The RABapp™ Handbook

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RABapp Rapid Access Biosecurity

NC STATE UNIVERSITY

Contents

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Chapter 1 The origins and oversight of RABapp™

1.1 The RABapp™ project

The Rapid Access Biosecurity (RAB) app™ project started in **December 2019** when Dr. Gustavo Machado, Assistant Professor at North Carolina State University and the app's creator, began helping swine companies prepare for outbreaks by enhancing biosecurity measures on their farms and and implementing contact tracing capabilities. Recognizing the urgent need to advance protection against livestock infectious diseases, Dr. Machado has worked with colleagues and collaborators to rapidly expand the RABapp™ project to a greater number of states and companies (Figure 1.1).

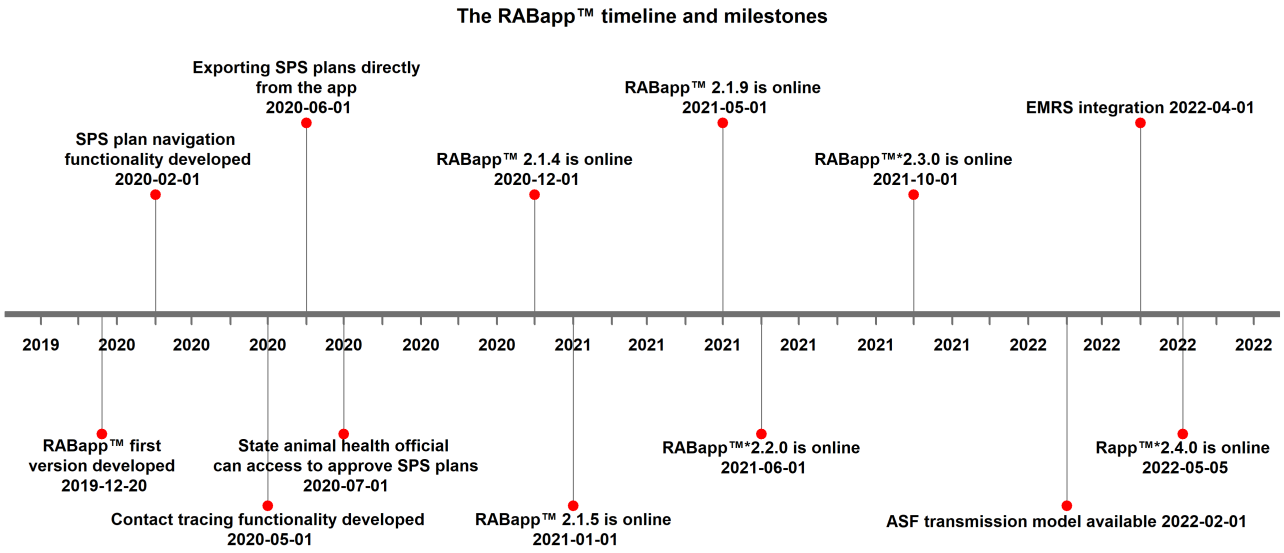

Figure 1.1: *RABapp™ timeline with number of participating farms and software version*

Within just two years, RABapp™ project has collated biosecurity information from almost **10,000 swine farms nationwide (Figure 1.2)**. Combined, these farms represent **34 swine companies** in **22 states**, interacting with officials from **14 State Departments of Agriculture.**

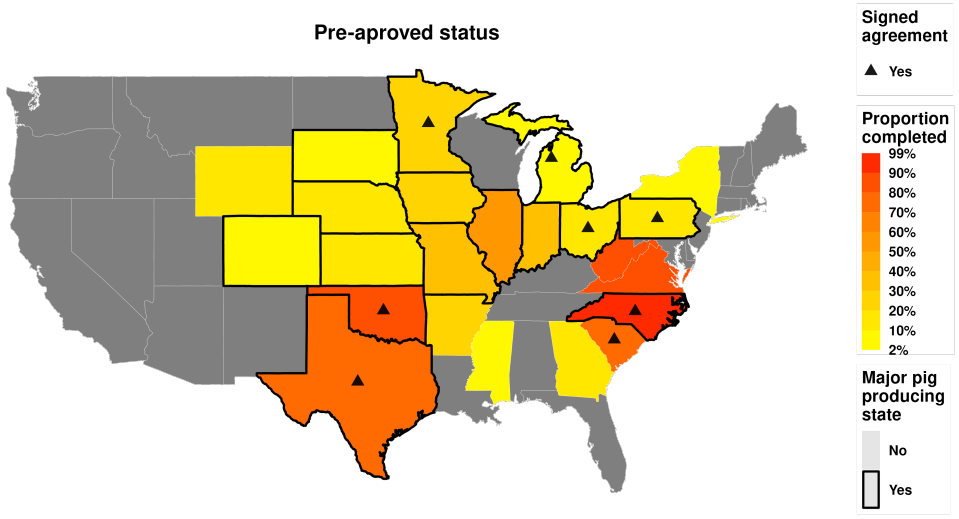

Figure 1.2: *The nationwide distribution and completion of Secure Pork Supply biosecurity plans in RABapp™*

Dr. Machado and his collaborators have also worked to assemble a robust consortium of academic researchers, swine companies, state animal health officials and industry veterinarians. Today, the RABapp™ consortium includes researchers from North Carolina State University, The Ohio State University, the University of Missouri and multiple State Departments of Agriculture, as well as large private veterinary practices and major swine production companies in the country's top 15 pig-producing states. **Together, these consortium members are utilizing RABapp™ to work towards a single goal:** ***to prepare the United States swine industry for large-scale foreign animal disease emergencies.***

1.2 RABapp™ advisory board

Preparedness for foreign animal disease emergencies requires input and action from diverse stakeholder groups, from swine industries to state governments across the country. For this reason, RABapp™ project is overseen by an advisory board comprised of swine industry representatives, government officials, and academic scholars.

1.3 RABapp™ development team

Development and maintenance of RABapp™ is led by Dr. Machado's research team at North Carolina State University's College of Veterinary Medicine. The group includes postdoctoral researchers, P.h.D. students, research technicians and research assistants, who work together to create state-of-the-art software and mathematical models for RABapp™. More details about the team's work in livestock infectious diseases can be found on the Machado Lab website.

1.4 Funding support for RABapp™

Development of RABapp™ was supported by North Carolina State University. Now operational, the RABapp™ team are working to expand the number of app users with additional funding provided by federal agencies listed

below:

- **North Carolina State University, College of Veterinary Medicine, Department of Population Health and Pathobiology**, Dr. Machado's Start-up funds.
- **Foundation for Food and Agriculture Research (FFAR), New Innovator Fellowship**, grant number (NIA21-64)
- **USDA Animal and Plant Health Inspection Service (APHIS), National Animal Disease Preparedness and Response Program (NADPRP)**, grant number (AP21VSSP0000C013)

With this funding support, the RABapp™ team has published a number of peer-reviewed papers in high impact journals, listed in **Section A.1.1 and in our group's web site**.

