uspest.org (2021), Oregon State University's **D**egree-**D**ays, **R**isk, and **P**henological Event Map-

Figure 6. Example degree-day lookup table map using the brown marmorated stink bug (Halyomorpha halys) model from the SAFARIS APHIS, PPQ Field Operations Weekly map series, The map uses a degree-day lookup table to associate cumulative degree-days with predicted life-stages present across CONUS on 5/18/2020. Thus, it provides a "snapshot in time" of phenology model predictions for a specific date and pest.



ping (DDRP) platform (Barker et al., 2020; DDRP, 2021), the USA National Phenology Network (Crimmins et al. 2017; USA-NPN, 2021), and the Spatial Analytic Framework for Advanced Risk Information Systems (SAFARIS, 2020), among others.

Phenological maps (i.e., a spatialized model) are typically of greater use to biosecurity practitioners than site-based models because surveillance activities occur across numerous localities. For example, the USDA, APHIS, CAPS program supports and oversees national and state surveys targeted at species of foreign and invasive plant pests. Maps that predict the timing of phenological events such as first spring flight are important for detection and monitoring program because they facilitate timely surveys and trap placement (Barker et al., 2020, Crimmins et al., 2020). These predictions are also relevant to eradication or management of established pests, because optimally timed operations (e.g., pesticide applications, sterile insect releases, and pheromone mating disruption) are more effective and cost-efficient.

Degree-day lookup table maps provide a “snapshot in time” of phenology model predictions for a specific date. When generated over multiple days or weeks, they provide a gradually changing view of the current or near-future status of pest phenology. For example, USA-NPN Pheno Forecast maps (USA-NPN, 2021) have versions that include 7-day National Digital Forecast Database (NDFD, 2021) forecasts to provide a 1-week “look ahead” prediction. Another example is the SAFARIS PestCAST (SAFARIS, 2020) maps that include a 1-month forecast that use the same 7-day NDFD forecast followed by three weeks of recent 20-year average PRISM data. As an example, Figure 6 shows a degree-day lookup table map for the brown marmorated stink bug (*Halyomorpha halys*) produced by SAFARIS for a weekly map series (FO Weekly). Predictions of where first adults are reproductively mature and active on any given date could help ensure that surveillance activities are optimally timed in the spring.

The workflow of generating a degree-day lookup table map involves using gridded T_{min} and T_{max} data from PRISM or other sources to calculate degree-day accumulations between a start date (usually January 1, although some models use other start dates) and a specified end date. Degree-day lookup tables are then used to associate degree-day accumulations with life stages, and output maps depict the results with color tables and legends. The simplicity of this approach and its applicability to multiple organisms has sustained its use for years.

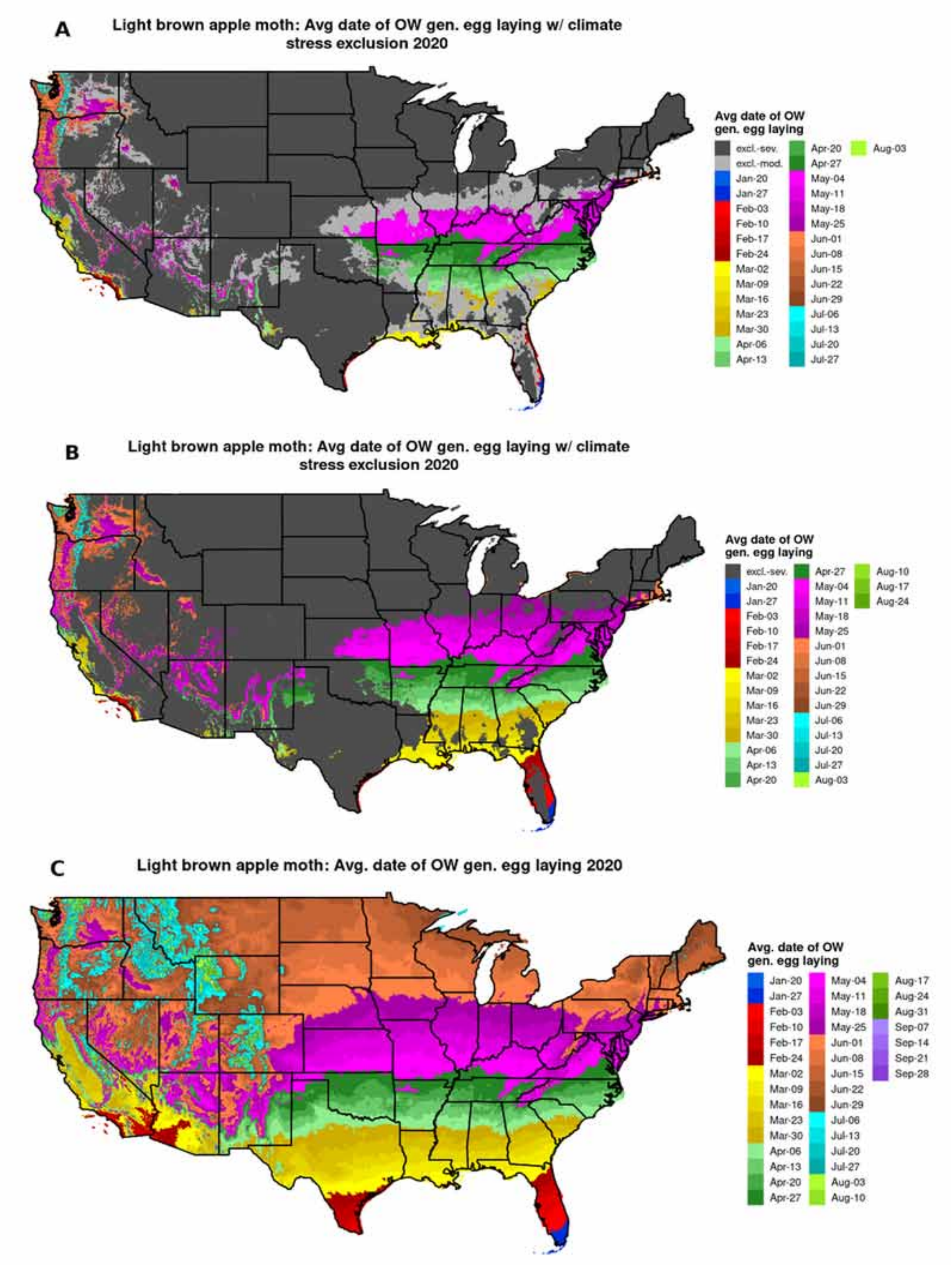
In contrast to a degree-day lookup table map, a phenological event map (or Pest Event Map; hereafter, PEM), depicts the *dates* on which accumulating degree-days reach a value (target degree-day total) that corresponds with a phenological event for a **poikilothermic** organism, an animal whose internal temperature varies considerably (Barker et al., 2020; Grevstad & Coop, 2015). As an example, Figure 7 shows PEMs produced by DDRP which depict the average oviposition date by the overwintering generation of light brown apple moth (*Epiphyas postvittana*) for 2020.

Pest Event Maps could be considered a more operational (tactical) product than degree-day lookup table maps because predictions may be generated weeks or months into the future. For example, a decision-maker may want to start planning their trap-setting operations several weeks before the estimated date of first spring flight. Additionally, dates are straightforward to interpret, which facilitates direct communication of operational support and the comparison of year-to-year variations of events.

Integrating Predictions of Where and When

Although degree-day models have been widely used for many years, they have not integrated information on risk of establishment and spread, which would offer answers to the questions of both where *and* when to survey for one or even multiple pests. Consequently, biosecurity practitioners would need to find or

*Figure 7. Example phenological event maps for light brown apple moth (Epiphyas postvittana) produced by DDRP for 2020. All three maps depict the predicted average oviposition date by the overwintering generation, but only maps (***A***) and (***B***) integrate predictions of climatic suitability. Map (***A***) depicts both moderate and severe climatic stress, whereas map (***B***) depicts severe stress only.*



develop two or more models to address each question separately. This situation, however, is changing. The DDRP platform, developed by researchers at Oregon State University, integrates mapping of phenology and climatic suitability to predict both where and when to expect insect pests (Barker et al., 2020).

DDRP's model outputs include gridded (raster) and graphical (map) predictions of the risk of establishment based on two levels of climate stress, number of generations, PEMs for up to four life stages and generations, and more traditional generation and stage maps (i.e., degree-day lookup table maps). Currently, the platform is being used to produce regularly updated (every three days) model outputs for CAPS Priority Pests, which are available at DDRP's homepage (DDRP, 2021). While DDRP is currently designed to model insects, its open-source code (link available at DDRP, 2021) could be modified to model other types of temperature-dependent pest organisms such as non-insect invertebrates, plants, plant-pathogenic bacteria and fungi, and insect plant and animal virus vectors.

The DDRP platform uses a process-based modeling approach in which degree-days and temperature stress are calculated daily and accumulate over time to model phenology and climatic suitability, respectively. Models are typically run using observed (recent or current) and future (forecast or recent average) temperature data to provide within-season decision support. Oregon State University has been using 4 km spatial resolution T_{min} and T_{max} from the PRISM database for real-time data, and either monthly-updated, daily-downscaled NMME (North American Multi-Model Ensemble) 7-month forecasts (Kirtman et al. 2014), or recent 10-year average PRISM daily data for forecast data.

Pest Event Maps for light brown apple moth (*Epiphyas postvittana*) produced by DDRP for 2020 illustrate the benefit of integrating predictions of phenology and climatic suitability (Figures 7A and 7B). If deployed as an operational product, a PEM that does not include climate stress exclusions (Figure 7C) could wrongly convince surveillance program directors to include areas that are not conducive to survival. For example, CAPS have conducted numerous surveys for light brown apple moth in Great Lakes and New England states in recent years but did not detect the species. This should be the case, as climate suitability models including DDRP have indicated, that establishment, and therefore detection, is highly unlikely because these areas are too cold for establishment. Using an integrated map as a standard product provides managers with knowledge of where to focus surveillance operations in the spring and could allow a significant amount of trapping personnel and resources to be re-directed to other species.

For an invasive species, areas that are not excluded by either moderate or severe temperature stress in DDRP (e.g., Figure 7A) are at highest risk of establishment because of increased population survival. Areas under moderate stress may represent temporary zones of establishment, and areas under severe stress do not allow for even short-term establishment. However, using two levels of stress may also provide a way to represent uncertainty for estimating the potential distribution. To potentially avoid under-predicting the risk of establishment, the potential distribution could be defined as areas not under severe climate stress as opposed to defining it using both stress levels (e.g., Figure 7B).

The focus of DDRP on real-time and forecasted risk of establishment at fine spatial scales (e.g., a single state or region) differs from programs like CLIMEX, which were designed to predict suitability based on coarse-scale (10′ and 30′ resolution) global climate data sets of averages of historical conditions, or on future projections from global circulation models. DDRP generates maps at a user-specified frequency, providing insight into how establishment risk changes over the growing season, and how extreme climate events such as a hard freeze may affect suitability. The climatic suitability map for the last day of the year (day 365) under investigation is usually of most interest because it provides insight into the potential distribution for an entire growing season.

Each model developed for DDRP, like all models, requires verification and testing, often referred to as validation. However, DDRP has primarily been used to model pests that are not (yet) present in CONUS (i.e., many of the CAPS Priority Pests), which hinders validating a model for this region. One exception is light brown apple moth, which has been established in California since at least 2006. Barker et al. (2020) used three population monitoring data sets for California to test the hypothesis that DDRP can correctly predict the timing of first spring egg laying and the generation length of the species. In general, they found support for this hypothesis, although there was variation in prediction error across years and regions. They also found that DDRP correctly predicted climatic suitability at most locality records for California.

DDRP models could be fitted and validated using climate data for the native or long-established range of a pest species. For example, Barker et al. (2020) used occurrence records and daily gridded T_{min} and T_{max} data (2005−2016) for Brazil to help fit a DDRP climatic suitability model for the small tomato borer (*Neoleucinodes elegantalis*) in that country. Similarly, the E-OBS daily climate dataset (Cornes et al., 2018) may be useful for fitting and validating DDRP climatic suitability models for pests in Europe. However, daily temperature data similar to PRISM are not currently known to be freely available for most countries. One solution to this issue is to use the CLIMEX program to help fit a DDRP climatic suitability model. Briefly, this involves running DDRP with historical PRISM T_{min} and T_{max} 30-year average data that matches the time-schedule of CLIMEX's climate data, and then fine-tuning DDRP parameters to maximize similarity between DDRP's and CLIMEX's predictions of temperature stress accumulation and the potential distribution in CONUS (Barker et al. 2020). Recently developed quasi-global daily temperature data sets such as CHIRTS-daily (Verdin et al., 2020) may also offer opportunities for fitting and validating DDRP models for species in any part of the world.

The use of temperature (T_{min} and T_{max}) as the sole environmental input in DDRP has sufficiently predicted the potential distribution for the insect species modeled thus far, as evidenced by validation analyses for two species (Barker et al., 2020). This finding suggests that using a relatively simple approach of temperature stress accumulations achieves a parsimonious balance between model simplicity and complexity. However, incorporating the effects of moisture stress into the climatic suitability model process would allow DDRP to model new categories of invasive pest threats including plant pathogens and weeds, and may increase model accuracy for moisture-sensitive insects.

Going forward, the development of climate data at higher temporal and spatial resolutions, both for the world and for CONUS, and the addition of non-temperature parameters to DDRP, should improve prediction reliability and, therefore, decision support. Some efforts have already been made in adding photoperiod-cued diapause parameters to DDRP, which has improved prediction accuracy for estimates of development and **voltinism** in three species of weed biological control insects (DDRP, 2020; Grevstad et al., in press). Modeling tools such as DDRP will be an important resource for guiding the design and implementation of surveillance operations for introduced pests, helping to achieve the goal of early detection.

Signs and Symptoms

When conducting detection surveillance, field observers must be trained to recognize the signs and symptoms that indicate a potential animal or plant health abnormality. However, the terminology of signs and symptoms differ depending whether one is referencing animal or plant disease.

Animal Disease

- A **sign** is a health issue that can be observed. It is an objective, observable phenomenon or evidence of disease that can be identified by others. A sign is objective. A veterinarian can usually diagnose a medical condition more easily if there are observable signs, e.g., a fever or a blister.
- A **symptom** is a health issue that is apparent only to the patient and cannot be observed by a veterinarian. It is a subjective experience that cannot be identified by anyone else but is a subjective description by the patient of a health issue. With animal disease, patients cannot describe the symptoms they are feeling, therefore diagnoses are made on observable signs.

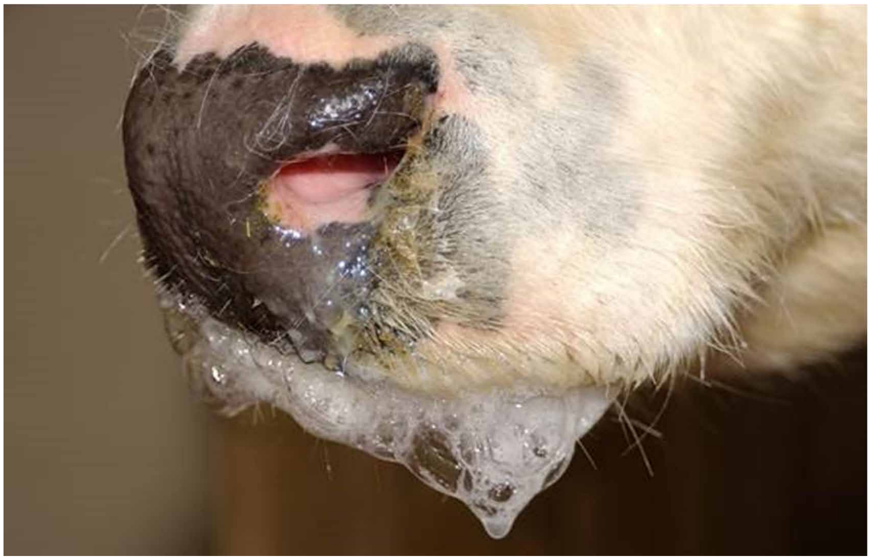
Plant Disease

- A **sign** is the physical evidence of the pathogen or pest. Fungal **fruiting bodies** are a sign of disease. Powdery mildew on a lilac leaf is the sign of the actual parasitic fungal disease organism. Bacterial canker of stone fruits causes gummosis, a bacterial **exudate** emerging from the **cankers**. The thick, liquid exudate is primarily composed of bacteria and is a sign of the disease, although the canker itself is composed of plant tissue and is a symptom. Signs are actual physical evidence of the occurrence of the pathogen in association with the unhealthy plant material.
- A **symptom** of plant disease is a visible effect of disease on the plant. Symptoms may include a detectable change in color, shape, or function of the plant as it responds to the pathogen. Leaf **wilt** and spots, with or without **necrosis** (the death of cells or tissue, usually accompanied by darkening to black or brown color) and **chlorosis** (the failure of chlorophyll development, caused by disease or a nutritional disturbance; fading of green plant color to light green, yellow, or white) are typical symptoms of plant pathogens causing disease. One does not actually see the cause of disease, but rather a result of the presence of the pathogen or pest.