Chapter 2 Benefits of RABapp™

2.1 What is RABapp™?

RABapp™ is a web-based tool for enhancing on-farm biosecurity preparedness and contact tracing across the U.S. swine industry (Figure 2.1). Using the latest data of infectious disease research and high quality data from swine companies and producers across the country, RABapp™ provides swine industry veterinarians, pork producers and animal health officials with rapid access to the following standardized information:

- Verified **Secure Pork Supply (SPS) biosecurity plans** for individual swine farms (described in Section 3.1).
- **Possible infection pathways** between swine farms and states based on transportation routes for different animals and products [7, 9, 11].
- **The risk level of individual swine farms** based on the volume of animals and products they receive from other sites.
- **Farms and regions affected by movement restrictions** based on the size and location of outbreak control zones, as determined by national control and eradication plans [2].
- **The effectiveness of control and eradication strategies** based on computer simulations of possible future outbreak emergencies [6, 11].

Using this information, swine companies, veterinarians and government departments can achieve:

1. Enhanced on-farm biosecurity preparedness.
2. Expedited decision-making during an infectious disease emergency.
3. Deployment of targeted outbreak responses to infected and at-risk farms.

Overall, RABapp™ serves to enhance the resilience of the swine industry by limiting disruptions to businesses during a foreign animal disease emergency.

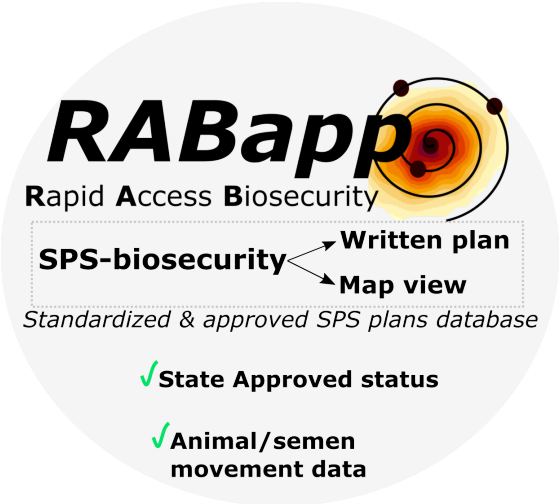

Figure 2.1: *The RABapp™ is a web-application*

2.2 Who uses RABapp™?

RABapp™ is currently deployed in deployment to **32 states**, encompassing **51 swine companies** and **14 State Departments of Agriculture**. The primary users of RABapp™ are swine industry veterinarians, swine producers and both state and federal animal health officials, who can use the tool to:

- **Enhance the on-farm biosecurity** of individual swine farms.
- **Rapidly distribute movement permits** to help uninfected farms resume standard operations during an outbreak.
- **Implement effective contact tracing** to help prevent the spread of infection to other farms.
- **Improve preparedness** by using computer simulations of infectious disease threats to test control and eradication strategies.

A key feature of RABapp™ is the integration of private data from swine companies and producers across the country, made possible by formal data sharing agreements that protect the confidentiality of individual companies, see (Appendix A) for more information. By integrating protected data behind university firewalls, RABapp™ captures the nationwide status of the outbreak while ensuring information for specific farms can only be accessed by authorized users based on their industry, academic or government affiliation. **As a result, RABapp™ allows animal health officials, pork producers and industry veterinarians to work in synchrony across the country.**

2.3 Why do we need RABapp™?

Large-scale foreign animal diseases such as African swine fever (ASF) remain a constant threat to countries worldwide [13, 16]. In the event of an outbreak in the U.S., state governments implement restrictions on the movement of animals and other products (e.g. semen and germplasm) between farms and pork production sites in affected regions, as described in the national response plan [2, 10].

Although this effectively limits the spread of diseases, movement restrictions can severely compromise the continuity of swine businesses [5, 14, 16]. Unable to transport animals and other vital products, companies risk major disruptions to their standard operations, causing problems for animal welfare, production, revenue, and long-term sustainability.

Due to the necessity of movement restrictions to limit disease spread [6, 7, 11], **one of the most important approaches to protecting swine businesses during an outbreak is to enable the safe and efficient resumption of animal and product transportation between farms and states**.

To this end, RABapp™ is designed to place high quality information at the fingertips of stakeholders to allow rapid, accurate decision-making under emergency conditions. This is particularly critical for diseases such as ASF [10], which can cause widespread devastation and long-term damage if outbreak responses are not implemented in a timely and equally effective manner across all regions of the country [15]. A description of the app and the data it uses is provided in the following chapter.

2.4 RABapp™ integration with other projects and platforms

Due to the need to quickly respond to animal health emergencies RABapp™ has integrated with other projects and platforms, as listed below:

1. Emergency Management Response System 2.0 (EMRS2)
2. Samsara (Real-time truck tracking)
3. AgView (coming Up)

Chapter 3 Data behind RABapp™

To enhance biosecurity preparedness and contact tracing, RABapp™ serves as a unique tool by integrating two key sets of data within a user-friendly interface:

1. **Secure Pork Supply biosecurity (section 3.1).**
2. **Movement of animals and products (e.g. semen, germplasm) between farms (section 4.2).**

Protected by confidentiality and data use agreements (see Appendix A for more details), these data are provided by swine companies from across the country (Figure **??**) and **processed by RABapp™ team using rigorous data analysis and quality control procedures** (explained in detail in Chapter 4). More information about these data are provided in the following sections.

3.1 Secure Pork Supply biosecurity plans

Developed by the swine industry, government officials and academic scholars at Iowa State University and the University of Minnesota, the Secure Pork Supply (SPS) Plan for Continuity of Business serves as a guideline for enhancing the biosecurity features of swine farms to improve preparedness for infectious disease outbreaks. Participation in the SPS plan program is voluntary, but highly recommended by the U.S. Department of Agriculture (USDA) due to the need for feasible, standardized procedures for restarting safe animal movements during outbreaks of foreign animal diseases [10].

The SPS plan includes a total of **169 biosecurity features**, ranging from cleaning and disinfecting stations to perimeter buffer areas. By developing the complete set of SPS biosecurity features, swine farms can enhance their preparedness for infectious disease outbreaks. To ensure all features are correctly included on a farm's plan, pork producers and veterinarians follow SPS guidelines and then produce a site-specific SPS plan. A completed SPS plan for a single farm contains two sections:

1. **A written section** describing the biosecurity features of the farm (**Figure 3.1**).
2. **A visual map** of the biosecurity features located across the site (**Figure 3.1**).

Using **rigorous data analysis and quality assessments** (Chapter 4), the RABapp™ team transform these SPS plan from any format that the pig producing companies and producers may have into easy-to-use, rapidly accessible information for enhancing emergency preparedness, decision-making and outbreak responses.

3.1.1 How does RABapp™ use SPS plans?

Although SPS plans help swine farms enhance their biosecurity features in preparation for an infectious disease outbreaks, **updating and accessing these plans in a timely manner before and during an emergency, is critical for swine industry resilience**. Here, RABapp™ serves as a vital tool by providing producers, veterinarians and government officials with:

- **Rapid access to the SPS plan status of farms across regions and states** to expedite the distribution of movement permits within control zones.
- **Visual, interactive maps of farm sites and their biosecurity features** to help producers and veterinarians view and update their plans for multiple sites and enhance their preparedness.
- **A secure portal to quickly update and edit SPS plans** to ensure producers, veterinarians and animal health officials have access to the latest biosecurity information.