Animal Pathogens

As stated previously, one of the first steps in surveillance of animal pathogens usually involves clinical observation and recognition of disease signs caused by the pathogen, followed by laboratory testing. In some cases, different diseases cannot be distinguished by the signs alone (Figure 8). The clinical signs of vesicular stomatitis infection primarily occur in cattle, horses, and pigs. Signs follow a typical viral incubation period of 3 to 7 days with an initial febrile period followed by **ptyalism** in cattle and horses (Bennett, 1986; Knight & Messer, 1983; Reif, 1994). Lesions of the oral mucosa include raised, blanched, and rarely fluid filled vesicles. The dorsal lingual surface often is affected but the gingival surfaces, palate and mucocutaneous junctions may also exhibit lesions (Reif, 1994). Vesicles are very short-lived and rupture leaving ulcerations and erosions. Lesions often coalesce to form large, denuded areas of oral mucosa with the presence of epithelial tags. Vesicular and/or ulcerative lesions outside of the oral mucosa occur on the snout of pigs, teats of cattle and coronary bands of pigs, cattle, and horses. Teat lesions are not as common as oral lesions but in cattle may be associated with severe mastitis. A similar pattern of clinical signs is seen in vesicular stomatitis, **Foot-and-Mouth Disease**, contagious **ecthyma**, poxvirus and pseudocowpox, and only laboratory testing can definitively discriminate one of these diseases from the other.

Figure 8. A wide range of important animal diseases are the so-called "vesicular" diseases, including vesicular stomatitis and foot-and-mouth disease (FMD). Excessive salivation followed by the appearance of blister-like lesions is seen in vesicular stomatitis, FMD, contagious ecthyma, poxvirus, and pseudocowpox. Only laboratory testing can definitively discriminate one of these diseases from the other.
Source: Photo source: United States Department of Agriculture



It is critically important to test any animal with clinical signs quickly to identify which pathogen is causing illness. Veterinarians and livestock owners who suspect an animal may have vesicular stomatitis or any other vesicular disease should immediately contact State or Federal animal health authorities. Diagnosis of the disease cannot be made based on clinical signs. Testing of samples at a facility approved by the U.S. Department of Agriculture's National Veterinary Services Laboratories (APHIS, 2021b) may be required. In either case, having the right diagnostic assays, be it isolation and culture, biochemical assays, immunoassays, or various molecular assays, is critical to the successful outcome of pathogen surveillance. Diagnostic methodologies and assays are covered in detail in another chapter of this book, so we leave it to the reader to fully invest themselves of this topic because it is so critical to a successful outcome.

Plant Pathogens

Surveillance of plant pathogens mainly involves visual observation and recognition of disease symptoms caused by the pathogen. Symptoms can include **blight**, **blotch,** canker, chlorosis, **defoliation**, **dieback**, **exudate**, **flagging**, **gall**, **leaf spot**, **lesion**, **mosaic**, **necrosis**, **ringspot**, **scorch**, **shot hole**, **stunting**, wilt, and others as well. Often, two or more symptoms may be present on a plant or population of plants. For example, symptoms of the **select agent** *Ralstonia solanacearum* race 3 biovar 2 on geraniums include wilting, chlorosis, and necrosis (Figure 9). Signs of a pathogen also may be visible, and can include **mildew**, **mycelium**, **sclerotia**, **spores**, **pustules**, and other fruiting bodies of the pathogen. Taken together, these can be diagnostic, or at least point the diagnostician in the right direction. However, as with animal disease, diagnostic testing is needed to correctly identify the pathogen causing the disease. For instance,

Figure 9. Advance wilting and abnormal leaf yellowing symptoms (chlorosis) caused by the select agent Ralstonia solanacearum race 3 biovar 2 on zonal geraniums.
Source: The Wisconsin Department of Agriculture, Trade and Consumer Protection

other races of *R. solanacearum* may cause similar symptoms, but only race 3 biovar 2 is categorized as a select agent, so it is important to get the diagnostics right and not rely completely on symptoms.

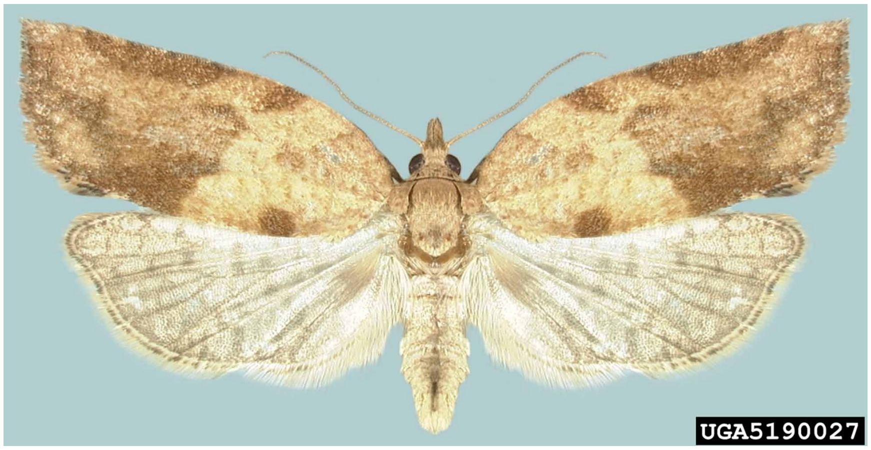
Pathogen Vectors

An important aspect in the surveillance of certain plant and animal pathogens is that some pathogens are vectored primarily by insects and other organisms. The surveillance program needs to be cognizant of this fact when planning for surveillance and may need to adjust resources to focus on the vector (Ferguson et al., 2014; Mastin et al., 2017; Mastin et al., 2021b). Ambrosia beetles vector several major plant pathogenic fungi that cause major diseases in tree species. The classic example in the United States is the spread of Dutch elm disease caused by the fungus *Ophiostoma ulmi* and vectored by three species of elm bark beetles. More recent are the emergence of Laurel wilt on redbay and avocado caused by the fungus *Raffaelea lauricola* and vectored by the invasive redbay ambrosia beetle *Xyleborus glabratus*, thousand cankers disease on walnut caused by the fungus *Geosmithia morbida* and vectored by the walnut twig beetle *Pityophthorus juglandis*, and Japanese oak wilt caused by the fungus *Raffaelea quercivora* and vectored by the oak ambrosia beetle *Platypus quercivora*, among others. A major disease threatening *Citrus* spp. is Citrus greening or Huanglongbing (HLB). This disease is caused by the bacterium *Candidatus* Liberibacter asiaticus and is vectored by the Asian citrus psyllid *Diaphorina citri*. Lethal yellowing of palms is caused by the phytoplasma *Candidatus* Phytoplasma palmae and is vectored by the planthopper *Haplaxius crudus*. Potyvirus plum pox virus is transmitted to stone fruits by about 20 different species of aphids. Many different genera of viruses are transmitted to a wide range of hosts by aphids, leafhoppers, planthoppers, whiteflies, thrips, and mites. Similarly, insect vectors are critical in consideration of animal disease introduction and spread. Blackflies, sand flies, and biting midges are the primary vector species transmitting Vesicular Stomatitis viruses. These relationships complicate the surveillance effort, but they must not be forgotten lest the surveillance results be compromised.

Insect Pests

Surveillance of insect pests and vectors create other unique challenges. Insects can be extremely mobile and fly long distances, e.g., spruce budworm (*Choristoneura fumiferana*) adults can easily disperse 20 km (Greenbank et al., 1980), or they can be more sedentary and move about slowly. Human assisted movement can be a critical factor in the dissemination of insects, e.g., European gypsy moth (*Lymantria dispar dispar*) and spotted lanternfly (*Lycorma delicatula)* or movement can be through fresh produce, soil, nursery stock, or green waste and conveyances, e.g., light brown apple moth (Figure 10). Other than a robust quarantine and inspection program, placing specific traps, with or without chemical attractant lures, is the most common methodology for insect surveillance. This takes advantage of the insect's mobility to go to the trap on its own accord if the right combination of trap, trap color, and chemical attractant is known. The challenge then is to bring together all these variables in a trap design coupled with the chemical attractants to employ an effective and efficient surveillance tool that is not cost prohibitive depending on the scope of the planned surveillance. The development of an effective and efficient trap and lure combination involves the bringing together the sciences of insect ecology, behavior, and chemistry.