RABapp™ also utilizes state-of-the-art software and mathematical models to extract crucial biosecurity information from SPS plans along with population level data and calculate the **infection risk level for specific farms based on their location within the transportation network**. Since biosecurity features and farm infrastructure reduce the possible entry of new infections, RABapp™ uses this data to pinpoint high risk farms while sharing the information with the stakeholders. **Using this information, swine companies can prioritize specific sites for enhance surveillance sampling and thereby increase the likelihood of detecting infections early.**

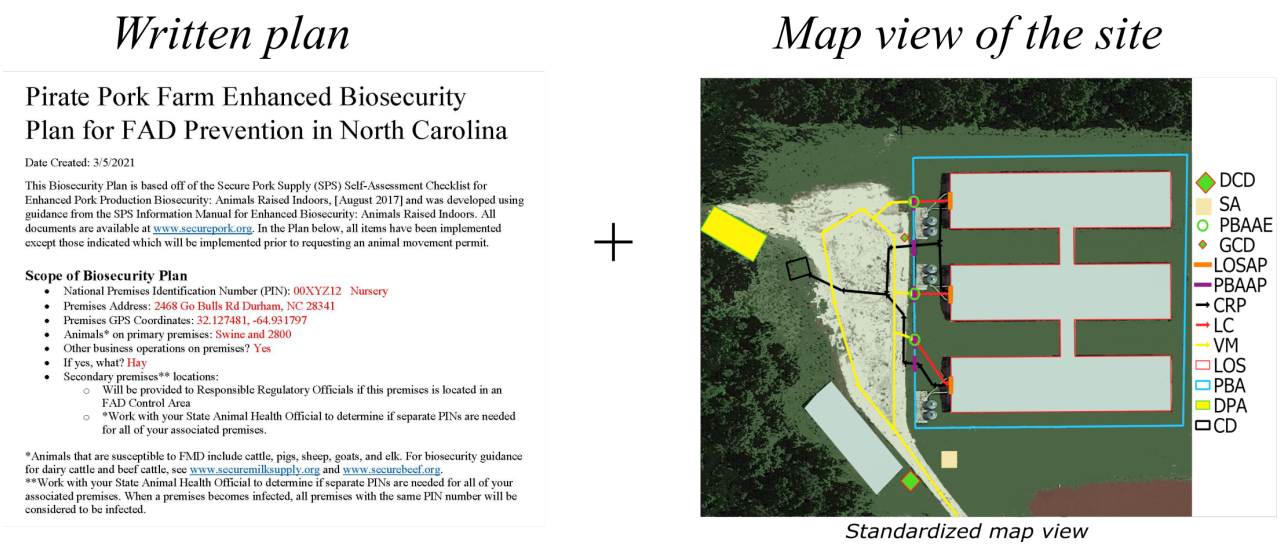

Figure 3.1: *Within RABapp™, a completed Secure Pork Supply plan for a single site will display all 169 biosecurity features as both a written description (left) and a visual map of the premises (right).*

3.1.2 Why is rapid access to SPS plans and movement data via RABapp™ important?

The need for rapid access to SPS plans within RABapp™ is heightened by the ongoing global circulation of major diseases such as ASF, foot and mouth disease and classical swine fever [16]. If such threats are detected in the U.S., control zones will be immediately established by government officials at the local, state and federal levels, as dictated by national control and eradication plans [2]. Within these control zones, infected farms will depopulated while farms with direct contact via transportation will be quarantined, and the movement of all animals and related products (e.g. semen and germplasm) will be restricted [2].

To resume animal and product transport within these control zones, individual farms must qualify for a movement permit distributed by government officials [2]. **Here, rapid access to up-to-date SPS plans and movement data (Section 3.2) via RABapp™ is critical, because one of the key criteria for obtaining a movement permit is the presence of specific, on-farm biosecurity measures approved by government officials.**

Note **A full description of all permit criteria is available on the in the USDA Foreign Animal Disease Preparedness Response Plan (FAD PReP, also known as the "Red Book") ([2]).**

RABapp™ integrates the SPS plans of individual farms into a nationwide, geographic information system (GIS) map, which helps protect business continuity in two key ways. First, the GIS map allows producers and veterinarians to easily view and update their SPS plans for all their sites to enhance their preparedness. In the event of an outbreak, this will ensure all farms are ready to implement their biosecurity plans. Second, during an outbreak, government officials can use the GIS map to assess the SPS plan status of all farms within control zones. This helps government officials rapidly distribute movement permits to specific farms and thus minimize business disruptions.

3.2 Movement data for animals and related products

Across the U.S. swine industry, animals and other products (such as semen and germplasm) are transported between farms and states. Although critical for standard operations, this transportation network is the fastest and most common way for an infectious disease to spread between farms and states [1, 7].

The integration of movement data with SPS plans is a unique feature of RABapp™. Using data shared by swine companies and pork producers throughout the country, RABapp™ calculates the **transportation network of farms** and displays this network within an interactive easy to use plot. Utilizing information extracted from SPS plans (Section 3.1), RABapp™ also calculates the **risk level of individual farms** based on each farm's biosecurity infrastructure and the volume of animals moving through specific sites. Combined, this enables pork producers, industry veterinarians and animal health officials to:

- **Perform effective contact tracing** to identify movement among infected and susceptible farms.
- **Identify new infections early** by deploying personnel to infected contacts and high risk sites to conduct sampling.
- **Draw control zones within the app**, which are used to guide the implementation of quarantines and other control strategies.
- **Efficiently distribute the data needed to expedite movement permits to be issued by the animal health authorities** to farms based on their location within the transportation network and control zone.

To achieve these outcomes, RABapp™ requires **high quality, up-to-date data** from swine companies across the country. The procedures and expertise used to ensure top data quality are described in the following chapter.

Chapter 4 RABapp™ data collection and quality assurance

Effective contact tracing, risk calculations, outbreak simulations and biosecurity preparedness can only be achieved with the high quality, accurate data. For this reason, **this chapter describes the RABapp™ team's efforts to maximize data quality, including their rigorous, streamlined protocols for data collection, processing, quality assessments and reporting**.

Working closely with the National Pork Board (Pork Checkoff), government animal health officials and swine industry representatives, RABapp™ team has also developed efficient protocols for cataloging, reviewing and approving SPS plans, digitizing farm infrastructure maps to ensure all SPS plan information is easily accessible online, and curating and integrating SPS plans with movement data to develop a unique resource for the swine industry.

4.1 Standardizing SPS biosecurity plans

The RABapp™ team provides extensive support for pork producers and industry veterinarians throughout the SPS plan development process. This involves the following stages (depicted in **Figure 4.1**):

1. Producers and veterinarians meet with the RABapp™ team to learn about SPS plans and enhanced farm biosecurity (**Stage 1**).
2. Producers and veterinarians submit a hand-drawn map and written list of the swine farm's infrastructure and biosecurity features to the RABapp™ team (**Stage 2**).
3. The RABapp™ team reviews, catalogs and pre-approves the complete list of 169 biosecurity features (**Stage 3**).
4. The RABapp™ team transforms the hand-drawn farm map into a digitized GIS map (**Stage 3**).
5. The RABapp™ team integrates the digitized GIS farm map, biosecurity list and movement data (collected separately, see Section 4.2) within the app (**Stages 2-3**).
6. Once the RABapp™ team verified the data provided meet the SPS Plan for Continuity of Business requirements, those farms are granted a status of pre-approved by RABapp™ team which them makes the data available via RABapp™ to the correspondent SAHO (**Stage 4**).
7. Producers and veterinarians attend a training session to learn how to access, interpret and use information within RABapp™ (**Stage 5**).
8. Producers, veterinarians and SAHOs start using RABapp™, uploading new data to the app when available (**Stages 4-5**).
9. Producers and veterinarians utilize RABapp™ team's ticket service to submit questions or problems as they arise (**Stage 5**).

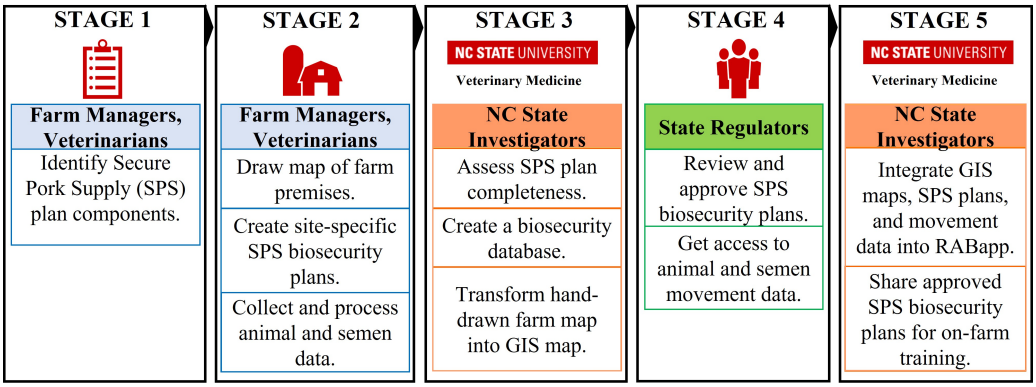

Figure 4.1: *Conceptual stages of integrating biosecurity plans and animal movement into RABapp™*

By working closely with producers and veterinarians in the country's top swine-producing states throughout the SPS plan development process, the RABapp™ team are working towards the **national standardization of SPS plans**, which will enhance the uniformity of biosecurity data quality across the country. More details about generating the written and map-view sections of the SPS plans are provided in the following two sections.

4.1.1 Generating the written section of SPS biosecurity plans

Comprised of 169 questions, the written section of the SPS biosecurity plan are highly detailed. A template of the SPS plan containing the 169-field questionnaire can be downloaded directly from the SPS website and is typically completed by industry veterinarians or farm managers for each farm (Figure 3.1). To provide effective support and maximize SPS plan accuracy, the RABapp™ team works closely with pork producers, veterinarians and farm managers to simplify and facilitate the process of completing this written section.

Within the written section, each question is designed to capture information about a specific biosecurity measure or aspect of the farm's infrastructure, and is separated into one of 10 sections, as recommended by the SPS Plan for Continuity of Business:

1. Biosecurity manager
2. Training
3. Protecting the pig herd
4. Vehicles and equipment
5. Personnel
6. Animal and/or semen or germplasm movement
7. Carcass disposal
8. Manure management
9. Pest control
10. Feed

Through online meetings, the RABapp™ team also works with companies and producers to guide achieving **pre-approval status** for their SPS plans - a critical component of the RABapp™ project. Issued by the RABapp™ team, pre-approval status is used to identify farms that have provided the minimum necessary information for generating an SPS plan, as stipulated by the U.S. Pork Industry Guide to the Secure Pork Supply Plan (available

in the SPS information manual for animals raised indoors). Once pre-approval status is achieved, the data from these farms are incorporated into RABapp™ while the state department continues to review and approve the plans. **This expedites data accessibility, ensuring the maximum quantity of high quality data is readily available in the event of an animal health emergency.**

Definition 4.1 (Pre-approval status)

Farms that provided the RABapp™ team with the information needed to generate a completed SPS plan and a map that include the necessary features received their status of pre-approved. ♣

4.1.2 Generating the map view section of SPS biosecurity plans

The first stage of generating the map view section of an SPS plan is completed by veterinarians or farm managers, who hand-draw existing biosecurity features on an aerial photograph of the farm (Figure 4.2, left-panel). Next, the RABapp™ team use the latest open-source software (QGIS) to transform these hand-drawn images into digital GIS maps. Importantly, the RABapp™ team ensures these GIS premise maps adhere to the SPS plan minimum requirements by using the appropriate symbols and colors. Examples of these symbols and colors for SPS plan biosecurity features are listed below and displayed in Figure 4.2, right-panel:

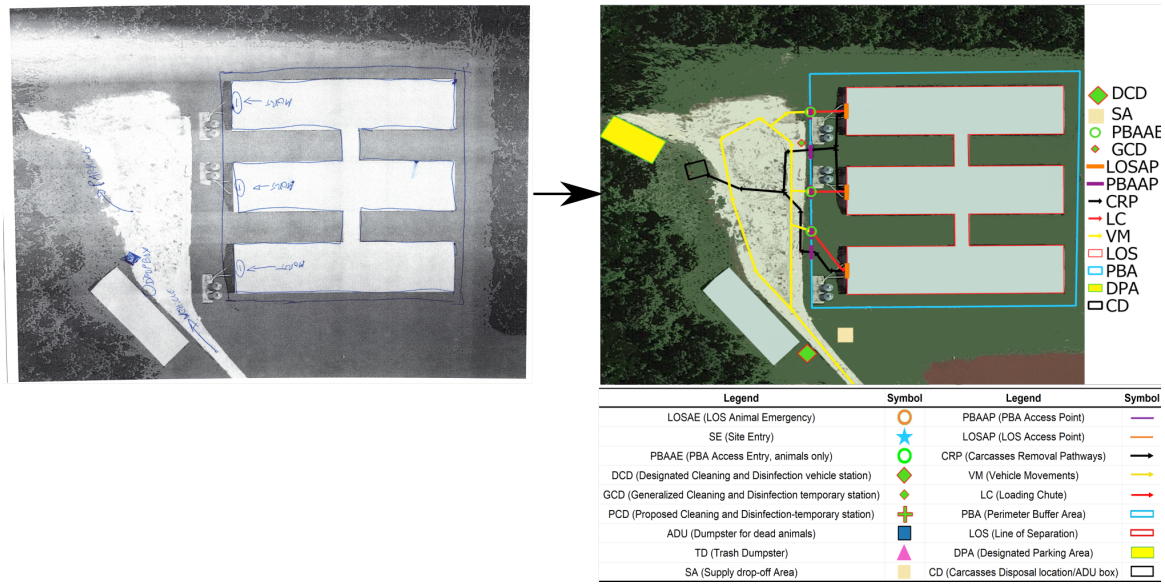

Figure 4.2: *RABapp™ team transforms aerial images with hand-drawn biosecurity features (left) into digital GIS maps that comply with SPS plan standards [4].*

For companies that have already constructed their own maps, the RABapp™ team still performs a review of the map to verify compliance with the SPS plan's minimum requirements [4]. Similar to the written section described above, by producing the final GIS maps for swine companies with the standardized symbols and colors for specific biosecurity features, the RABapp™ team not only provides a valuable service to companies, but also helps harmonize the quality and appearance of farm maps across the country. When viewing multiple farms within RABapp™, viewers can rapidly benchmark the biosecurity features of different farms.