Figure 10. Epiphyas postvittana, Light brown apple moth
Source: Photo by Natasha Wright, Braman Termite & Pest Elimination, Bugwood.org https://www.invasive.org/browse/detail.cfm?imgnum=5190026



Providing that adequate resources are available to get started, research to develop an attractant is needed. Collaboration with researchers in locations of the pest's origins now needs to be established and certified and permitted containment facilities need to be established. Once funding, research collaborations, a containment facility, and permits are in place, initial work can begin to collect insect and host material in both the native and local invasive range. Work can begin establishing effective rearing protocols involving host plant materials, artificial diets, and the correct environmental conditions. A healthy population of the target species is critical to the work that is yet to come.

Learning how the target species behaves in response to stimuli gives valuable insights into how it finds a host or a mate in the environment. The collection of volatiles emitted by various host plants, or different parts of plants, is an important first step to study the role of the host plant in the behavior of the target species. One of the most often used behavioral bioassays in chemical ecology research to study how arthropods locate their hosts involve the use of a device called a Y-tube **olfactometer** (Calatayud et al., 2014). This bioassay tests possible sensory stimulation responses with the observation of how the target species responds to the stimulation. It can be used to determine the attractiveness of plant volatiles to the target species, to pheromones from its own species, and/or **kairomone**s from other species. Wind, or flight tunnels also have been used to test the response of the target species to host plants and other stimuli (Cardé & Hagaman, 1979). These bioassays are important to determine specific compounds that the target species responds to for incorporation into a potential lure.

The collected natural volatiles and extracts are made of numerous compounds. To determine the compounds that make up a promising volatile or extract, an analytical method known as **gas chromatography–mass spectrometry (GC-MS)** is employed (Millar & Haynes, 2012). A GC-MS chemical analysis can identify different substances within the active insect and plant compounds. A comparison can be made between the composition of male and female collected volatiles, as well as among those of various hosts. Purification and/or synthesis of compounds of interest can then be conducted using the appropriate chemical methodology.

The antennae on insects are important sensory appendages. On the surface of the antenna, there are morphologically and functionally different types of **sensilla** that are sensitive to various chemical and physical stimuli. For instance, insects oscillate their antennae vigorously when they detect attractive odors such as sex pheromones. Behavioral studies are then conducted to determine what purified compounds cause a reaction of the insect's antennae using observation, electrodes, or other technology (Millar & Haynes, 2012). This research further narrows down the list of potential candidates that may be incorporated into a potential lure.

A short list of antennally-active compounds is further analyzed using GC-MS, **nuclear magnetic resonance** (NMR), and microchemical reactions. Nuclear magnetic resonance is used to study the physical, chemical, and biological properties of matter. For our purpose, it is used in combination with chemical tests to determine molecular identity and structure of the antennally-active materials. This knowledge will point to the chemical pathway for the synthesis of the active material if it is not commercially available. Behavioral studies are once again conducted to determine the efficacy of the synthetic attractants. At this stage, studies on the synergism of several compounds are tested along with various ratios of the attractants.

At the end of this research, one should have a good idea of what compounds and materials, and at what concentrations, will attract the target species and be suitable for lure development and field testing. For example, the lure for summer fruit tortrix moth (*Adoxophyes orana*) contains four **semiochemicals**: (*Z*)-9-Tetradecenyl acetate (Z9 -14: Ac), (*Z*)-11-Tetradecenyl acetate (Z11-14: Ac), (*Z*)-9-Tetradecen-1-ol (Z9-14: OH), and (*Z*)-11-Tetradecen-1-ol (Z11-14: OH) (CAPS, 2021a). Other species may require multiple lures. A semiochemical is a chemical compound that is released by an organism that influences the behavior or physiology of the same or different species. Therefore, the purpose of this line of research is to find a chemical, or set of chemicals, that when placed in a trap will attract the target species to the trap, and thus be caught. The more specifically efficacious the lure, the better the results will be.

The next step in the process is to determine the formulation of the lure. One needs to determine what is to be added to the lure mixture to maximize stability, shelf life, and field life, and under what conditions the lure mixture will remain efficacious (Nielsen et al., 2019). The choice of a release matrix also will need to be considered. This is the physical structure that will hold the lure formulation for storage, shipping, and attachment to a trap. For the *Adoxophyes orana* lure, the dispenser or container is a rubber septum (Figure 11). Other examples of dispensers are termed polysleeves or bubble caps, all with semipermeable membranes that allow the volatiles to escape. There are others as well. While the rubber septum is the most common, the choice of dispenser may be determined by the chemical properties of the lure formulation. Studies will then be conducted to evaluate the rate of release of the volatiles to determine if the concentration of the released volatile and how the concentration of the released volatile degrades over time. This is important information that will determine how long a lure remains viable, and when it needs to be replaced.

Figure 11. Rubber septa used to hold lure formulations
Source: United States Department of Agriculture

Experimental trap design is the next step in the process. Shape, size, and color all are part of the overall effectiveness of the development program. Knowledge about the flight pattern of the target species, what shapes it is attracted to, and the ability of the species to escape the trap are all important considerations in effective trap design. With the advent of 3D printers and the correct software, different aspects of a design can be tested and modified in a relatively short period of time. Perhaps the most important aspect of trap design is the color or color combination. For some species, it makes no difference, but for others it makes a large difference. Behavioral studies can be conducted to determine a response to different colors, or shades of a color. These can be conducted in flight tunnels. **Electroretinogram** studies also can be conducted where electrodes are inserted into the insect's retina, and an electrical response can be measured in response to different color stimuli. For example, with emerald ash borer (EAB, *Agrilus planipennis*), a purple-colored trap is more efficacious when placed on the trunk of an ash tree, whereas a light-green colored trap is better suited when trapping for EAB in the tree canopy (Crook et al., 2009).

Once potential trap and lure formulations have been identified, field testing needs to take place in the target species' native range, to determine if it will attract the target species. The collaborators identified previously will be an enormous help in setting up, monitoring, and collecting results. Analysis of the results may lead to modifications to the trap design and/or reformulation of the lure, and further field tests to address the modifications. This will be an iterative process until an effective trap design and lure formulation are determined for the target species.

The last step before a trap and lure can be deployed in a surveillance program is the procurement of the trap and lure. If a trap is not already commercially available, then a Statement of Work (SOW) will need to be developed with the exact description and dimensions of the trap for a manufacturer to accurately produce the traps in the quantity needed. Whether this needs to be put out for bid, or singularly contracted, will be determined by the organization developing the trap and/or conducting the surveillance. Likewise, for the lure. In many instances in USDA, APHIS, the semiochemicals are purchased separately and formulated inhouse to specifications, and then added to the release matrix or dispenser. In other instances, the semiochemicals may not be readily available from commercial sources. A contract or other form of agreement may need to be developed with a researcher or company to synthesize and deliver the ingredients or the final lure to the desired specifications. The contract will specify whether the complete, packaged lure in the dispenser will be the product delivered, or just the chemical lure to be placed in the dispenser either inhouse or elsewhere.

The Importance of Standard Methodology

The documentation of negative data in a surveillance program is extremely important. While a positive detection often comes from outside an ongoing surveillance program and from various sources using different methodologies, the implementation of standard and scientifically based survey methodology is the cornerstone of valid negative data. Negative, or absence, data from surveillance strengthens and facilitates trade and the safeguarding of agriculture and the environment. Therefore, all surveillance programs should strive to ensure that all negative data is valid and consistent. This is the end result of putting the necessary effort into determining what pests and pathogens to target, determining what pests and pathogens are of primary importance, where and when to conduct surveillance activities for high priority pests and pathogens, and to develop standard surveillance methodology so that surveillance results are directly comparable across state, regions, and countries. It is then vitally important that all these facets of the surveillance program be properly documented so that agricultural producers and trading partners accept the surveillance results.

To ensure consistency and standardization across the country, the CAPS program in the United States developed the Approved Methods for Pest Surveillance (CAPS, 2021a). These methods, including specific trap and lure combinations and diagnostic tests, are the only survey methodology accepted by the CAPS program to report valid negative, or absence, results. As with any surveillance program designed to survey for pest and pathogens not known to be present, the CAPS program strives to ensure that all negative data is valid and scientifically sound (ISPM 6, 2019). Likewise, the NAHLN has established and implemented standards to ensure confidence in diagnostic test results, both domestically and internationally, including quality management systems, standardized testing, training of personnel, assurances of secure communication, and preparedness (APHIS, 2021j).