4.2 Capturing high quality movement data

The ability of RABapp™ to build detailed, nationwide transportation networks (Figure 4.3) for contact tracing, risk calculations and outbreak simulations depends heavily on the quality of movement data shared by swine companies. For this reason, the RABapp™ team performs rigorous quality checks to ensure all movement data achieves the highest level of accuracy and completeness, described in the following sections.

To enhance the long-term sustainability of RABapp™ project, the team also produces data quality reports for swine companies to help them improve their movement data over time. **Ultimately, this continuous, collaborative process of data collection, processing and analysis advances the effectiveness of contact tracing, risk calculations and outbreak preparedness across the U.S. swine industry.**

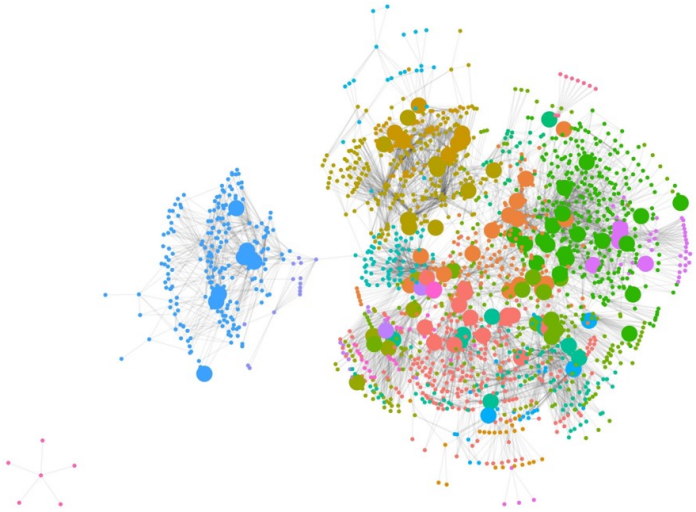

Figure 4.3: *RABapp™ plot displays the extraordinary complexity of swine transportation networks throughout the country [6, 7, 9]. Transportation routes are shown as gray lines, and farms are displayed as colored circles. Generating these networks for contact tracing, risk calculations and other RABapp™ functions relies heavily on high quality movement data.*

4.3 Movement data quality assessment

All participating swine companies and pork producers share a movement data report for all animals and related products (e.g. semen, germplasm) with the RABapp™ team via secure routes. Reports are provided by producers and companies once per month to capture fluctuations in movement patterns and measure changes in the risk of disease propagation. After loading the data into internal servers, the RABapp™ team performs the following data quality assessment steps:

1. Check the accuracy of the timeline of the movement data provided by companies and producers.
2. Quantify the total number of individual animals/products per transport load within the data data provided by companies and producers.
3. Identify farms that are included in movement data but absent in the animal population databases provided by companies or producers. *This information is critical for accurate contact tracing (Figure 4.6).*

After performing this thorough assessment for each movement data report, the RABapp™ team produces a **data quality control report** containing in-depth information about any missing data, errors and corrections performed by the RABapp™ team. These data reports are shared with the company/producer to help improve data collection. **Over time, these reports help businesses across the country improve movement data quality, and thus the effectiveness of RABapp™ in enhancing swine industry resilience.**

4.4 Building a movement observatory

A critical feature of RABapp™ is its ability to recognize that animal/product transportation fluctuates on a monthly basis. To provide producers and companies with reports that capture this variation, RABapp™ contains a "movement observatory".

The movement observatory shows each company how their movement changes over time, within and across states (Figures 4.4 and 4.5). To build the observatory, RABapp™ team uses the movement data that has passed all quality assurance steps (Section 4.3). For each company, the observatory is subdivided into three major reports:

- Monthly movement variation summaries (Section 4.4.1).
- High-risk farm identification (Section 4.4.2).
- Farm risk groups (Section 4.4.3).

Each of these observatory subdivisions are described in detail in the following sections.

4.4.1 Monthly movement variation summaries

The first subdivision of the movement observatory is a monthly summary of movement across a company's system of farms. **Produced on a monthly basis, these summaries allow companies to see how movement varies within their network of farms over time.** These monthly summaries contain three key sets of information (Figure 4.4):

- The number of active farms for a specific company or group of farms(Figure 4.4A).
- The number of transportation loads moved across the network of farms (Figure 4.4B).
- The volume of animals transported across the network of farms (Figure 4.4C).

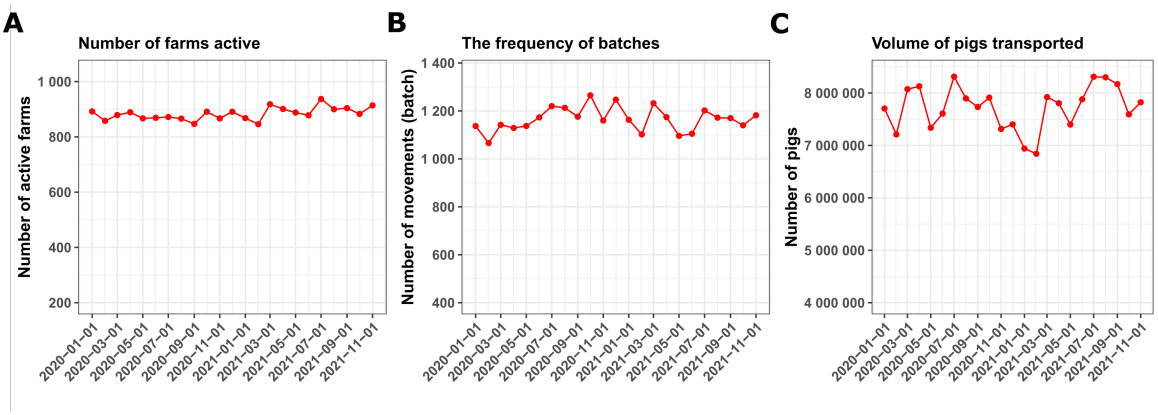

Figure 4.4: *Monthly movement variation summaries including the number of active farms, transportation loads and number hogs transported.*

Generating these summaries involves state-of-the-art network analysis techniques to construct comprehensive plots of animal/product movement at the farm, company system, county and state level [3, 11]. First, the RABapp™ team take movement data for each company and calculate network metrics that provide information about how an outbreak could spread throughout a company's network of farms. An example metric is the Giant Weakly Connected Component (GWCC), which shows how many company farms are connected to each other. **If a high number of the company's farms are connected to each other, this increases the likelihood of an outbreak spreading to all farms within the company (Figure 4.5)**. In short, a higher GWCC value indicates a greater chance of an outbreak spreading throughout the company farm network.

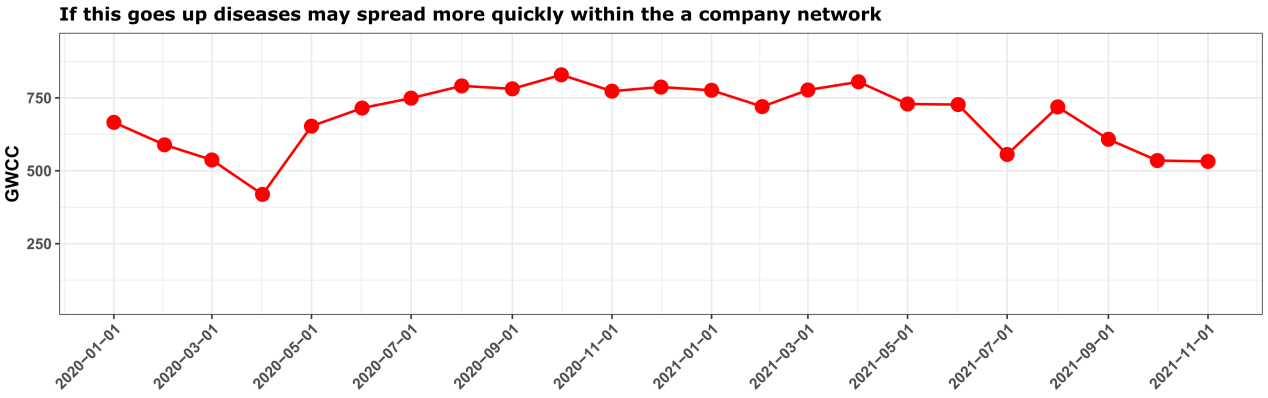

Figure 4.5: *Monthly GWCC of a specific company.*

By calculating this value for each company on a monthly basis, RABapp™ shows companies how outbreaks could spread across their farms at different times in the year (Figure 4.5). **RABapp™ also provides a GWCC value for each farm type (e.g. sow farm, finisher farm) within the company network, allowing companies to see if the outbreak is more likely to affect specific farm types.** For instance, if the GWCC value for finisher farms is higher than sow farms, this indicates that an outbreak is more likely to affect the company's finisher farms than sow farms.

Definition 4.2 (Giant Weakly Connected Component [GWCC])

GWCC is one of several network metrics used by RABapp™ to show how an outbreak will spread across a company's network of farms. The GWCC value indicates how many company farms are connected to each other, which in turn signifies the likelihood of an outbreak spreading to all farms within the company. ***The higher the GWCC value, the greater the chance of an outbreak spreading throughout the company's farm network.*** *(Peer-reviewed research demonstrating the application of GWCC to swine disease propagation can be found here: [6, 11].)*

♣

4.4.2 High-risk farm identification

Identifying farms that are at high risk of an outbreak is the second subdivision of the movement observatory. To identify high risk farms, the RABapp™ team uses the movement data (developed and assessed in Section 4.4.2) and a network-based analysis technique to analyze whether farms are connected directly or indirectly via transportation routes. Direct and indirect connections (also known as "contact chains") are classified as follows (also displayed in Figure 4.6):

- **Direct contact chain:** If Farm A and Farm B are directly connected, this means a transportation vehicle travels directly from Farm A to Farm B.
- **Indirect contact chain:** If Farm A and Farm B are indirectly connected, it means a transportation vehicle leaves Farm A, travels to other sites (e.g. Farm C), and then arrives at Farm B.

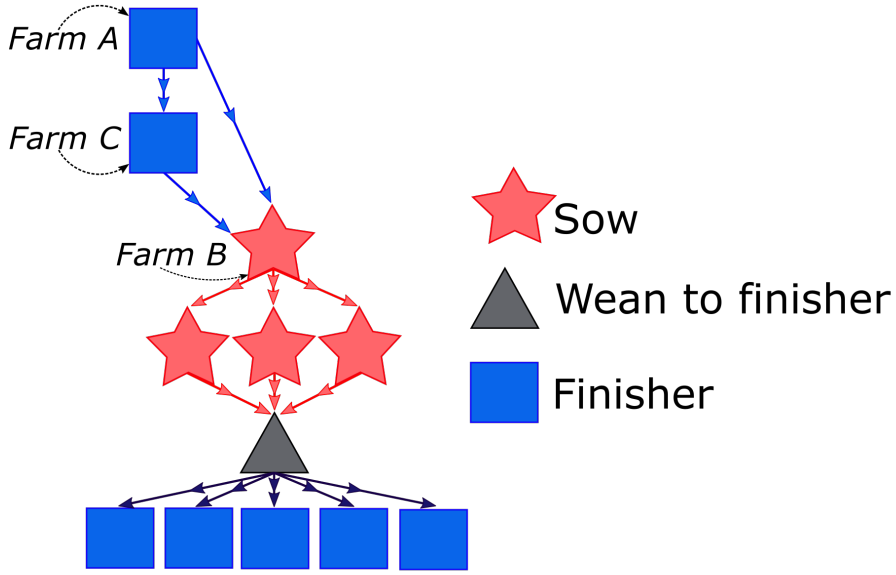

Figure 4.6: *Diagram showing the direct and indirect contact chains between farms. Direct contact chains are direct connections between two farms (e.g. Farm A and Farm B have a direct contact chain); indirect contact chains involve multiple farms (e.g. Farm A and Farm B also have an indirect contact chain via Farm C).*

Identifying direct and indirect contact chains between farms is critical for understanding how animals and products move across farms throughout the state and country. After creating a contact chain map, the RABapp™ team evaluates the direction of the contact chain - in other words, whether the transport vehicle is **arriving at the farm** (ingoing contact chain) or **leaving the farm** (outgoing contact chain).

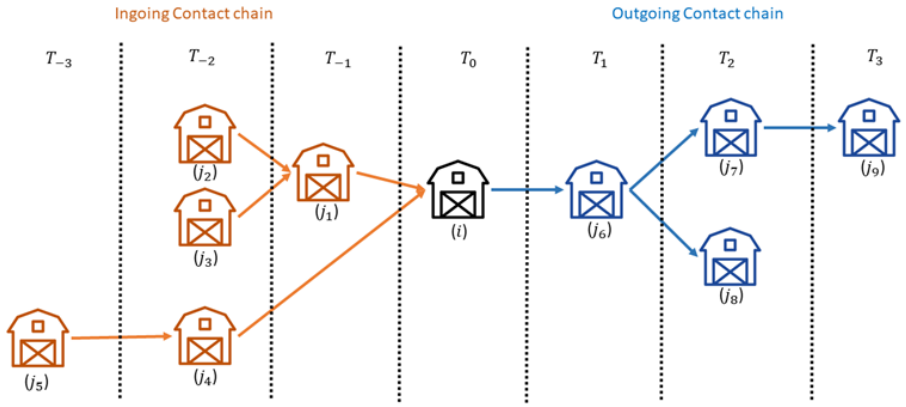

Figure 4.7: Example of a farm network image displaying the ingoing (orange) and outgoing (blue) contact chains of a particular farm (i). In addition to the direction of the movement (and therefore potential disease spread), the network image also displays the farms that are likely to be affected at different times (T-3, T-2, T-1...), based on typical fluctuations in movement across weeks and months.

After identifying direct/indirect and incoming/outgoing contact chains, the RABapp™ team can construct an image of the entire swine farm network. An example of this network image is shown in Figure 4.7. In this figure, the farm of interest (black) has an incoming contact chain (orange) comprised of five farms, and an outgoing contact chain of (blue) of four farms. Using this figure, the RABapp™ team can start to predict how an infection might spread between farms in the event of an outbreak. Based on where the outbreak is detected and the position of the farm within the contact chain, the RABapp™ team can start to pinpoint which farms are more likely to be infected (higher risk) than others.