Where and How to Store and Maintain the Data

The final question to ask when establishing or reviewing a surveillance program is where or how to store the resulting survey results and other information. While the topic is at the end of this chapter and is the final destination or repository for the data, it likely should be one of the first questions asked of the surveillance program, and not be an afterthought. Determining what data and information to collect, what is needed for further analyses, and how to present and share the information are all critically important. Applicable privacy laws that include and restrict sharing of Personal Identifiable Information (PII) and organizational data sharing policies need to be considered as well. The data management initiative should be developed in parallel with the surveillance aspects of the program and should complement and support the surveillance.

As an example, in the United States the CAPS surveillance program was established in the early 1980s. By the mid-1980s, an early version of National Agricultural Pest Information System database (NAPIS, 2021) was developed at Purdue University. The NAPIS database now houses over 5.44 million summarized survey result records for 6,394 insects, pathogens, weeds, mollusks, and biological control organisms. Access to the NAPIS database is controlled and role-based to preserve the integrity of the stored information. Rules and approval processes have been developed to prevent changing the data but allowing corrections to be made to ensure that the information is valid. One of the most important system rules implemented validates negative data entry against the approved surveillance methods for each pest prioritized for survey (CAPS, 2020, 2021a). Negative data not conforming to the approved method is not accepted into the database (<u>confirmed</u> positive data can be entered from any source or methodology). The NAPIS database validates the incoming information in that it not only checks that the required fields contain the correct type of information, but that the required fields contain the correct information. In this manner, the approved surveillance methods are enforced, resulting in validated negative data. The data collection, maintenance, and storage systems developed over time along with the surveillance program to meet the program's needs.

Sharing the Results of Surveillance

Sharing information and data outside of one's organization can be problematic based on local and organizational privacy laws, regulations, and rules, and the data sharing policies of the organization. Memoranda of understanding that spell out data sharing policies may need to be signed between and among cooperators and outside organizations where each side agrees to protect the information. Yet, the sharing of information and data does need to occur to promote cooperation and facilitate trade. Cooperators and trading partners will need to review and evaluate the data. Therefore, it is necessary to have valid data backed by scientifically sound surveillance methodology, and to have it available for review.

Following the example from above, summarized results from the NAPIS database are shared with cooperators, trading partners, and the public through the Pest Tracker (2021) website. The Pest Tracker website contains survey results summarized at the county level for over 140 pests and pathogens. The website contains pest and pathogen information, county-level survey maps for the last 10 years for most pests, state-specific information to include planned surveys for the current year, and contact information, as well as outreach material and videos. The Pest Tracker website is the forward-facing outreach component of the United States surveillance program and NAPIS database. In 2020, there were 7,437 sessions of non-United States users with 11,260 page visits to the Pest Tracker website (personal communication). The Pest Tracker website fulfills the United States' obligation to make survey data available under the IPPC (2021) and ISPM 6 (2019).

The National Plant Diagnostic Network (NPDN) collects all diagnostic data from across the United States and stores it in a National Repository (Stack et al., 2006). Diagnostic laboratories in every state receive sample from client growers and state surveillance authorities. The diagnostic data feed into a centralized data system. The first time a pest or pathogen name comes up in a state, an alert is automatically sent to an APHIS PPQ identifier, adding a layer of passive surveillance to the active surveillance of the CAPS program and the NAPIS database.

On the animal side, the NAHSS system (APHIS, 2020e) gathers data from a veterinary diagnostic laboratory network, including the NAHLN laboratories (APHIS, 2020c), stores and manages the data, and provides analyses to decision makers. NAHSS includes passive and active surveillance for reportable diseases, including those reported to the World Organization for Animal Health (OIE) as well as those diseases covered by federally funded surveillance programs. In addition, the surveillance system includes monitoring for diseases that States are not mandated to report. In all cases, this data gathering involves survey methodology to detect, delimit, and monitor for specific threats. Part of NAHSS is the National Animal Health Reporting System (NAHRS) (APHIS, 2020d) which gathers data from participating State animal health officials on the presence of the National List of Reportable Animal Diseases in the United States (APHIS, 2020f). The United States meets its OIE reporting obligations using a variety of sources including NAHRS reporting, CFSPH reporting, foreign animal disease reports, national program disease surveillance reports, and others. Zoonotic disease affecting humans as well as other animal species are also tracked by the U.S. Centers for Disease Control (CDC, 2021). These reports are available through OIE (OIE, 2021).

CONCLUSION

The focus in an early detection surveillance program is to determine if a pest is present or absent in order to facilitate market access, trade and the movement of crops, forest products, animals, animal products, and other commodities and goods within a country or internationally. This chapter has summarized various components, topics, and issues that are part of an early detection surveillance program and has focused on two broad categories of surveillance: general or passive, and specific or active surveillance. These are broadly defined as gathering information from all sources and surveys targeting specific pests and pathogens, respectively. Within these two approaches to surveillance, there are multiple variations on the themes. Table 1 lists several of these different variations. Developing and deploying any of these approaches to surveillance will depend on the goals, resources, funding, and other variables available to the surveillance program. The authors suggest the reader to investigate these various approaches to understand the breadth of surveillance options that have been developed. The authors then challenge to reader to expand on what was presented and to develop surveillance programs that are more effective and efficient in achieving the overall goal of detecting and identifying foreign or exotic pests and pathogens once they pass your borders.

CASE STUDY: VESICULAR STOMATITIS (VS)

vesicular stomatitis must be considered one of the most enigmatic animal diseases of the western hemisphere and provides a particularly salient example of the influence of the environment on the introduction and subsequent expansion of disease into new areas. vesicular stomatitis viruses (VSV) are members of the family Rhabdoviridae which include viruses that infect vertebrates, invertebrates and many plant species (Wagner & Rose, 1996). Although there are many members of the *Vesiculovirus* genus, two are of particular interest in the United States, vesicular stomatitis virus - New Jersey serotype (VSV-NJ) and vesicular stomatitis virus – Indiana serotype (VSV-IN). Timely detection of disease emergence requires access to target populations, a network of laboratories to diagnose and differentiate disease, and training and awareness programs for individuals involved in handling animals and animal products for identification and reporting. Once there is a report, a timely response and investigation of suspected cases to confirm and to acquire accurate knowledge of the situation for further action is essential.

vesicular stomatitis is a disease of the western hemisphere with areas throughout South America, Central America and Mexico considered endemic. A review of vesicular stomatitis in Mexico showed that cases occurred in every year between 1981 and 1995 with both serotypes identified in most years. This review also indicated that vesicular stomatitis has a national distribution in Mexico although most cases occur in the southern states of Chiapas, Tabasco, and Veracruz. The central area of Mexico also is considered endemic although at a lower level and the northern area of Mexico is more similar to the southwestern United States with sporadic cases occurring. Outbreaks of vesicular stomatitis in the U.S. are sporadic and although once proposed to occur in a 10-year cycle, have occurred in a total of 6 years between 2010 and 2020. Outbreaks in the U.S. can have significant impacts on trade and due to the inability to distinguish vesicular stomatitis from Foot and Mouth Disease in pigs and cattle, requires extensive monitoring and investigation of positive premises by animal health regulatory agencies.

vesicular stomatitis viruses are classified as arboviruses with blackflies (Simuliidae), sand flies (Lutzomyia), and biting midges (Culicoides) as the primary vector species. Flight ranges of these insect vectors vary but none would be adequate to explain the often-large distances observed between either individual or clusters of infected premises. Backward trajectories of winds were examined for vesicular stomatitis outbreaks in 1982 and 1985 (Sellers & Maarouf, 1990). Findings from the trajectory analysis suggest the feasibility of infected insects being transported for long distances on wind currents and subsequently landing on non-infected premises many miles from the infected premises or cluster of premises. vesicular stomatitis virus is just one example, numerous pathogens exhibit lifestyles involving multiple animal hosts and insect or arthropod vectors adding significant complexity to surveillance.

With the primary mechanism of transmission of VSV by insects and arthropods, the influence of the environment could be expected. Observational, landscape scale studies conducted during outbreaks or retrospectively have identified environmental factors associated with livestock premises housing infected animals including distance of animals to various water body types, access to pasture, precipitation, and others (Hurd et al., 1999; McCluskey et al., 2003). For example, Elias et al. (2018) investigated the contributions of hydrological factors on the emergence of VSV in the western United States. Their results indicated that vesicular stomatitis positive premises were detected near stream networks. Overall, 72% of positive premises were located within 1 km of rapidly moving freshwater habitats and all index cases occurred after peak annual streamflow, with 89% occurring after streams returned to baseflow. This finding supports developing early warning surveillance for vesicular stomatitis through stream and streamflow monitoring in locally relevant geographic areas. Knowledge of the timing of streams return to baseline flows can be used to increase communications to livestock owners about insect control on individual animals and in the livestock housing environment.

Peters et al. (2020), using spatial distribution models based on human-guided machine learning, and constructed using geo-referenced harmonized maps, investigated environmental and epidemiological variables that described the relationship between vesicular stomatitis occurrence and the environment. They examined two events that were temporally and phylogenetically distinct, the first a disease incursion year (2004) and the second a disease expansion year (2005). They then tested the identified relationships identified in additional incursion and expansion years, 2014 and 2015 respectively, at a local and landscape/regional scale. Emblematic disease ecology drivers were identified (climate, drought, hydrology, land surface properties, pedology, topography) and within each driver, variables expected to influence the disease events were selected. The results presented in this study were extensive and according to the authors "yield new insight into factors governing the spatial patterns in vesicular stomatitis occurrence." Greater than 470 variables within the identified drivers were investigated with hydrology, vegetation, and climate important drivers in both 2004 and 2005, elevation important in 2004, and soil properties important in 2005. Veterinarians and regulatory officials can use these results to develop early warning strategies and enhanced communications with livestock owners about biosecurity measures and mitigations.

CASE STUDY: SOYBEAN RUST (SBR)

Detection

Soybean rust (SBR) is caused by the fungus *Phakopsora pachyrhizi* Sydow. The disease is spread by **urediniospores** transported long distances by winds (Miles et al., 2003). If they are protected from ultraviolet radiation by cloud cover, the spores may remain viable in the air for many days (Isard et al., 2006a). Soybean rust causes moderate to severe soybean (*Glycine max* Merrill) yield loss wherever established (Sikora et al., 2014). The fungus produces foliar lesions on soybean, kudzu, and other legume hosts, reducing photosynthetic area and potentially causing premature defoliation. Severe yield losses can result if defoliation occurs during the mid-reproductive growth stages of soybean (Bromfield, 1984).

Soybean rust was first reported in Japan in 1902 and was confirmed throughout much of southeast Asia by 1934 (Bromfield & Hartwig, 1980). In the early 1990s, it was found in Africa (Pretorius et al., 2001). The disease was detected in Paraguay in 2001 (Morel et al., 2004) and spread throughout South America over the next 3 years. During this period, the USDA began preparing for a U.S. incursion of SBR by supporting education, training, and surveillance programs, enhancing diagnostic facilities, backing offshore fungicide evaluation trials, funding risk assessments, and searching breeding materials for novel sources of host plant resistance (Livingston et al., 2004). The sense of urgency stemmed not only because *P. pachyrhizi* had demonstrated aerial spread among other major soybean growing areas, but also because soybean is produced on about 30 million hectares annually in the U.S., with a value between $18 and 32 billion (NASS, n.d.).

In 2003, research groups began developing models to assess the risk and pathways of *P. pachyrhizi* incursions into the United States. An aerobiology process model (Integrated Aerobiology Modeling System (IAMS)) was specified for the SBR system to simulate spore production, escape of spores from the crop canopy, turbulent transport and dilution in the atmosphere, survival of spores while airborne, deposition of spores into a soybean crop, and colonization of a soybean crop (Isard et al., 2005). Field research was conducted during January and February 2004 in Paraguay to parameterize spore production, escape, and survival stages (Isard et al., 2006a). Historical meteorological data (1999-2004) were then used to simulate daily spore movement from the infected soybean production region in southern Brazil and Paraguay. The IAMS model output revealed that aerial movement and deposition of viable spores in the U.S. was not likely to occur from this region. However, simulations indicated that the pathogen was likely to spread into areas north of the equator in South America. Model runs were also conducted for days between July and September in the historical dataset for soybean production areas in Venezuela, Roraima State in Brazil, Guyana, and Suriname assuming that soybean rust infestations were present in these regions. The output from these simulations revealed that deposition of viable spores would occur primarily in Central America and that the deposition zone shifted further north with the **Intertropical Convergence Zone** as summer progressed, extending as far north as southern and eastern Mexico. There were two tropical weather systems in the five-year record that resulted in direct transport to and deposition of viable spores in the southeastern United States.

The IAMS model was then configured to run on real-time and forecast meteorological data for days during the 2004 tropical cyclone season in the Caribbean basin. In July 2004, an advanced SBR infestation was found in central Columbia (Isard et al., 2005). The IAMS simulations indicated that transport and deposition of viable SBR spores from northern South America to the U.S. could only have occurred in association with one tropical cyclone that season, Hurricane Ivan. A second aerobiological transport model using short-term climate model output also forecast the possible incursion of SBR spores into North America from the Columbia source region in association with Hurricane Ivan (Stokstad 2004). Output from the IAMS model became the basis for the USDA Economic Research Service assessment of the risk of a SBR incursion and its potential impact on U.S. agriculture (Livingston et al., 2004).

In autumn 2004, SBR was found infesting soybean fields in Louisiana (Schneider et al., 2005). The IAMS simulations conducted the evening of the discovery showed that airflows converging into Hurricane Ivan as it made landfall along the Gulf Coast had likely transported viable rust spores to the southeast United States from an infected source area in Columbia. The model output indicated that spores from the Rio Cauca source area released on September 7-9 remained viable during transport and were deposited in rain between September 15-18 in the southeastern United States. A model generated map delineating regions of spore deposition associated with the hurricane was provided to the USDA APHIS Soybean Rust Rapid Response Team and was used successfully to scout for the pathogen. *Phakopsora pachyrhizi* was confirmed by polymerase chain reaction (PCR) methodology (Frederick et al., 2002) at numerous locations in nine states in the Mississippi River valley and southeast United States within three weeks of the initial discovery and was identified but not confirmed at many other locations in the same region. Most of the positive observations corresponded to the area of spore deposition predicted by IAMS output (see Figure 5 in Isard et al., 2005). Subsequent scouting along the Gulf of Mexico revealed that soybean rust was overwintering on kudzu.

Monitoring to Determine if Establishment Occurred

During the 2004/2005 winter, the USDA implemented a coordinated framework for providing soybean growers with decision support for managing SBR including surveillance, reporting, prediction, management, and outreach components (Isard et al., 2006b). The USDA APHIS and Risk Management Agency (RMA) funded SBR monitoring allowing real-time reporting and mapping of the disease, and the development of predictive models of disease spread. APHIS and the Cooperative State Research, Education, and Extension Service (CSREES, now the National Institute of Food and Agriculture (NIFA)) provided funds to the IAMS team for the construction and operation of an Information Technology platform (Soybean Rust Information System; later named the Integrated Pest Management Pest Information Platform for Extension and Education (ipmPIPE)) to integrate soybean rust monitoring, database construction, aerobiological modeling and communications to stakeholders (Isard *et al.*, 2006b). The framework received unprecedented support from growers, national and state soybean commodity associations, agricultural businesses, and USDA agencies.

In spring 2005, soybean "sentinel" plots were established in North America to monitor for the disease (Giesler & Hershman, 2007). **Sentinel plots** were planted earlier than local commercial soybeans to provide early warning of disease and utilized a variety of soybean maturity groups to prolong monitoring throughout the season. Observations from sentinel plots were supplemented by "mobile scouting" in commercial soybean fields and neighboring kudzu sites. Mobile scouting became the predominant surveillance choice at northern latitudes once it was determined that SBR rarely occurred in the continental interior of North America.

Disease observation data were collected with a standard protocol and uploaded into the ipmPIPE database. High fungicide efficacy requires applications before the SBR reaches 5% **incidence** in the lower-canopy foliage (Dorrance et al., 2008), and thus timely communication is paramount for successful disease control. The primary use of the observation data was to populate a map on the ipmPIPE public website indicating presence of SBR in counties linked to state-specific commentary on risk and disease management. A secondary use of the data was to parameterize daily predictive models for the aerial transport and deposition of SBR which aided mobile scouting and recommendations of fungicide applications for soybean farmers.

SBR was monitored on a weekly basis during the growing season throughout the soybean growing region in the decade following its incursion into North America. Thirty-five states and five Canadian provinces established soybean sentinel plots in 2005. The number of sentinel plots in North America peaked at 984 in 2008 and expanded to include plots in soybean production areas in Mexico. By 2012, the number of plots had declined to 285 (Sikora et al., 2014), and continued to decline thereafter. Although monitoring for soybean rust continues in a few southern states today, the nationwide network and information system is no longer functional. This decline primarily occurred because SBR did not become a significant problem in the continental interior of North America. Ten years after its incursion, soybean rust had been reported in 20 states and Ontario, Canada (Sikora et al., 2014).