Importantly, since transportation between each farm throughout these contact chains will fluctuate over time, the RABapp™ team also integrate another layer of accuracy into their network analysis. By accounting for variations in movement across different time frames - such as one week, one month and three months - **the RABapp™ team estimate not just the direction of the disease spread, but also the size and speed of the spread** (displayed as "T0", "T1", "T-1" etc. in Figure 4.7).

This is critical for not only anticipating the number of farms that could be impacted by the outbreak, but the damage that could be incurred if there is any delay in disease detection. **Consequently, a major purpose for this network analysis and high risk farm identification is to identify which swine farms should be prioritized for sampling and contact tracing to maximize the chances of early outbreak detection** [12].

4.4.3 Farm risk groups

The third and final subdivision of the movement data observatory is the creation of farm risk groups. Using the contact chains and networks constructed in the sections above (see Figure 4.7 for an example), the RABapp™ team categorizes farms into **risk groups**.

In total, the RABapp™ includes five risk groups:

- Very high
- High
- Medium
- Low
- Very low

On average, farms are classified as very high risk if they have high ingoing and outgoing contact chains, whereas farms with low ingoing and outgoing contact chain are lower risk. Importantly, the RABapp™ team utilizes statistical and mathematical modeling methodologies to increase the accuracy of their risk group assessments.

To categorize each farm into different a risk group, the RABapp™ team uses the following information:

1. The **ingoing contact chains** of the farm.
2. The **outgoing contact chains** of the farm.
3. The consistency of movements between farms within a network (also known as **fidelity**).

Fidelity, represents an important aspect of movement data analysis in RABapp™. If a network has high fidelity, this means animals/products are frequently transported between the same farms, so the connections between the farms remain consistent. In contrast, if a network has low fidelity, the connections between the farms are inconsistent because the transportation routes often change.

Accounting for movement fidelity is critical for determining the accuracy and efficiency of contact tracing [8]. If a company's farm network has high fidelity, contact tracing will be easier and more accurate because the connections between farms are well known and consistent. If a company's farm network has low fidelity, contact tracing will be more difficult because there will be more unknown and inconsistent connections between the farms.

For this reason, fidelity affects the risk calculations for swine farms. Very high risk farms tend to be farms with high levels of movement to and from the farm (ingoing and outgoing contact chains) and low fidelity (inconsistent, unknown connections). By comparison, very low risk farms have low levels of movement to and from the farm (ingoing and outgoing contact chains) and high fidelity (very consistent, well-known connections).

Once the calculations are complete, the RABapp™ team creates and shares **a "hotlist" of the most high risk farms** with swine companies and producers, and uploads this information into the RABapp™. Using this information, swine companies and producers can invest their time and resources in preemptively enhancing biosecurity and disease detection at specific sites, thus enhancing their ability to efficiently prepare for and respond to outbreaks.

Chapter 5 How to use RABapp™

RABapp™ (current version: v2.4.0) is a stable web-application developed and maintained by a livestock infectious disease research group at North Carolina State University, the Machado Lab. Overseen by an advisory board comprised of swine producers, industry veterinarians, academic researchers and government officials (listed in Section 1.2), RABapp™ is designed to enhance the resilience of the U.S. swine industry against foreign animal disease emergencies. A full version history of RABapp™ is provided in Chapter 8, and a list of participants from the country's top swine-producing states is provided in Chapter 1.

RABapp™ has three core functionalities that can be used to:

1. **Enhance swine industry preparedness for infectious disease outbreaks** by collecting, approving and storing nationally standardized SPS biosecurity plans [4].
2. **Expedite effective contact tracing and outbreak responses at the company, county and state level** by collecting and analyzing high quality animal/product movement data.
3. **Transmission models** to combat current endemic disease outbreaks and FAD epidemics.

Within RABapp™, authorized users with appropriate permissions can **view and download** data that has been assessed for completeness and accuracy using rigorous quality assurance protocols (described in detail in Chapter 4). This includes all SPS plans, which are only made available within RABapp™ when the team has review and approved the plans for compliance with the minimum SPS requirements [4].

In addition to viewing and downloading information, authorized users can use RABapp™ to **quickly and easily update biosecurity information** for specific farms to ensure their SPS plans remain up-to-date. The following sections describe these features of RABapp™ in more detail.

Definition 5.1 (RABapp™ web-application)

RABapp™ is a web-based application that provides authorized users with rapid access to approved, high quality SPS plans and swine industry movement data. The overall goal of RABapp™ is to help swine companies, pork producers and government animal health officials make well-informed disease control decisions before and during infectious disease emergencies. By ensuring accurate, complete and up-to-date SPS plans and movement data are readily available, RABapp™ serves to enhance swine business continuity in the U.S. by protecting animal health, normal business functions and business productivity. Furthermore, by providing easy access to high quality data from across the U.S., RABapp™ also helps multiple sectors work together to deploy harmonized, coordinated responses to emergencies, and thereby mitigate the impact of outbreaks on producer livelihoods throughout the country. ♣

5.1 Navigating RABapp™ tool

After logging into RABapp™, users will arrive at the *SPS plan status* tab, which serves as the app's home tab. From here, users can use the menu bar at the top of the page to access a number of key functionalities, described

in the following sections:

1. **SPS plan status tool** (Section 5.1.1) - *RABapp™ home tab*.
2. **SPS navigation and download tool** (Section 5.1.2).
3. **Update SPS plans tool** (Section 5.1.3).
4. **State approval tool** (Section 5.1.4).
5. **Disease surveillance and disease dissemination tool** (Section 5.1.5).
6. **Import movements** (Section 5.1.6).

Note **Step-by-step instruction videos for using this map are available within the RABapp™.**

5.1.1 Tab 1: SPS plan status

The *SPS plan status* tab serves as the home tab for RABapp™. In addition to displaying the number of SPS plans completed per state, the tab also displays an **interactive GIS map**, where users can view swine farm biosecurity details and contact chains (Figure 4.6). ***Importantly, RABapp™ users are only authorized to access information associated with their own company/producer group.*** Basic features of the interactive map are described below:

1. View specific swine farms using filters such as company/producer group, veterinarian name and premise identification numbers (PremIDs).
2. Set the **desired control area** for infected farms (e.g. 5 km radius around infected premises).
3. Choose a date range (*mm-dd-yyyy* to *mm-dd-yyyy*) to incorporate animal movements within a specific time period. When necessary, past dates can be selected for **backward contact tracing**.
4. Access a variety of site-specific information, such as production type and total animal capacity.
5. Visual displays of each site's **SPS-approved biosecurity features** in accordance with SPS plan guidelines [4] (Figure 4.2). Standardized colors and symbols for SPS biosecurity features enable direct comparisons between farms within the map (Figure 4.2).
6. View **contact chain information and movement summaries**, described in more detail in Section 5.1.2 below.

Note **Step-by-step instructions for using this map are available in this video within the RABapp™.**

5.1.1.1 Additional Tab 1 features: Contact chains and summary tables

As described above, when using the interactive GIS map in the *SPS plan status* tab, users can view contact chain information for each farm (Figure 5.1). *(See Section 4.4.2 for a full explanation of contact chains.)* There are four main ways to view this contact chain information:

1. **Basic contact chain** (Figure 5.1 left image): View the number of ingoing and outgoing contact movements for a specific farm to assess the flow of animals/products to and from the farm, and the number of direct and indirect connections with other farms.
2. **Contact chain by production type** (Figure 5.1, left image): View the number and ingoing and outgoing movements for farms represented by different symbols based on their production type (e.g. sow, wean to

finisher).