Due in large part to the sentinel plot system, management of SBR in North America has been highly effective. Observations of SBR in sentinel plots in southern states during the early growing season trigger timely monitoring and targeted fungicide applications in local commercial fields controlling the disease until pod set in late summer. These applications keep inoculum levels low in the southern United States. Thus, throughout most of the growing season, even when weather is conducive to northward transport of spores, the risk of soybean yield loss in the large continental interior production region of the United States and Canada is minor (Isard et al., 2011). Over time it was determined that in the south, fungicide applications were no longer necessary to protect yield once soybeans reach the late bean fill stage. However, because the pathogen often thrives and spreads aggressively in commercial fields in the late fill stages, soybean rust has been observed in the northern growing region late in the growing season (Isard et al., 2011). By late August and September when this movement occurs, most soybean plants within the continental interior are in their late stages of development and yields are no longer reduced by the disease. In short, the soybean rust sentinel plot network coupled to the ipmPIPE information delivery system enabled control of soybean rust in North America. Timely control practices in southern soybean fields suppress buildup of inoculum and delays subsequent spore movement northward, protecting the substantial acreage of soybean produced in the North American continental interior.

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KEY TERMS AND DEFINITIONS

Ambrosia Beetles: Beetles of the weevil subfamilies Scolytinae and Platypodinae (Coleoptera, Curculionidae), which live in nutritional symbiosis with fungi. The beetles excavate tunnels in dead or stressed trees in which they cultivate fungal gardens, their sole source of nutrition.

Blight: A sudden, severe, and extensive spotting, discoloration, wilting, or destruction of leaves, flowers, stems, or entire plants.

Blotch: Dead areas of tissue on the foliage, irregular in shape, and larger than leaf spots.

Canker: A plant disease characterized (in woody plants) by the death of cambium tissue and loss and/or malformation of bark, or (in non-woody plants) by the formation of sharply delineated, dry, necrotic, localized lesions on the stem.

Chlorosis: The yellowing or whitening of green plant parts as a result of chlorophyll breakdown or production failure.

Climate Normals: A 30-year average of a weather variable for a given time of year.

Defoliation: The loss of leaves from a plant, whether normal or premature.

Delimiting Survey: Surveillance conducted to determine the boundaries over an area where a pest has been detected or considered to be established or invasive.

Detection Survey: Surveillance conducted in an area over a specified period of time to determine if a pest is present or absent.

Diapause: A physiological condition or state of restrained development and reduced metabolic activity which cannot be directly attributed to unfavorable environmental conditions. Visual consequences of diapause in postembryonic stages includes lowed or suspended growth, differentiation, metamorphosis, or reproduction.

Dieback: The progressive death of shoots, leaves, or roots, beginning at the tips.

Ebola: Ebola virus disease (EVD), formerly known as Ebola haemorrhagic fever, is a rare but severe, often fatal illness in humans. The virus is transmitted to people from wild animals and spreads in the human population through human-to-human transmission.

Ecthyma: A skin infection characterized by crusted sores beneath which ulcers form.

Electroretinogram: A diagnostic test that measures the electrical activity of the retina in response to a light stimulus; used to measure photoreceptor responses in insect retinas to different wavelengths of visual stimuli so they can identify the most attractive colors, patterns, and intensities.

Endemic: Referring to a disease or condition regularly found among a particular people or in a certain area.

Epizootics: Widespread, rapid occurrence of a disease affecting many individuals or a large proportion of an animal population at same time.

Exudate: A liquid excreted or discharged from diseased tissues.

Fecundity: The ability to produce an abundance of offspring or new growth.

Flagging: An isolated, wilted, or necrotic branch with dead leaves attached.

Foot-and-Mouth Disease (FMD) or Hoof-and-Mouth Disease (HMD): An infectious, and sometimes fatal, viral disease that affects cloven-hoofed animals, including domestic and wild cattle, buffalo, sheep, goats, and swine. FMD has severe implications for agricultural trade and farming and ranching, since it is highly infectious and easily spread through contact with contaminated equipment, vehicles, clothing, and feed, and by domestic and wild predators. Its containment requires considerable efforts in vaccination, strict monitoring, trade restrictions, quarantines, and the culling of both infected and healthy (uninfected) animals.

Fruiting Body: Various shaped structures that contain the spores of a fungus.

Gall: An abnormal swelling or localized outgrowth produced by a plant as a result of attack by a fungus, bacterium, nematode, insect, or other organism.

Gas Chromatography-Mass Spectrometry (GC-MS): An analytical method that combines the features of gas-chromatography and mass spectrometry to identify different substances within a test sample; separates chemical mixtures (the GC component) and identifies the components at a molecular level (the MS component).

Hypha (pl. hyphae): A single, tubular filament of a fungal thallus or mycelium; the basic structural unit of a fungus.

Incidence: The frequency at which individuals within a specific population develop a given symptom or quality.

International Plant Protection Convention (IPPC): An intergovernmental treaty signed by over 180 countries, aiming to protecting the world's plant resources from the spread and introduction of pests, and promoting safe trade. The Convention introduced International Standards for Phytosanitary Measures (ISPMs) as its main tool to achieve its goals, making it the sole global standard setting organization for plant health. The IPPC is one of the "Three Sisters" recognized by the World Trade Organization's (WTO) Sanitary and Phytosanitary Measures (SPS) Agreement, along with the Codex Alimentarius Commission for food safety standards and the World Organization for Animal Health (OIE) for animal health standards. https://www.ippc.int/en/.

International Standards for Phytosanitary Measures (ISPMs): Standards are adopted by the Commission on Phytosanitary Measures (CPM), which is the governing body of the International Plant Protection Convention (IPPC). Standards provide guidance to contracting parties in meeting the aims and obligations of the Convention. The intention of ISPMs is to harmonize phytosanitary measures for the purpose of facilitating international trade. ISPMs can cover a wide range of issues, including surveillance, pest risk analysis, establishment of pest free areas, export certification, phytosanitary certificates, and pest reporting. The IPPC encourages adoption of these standards, but they only come into force once contracting (members) and non-contracting parties to establish requirements in national legislative instruments. Compares with the Animal Health Codes on the OIE website. https://www.ippc.int/en/core-activities/standards-setting/ispms/.

Intertropical Convergence Zone: A narrow zone near the equator where northern and southern air masses converge, typically producing low atmospheric pressure.

Kairomone: A chemical substance emitted by an organism and detected by another of a different species which gains advantage from this, e.g., a pest seeking a host.

Leaf Spot: A plant disease lesion typically restricted in development in the leaf after reaching a characteristic size; an obvious, defined lesion or area of diseased tissue, on a leaf.

Lesion: A localized diseased area or wound.

Mildew: A thin coating of mycelial growth and spores on the surfaces of infected plant parts.

Monitoring: An ongoing process to verify an event; an official ongoing process to verify phytosanitary situations, e.g., monitoring survey.

Monitoring Survey: Surveillance designed to verify the status and various characteristics of an existing pest population within a defined area; Ongoing survey to verify the characteristics of a pest population (ISPM 5).

Morbidity: The state of being symptomatic or unhealthy for a disease or condition. It is usually represented or estimated using prevalence or incidence (Hernandez & Kim, 2020).

Mortality: Mortality is related to the number of deaths caused by the health event under investigation. It can be communicated as a rate or as an absolute number (Hernandez & Kim, 2020).

Mosaic: A disease symptom characterized by nonuniform coloration, with intermingled normal, light green and yellowish patches, usually caused by a virus.

Mycelium: A mass of hyphae constituting the body (thallus) of a fungus.

Necrosis: The death of cells or tissue, usually accompanied by darkening to black or brown color.

Nuclear Magnetic Resonance (NMR): A spectroscopic technique to observe local magnetic fields around atomic nuclei; an analytical chemistry technique used in quality control and research for determining the content and purity of a sample as well as its molecular structure; used to identify monomolecular organic compounds.

Objective Prioritization of Exotic Pests (OPEP): Developed by USDA, APHIS to prioritize exotic pests according to the impacts they are likely to have if introduced into the United States. Separate models were developed and validated for arthropods and plant pathogens (including nematodes). Risk criteria consist of questions focused on biology and natural history, pest damage, research, and management elsewhere in the world. Control measures and production practices in place in the United States are also considered when predicting the potential impacts. Questions require objective, documented evidence from primary scientific literature and are statistically weighted based on their ability to predict impact. Each model predicts the likelihood each organism will cause high, moderate, or low impact (as defined by APHIS) in the United States. The results of each assessment are used to develop a prioritized list to help focus resources on those pests that are most likely to cause significant impacts.

Office International des Epizooties (OIE): See World Organization for Animal Health.

Olfactometer: Devices used to present odor stimuli in a standardized laboratory setting; a device used to study insect behavior in presence of an olfactory stimulus.

Oviposition: The deposit or laying of eggs.

Phenology: The study of the timing of recurring biological events and the causes of their timing with regard to weather and climate.

Pheromone: A chemical substance produced and released into the environment by an animal, especially a mammal or an insect, affecting the behavior or physiology of others of its species; a secreted or excreted chemical factor that triggers a social response in members of the same species.

Poikilothermic: An organism with variable body temperature that fluctuates with and is similar to the temperature of its environment: a cold-blooded organism.

Prevalence: The proportion of the population with a given symptom or quality.

Ptyalism: A condition that causes the overproduction of saliva.

Pustule: A small, blister-like elevation of epidermis formed as spores emerge.

Ringspot: A disease symptom characterized by yellowish or necrotic rings enclosing green tissue.

SARS: See Severe Acute Respiratory Syndrome.

Sclerotium (pl. Sclerotia): A vegetative resting body of a fungus, composed of a compact mass of hyphae with or without host tissue, usually with a darkened rind.

Scorch: Any symptom that resembles the result of flame or fire on the affected part, often seen at the margins of leaves.

Select Agent: Biological agents and toxins that have been determined to have the potential to pose a severe threat to public health and safety, to animal and plant health, or to animal or plant products; regulated through the Federal Select Agents Program.

Semiochemical: A chemical substance or mixture released by an organism that affects the behaviors of other individuals; a pheromone or other chemical that conveys a signal from one organism to another to modify the behavior of the recipient organism.

Sensillum (pl. sensilla): An arthropod sensory organ protruding from the cuticle of exoskeleton, or sometimes lying within or beneath it.

Sentinel Plot/Population: A survey methodology that consists of plots of land with a specific crop or plant species or defined populations of animals that are routinely or consistently monitored for the presence of a pest or pathogen.

Severe Acute Respiratory Syndrome (SARS): A viral respiratory disease caused by a SARS-associated coronavirus. It was first identified at the end of February 2003 during an outbreak that emerged in China and spread to 4 other countries.

Shot Hole: Small fragments of leaves falling off and leaving small holes in the leaf tissue.

Sign, Animal: A health issue that is an objective, observable phenomenon or evidence of disease that can be identified by others.

Sign, Plant: An indication of disease from direct observation of a pathogen or its parts (contrasts with symptom).

Spore: A reproductive structure of fungi and some other organisms, containing one or more cells; a bacterial cell modified to survive an adverse environment.

Standard: Document established by consensus and approved by a recognized body that provides for common and repeated use, rules, guidelines, or characteristics for activities or their results, aimed at the achievement of the optimum degree of order in a given context.

Stochasticity: By random chance or probability.

Stunting: The reduction in height of a vertical axis resulting from a progressive reduction in the length of successive internodes or a decrease in their number; abnormally small plant growth.

Surveillance: An official process which collects and records data on pest presence or absence by survey, monitoring, or other methods.

Surveillance, Active: Proactive targeting of specific plant or animal populations over a period of time to collect detailed information on the health status of the population; An active search for cases or occurrences of the pest or disease.

Surveillance, Passive: There is no active search for cases. It involves passive notification by surveillance sites and reports are generated and sent by local staff or the public; Information and data is gathered from all sources.

Surveillance, General: A process whereby information on pests of concern in an area is gathered from various sources. Sources may include national or local government bodies, research institutions, universities, museums, scientific societies (including those of independent specialists), producers, consultants, the general public, scientific and trade journals, unpublished data, and the websites of other National Plant Protection organizations (NPPOs) or international organizations (ISPM 6, https://www.ippc.int/en/publications/615/).

Surveillance, Specific: A process whereby information on pests of concern in an area is obtained over a defined period. Organizations actively gather specific pest-related data. Specific surveillance includes surveys that are conducted to determine the characteristics of a pest population or to determine which species are present or absent in an area (ISPM 6, https://www.ippc.int/en/publications/615/).

Survey: An official procedure conducted over a defined period to determine the presence or absence of pests, or the boundaries or characteristics of a pest population, in an area, place of production, or production site (ISPM 5, https://www.ippc.int/en/publications/glossary-phytosanitary-terms/).

Symptom, Animal: A health issue that is apparent only to the patient and cannot be identified by anyone else; a subjective description by the patient of a health issue.

Symptom, Plant: An indication of disease by reaction of the host, e.g., canker, leaf spot, wilt (contrasts with sign).

Terrestrial and Aquatic Animal Health Code: Provides standards for the improvement of animal health and welfare and veterinary public health worldwide, including through standards for safe international trade in terrestrial animals (mammals, reptiles, birds, and bees) and their products. The health measures in the *Terrestrial Code* should be used by the Veterinary Authorities of importing and exporting countries to provide for early detection, reporting, and control agents that are pathogenic to animals or humans, and to prevent their transfer via international trade in animals and animal products, while avoiding unjustified sanitary barriers to trade. Compare to the International Standards for Phytosanitary Measures on the IPPC website. https://www.oie.int/en/what-we-do/standards/codes-and-manuals/

Urediniospore: The asexual, dikaryotic, often rust-colored spore of a rust fungus, produced in a structure called a uredinium; the "repeating stage" of a heteroecious rust fungus, i.e., capable of infecting the host species on which it is produced.

Uredinium (pl. uredinia): The fruiting body (sorus) of a rust fungus that produces urediniospores.

Vector: An organism or object that transports or transmits a pest, parasite, or pathogen from one area or host to another place or host.

Vesicular: Pertaining to or consisting of vesicles or small sacs or bladders.

Vesicular Stomatitis: A virulent disease of livestock in New World caused by any of several arboviruses assigned to Rhabdoviridae. Transmission to humans by phlebotomine sand flies (*Lutzomyia* spp.) implicated during epizootics.

Voltinism: Pertaining to organisms with many generations in a year or season. Term often applied to Lepidoptera, Diptera and other insects of economic importance.

Wilt: The drooping of leaves and stems from lack of water (i.e., inadequate water supply or excessive transpiration); a vascular disease that interrupts normal water uptake.

World Organization for Animal Health (OIE): The need to fight animal diseases at global level led to the creation of the Office International des Epizooties through the international Agreement signed on January 25, 1924. In May 2003, the Office became the World Organization for Animal Health but kept its historical acronym OIE. The OIE is the intergovernmental organization responsible for improving animal health worldwide. It is recognized as a reference organization by the World Trade Organization (WTO), and in 2018 has a total of 182 Member Countries. The OIE maintains permanent relations with nearly 75 international and regional organizations and has Regional and sub-regional Offices on every continent. The organization is placed under the authority and control of a World Assembly of Delegates consisting of Delegates designated by the Governments of all Member Countries. https://www.oie.int/about-us/

Zika: Zika virus is a mosquito-borne flavivirus that was first identified in Uganda in 1947 in monkeys. It was later identified in humans in 1952 in Uganda and the United Republic of Tanzania.

Zoonoses: Diseases and infections naturally transmitted between vertebrate animals and humans.

APPENDIX

Acronyms

ADSM: Animal Disease Spread Model
AHP: Analytical Hierarchy Process
APHIS: Animal and Plant Health Inspection Service
CAPS: Cooperative Agricultural Pest Survey
CDC: Centers for Disease Control and Prevention
CIS : Comprehensive and Integrated Surveillance
CONUS: Continental United States
DDRP: Degree-Days, Risk, and Phenological Event Mapping platform
NPN: National Phenology Network
EDDMapS: The Early Detection & Distribution Mapping System
EDRR: Early Detection & Rapid Response
FAO: the Food and Agriculture Organization of the United Nations
GPHIN: Global Public Health Intelligence Network, Health Canada
iPiPE: Integrated Pest Information Platform for Extension and Education
IPPC: International Plant Protection Convention
ISID: International Society for Infectious Diseases
ISPM: International Standards for Phytosanitary Measures
NAADSM: North American Animal Disease Spread Model
NAHLN: National Animal Health Laboratory Network
NAHRS: National Animal Health Reporting System
NAHSS: National Animal Health Surveillance System
NAPPO: North American Plant Protection Organization
NDFD: National Digital Forecast Database
NPDN: National Plant Diagnostic Network
NVSL: National Veterinary Services Laboratories
OIE: Office International des Epizooties (World Organization for Animal Health)
OPEP: Objective Prioritization of Exotic Pests
PAS: Phytosanitary Alert System
PRISM: Parameter-elevation Relationships on Independent Slopes Model
SAFARIS: Spatial Analytic Framework for Advanced Risk Information Systems
USDA: United States Department of Agriculture
WAHIS: World Animal Health Information System Interface
WHO: World Health Organization of the United Nations
WTO: World Trade Organization