3. **PRRS contact chain:** Companies and producers that have shared PRRS outbreak data can view the contact chains of farms that have been infected with PRRS virus within a selected time frame (Figure 5.1, right panel).
4. **SPS approval status of contact chain farms:** View the SPS approval status of all farms within the contact chain(s) of a specific farm (Figure 5.2).

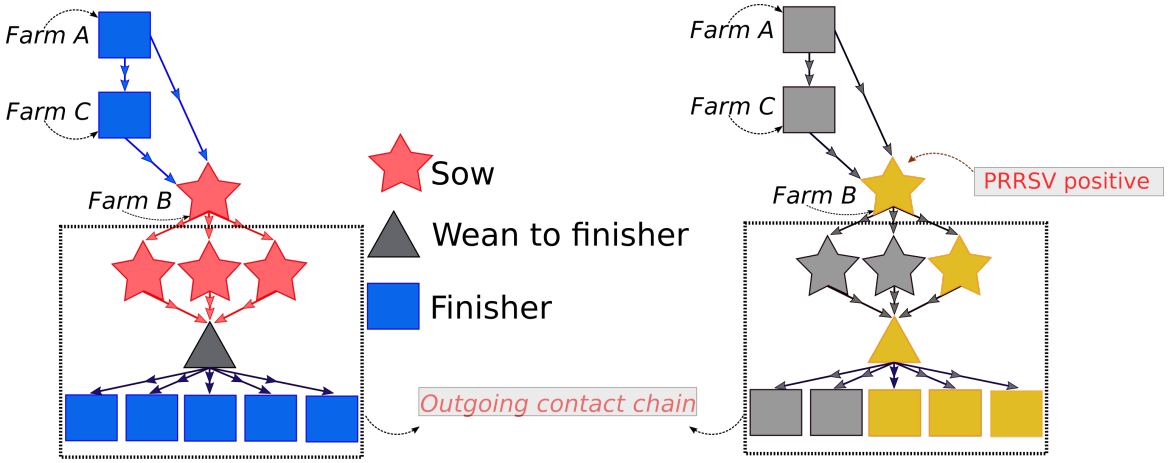

Figure 5.1: ***Left image:*** *This diagram illustrates ingoing and outgoing contact chains for a farm of interest (Farm B). For example, Farm B has two farms within its ingoing contact chain (Farm A and Farm C) and nine farms within its outgoing contact chain (all farms within the gray square).* ***Right image:*** *This diagram shows the same contact chains, but highlights which farms have been infected with PRRS (yellow) based on existing outbreak data.*

Note **Step-by-step instructions for using these contact chain features are available within the RABapp™.**

Finally, to supplement the interactive map and contact chain features in the *SPS plan status* tab, RABapp™ users can also view tables summarizing the information displayed in the map, such as the SPS approval status and number of animals moved to and from farms within a selected control zone (Section 5.1.1).

PremID	*Farm name*	*SPS approval status*	*Licensed veterinarian*
00WOLF3	WOLF01	PRE-APPROVED	VETERINARIAN 01
11WOLF3	WOLF02	APPROVED	VETERINARIAN 02

Figure 5.2: *An example table displaying either pre-approval or approved status. This information is available for all SPS plans for each farm within RABapp™.*

5.1.2 Tab 2: SPS plan navigation and download

This tab contains tools that allow swine companies and animal health officials to view and download SPS plans that have been assessed and finalized by the RABapp™ team. ***(Importantly, RABapp™ users are only authorized to access information associated with their own company/producer group.)***

Users can select multiple farms by filtering SPS plans for one or multiple farms, and then click through the pages to view all 169 fields of the plan. To expedite the process for larger numbers of farms (e.g. to access all farms overseen by a specific veterinarian), multiple SPS plans can be selected and displayed side by side.

Once the SPS plans have been selected, they can be downloaded as either:

- **PDF files within a zip file:** This option provides users with the SPS plans - including both the written and map view components (Figure 3.1).
- **CSV or Excel files:** This option provides users with SPS plans in a table format, with rows representing individual farms and columns displaying each of the 169 SPS plan fields.

Note **Step-by-step instructions for selecting and downloading plans are available within the RABapp™.**

5.1.3 Tab 3: Update SPS plans (swine companies and producers only)

This tab allows swine companies and producers to quickly and easily update one or multiple SPS plans within RABapp™. There are three ways to update the plans:

1. Update individual plans one at a time.
2. Update a single field for multiple plans simultaneously (e.g. if a new veterinarian takes charge of 10 farms, the veterinarian name field can be changed for all farms in a single upload).
3. Upload multiple fields for multiple farms by uploading an Excel or CSV file containing a table of all SPS plans. *(This table is only provided by the RABapp™ team when SPS plans have achieved pre-approval or approved status (Section 5.1.1).)*

Once all changes have been made, users can submit their updated information/files to the RABapp™ team for review. When these changes have been reviewed and accepted by the RABapp™ team, the updated information is incorporated into the new version of the SPS plan within RABapp™.

Note **Step-by-step instructions for using this update feature are available in this video within RABapp™.**

5.1.4 Tab 4: State approval tool

The *State approval tool* allows state animal health officials (SAHOs) to review and approve SPS plans within RABapp™. After selecting a farm of interest in the tool, SAHOs can review the SPS plan in two formats:

1. **PDF view:** Within the PDF, which adheres to the SPS Plan for Continuity of Business template, SAHOs can review both the written description of the SPS plan and the farm biosecurity map.
2. **Table view:** Within the table, each row represents an SPS plan question and answer. SAHOs can review the answers and use an "Approve" column to accept or reject an answer. If an answer is rejected, SAHOs can add comments to provide an explanation for the rejection, which then is addressed by the RABapp™.

Once the review has been completed, SAHOs submit the plan and their comments to the RABapp™ team within the app. The RABapp™ team assess all comments and, where necessary, follow up with the company/producer to assist with corrections or troubleshoot any issues.

In addition to reviewing and approving SPS plans, SAHOs can also use this tool to download SPS plans in the event of either a state or national emergency. In this way, RABapp™ serves as a centralized tool for updating, reviewing and approving SPS plans, as well as an easily accessible SPS plan repository to expedite information sharing during an emergency.

Note **Step-by-step instructions for using this approval tool are available in this video within RABapp™.**

5.1.5 Tab 5: Disease surveillance and transmission models

Thanks to the increasingly broad participation of the swine industry in the RABapp™ project (Section 2.2), the team has utilized extensive movement and farm location data from swine companies to develop **three state-of-the-art transmission models**. These models are available within the *Disease surveillance tab*. The first two models enable the reconstruction of weekly outbreaks for two endemic diseases, PRRS and PEDV, while also providing short forecasts. *Of note, this tab is only available for states with at least 80% of all commercial farm locations in the RABapp™ database.*

Driven by these models, this tab generates **weekly PRRS and PEDV risk maps and the location of farms for each risk level**. These farms and their risk levels are displayed within interactive maps and tables within the tab. (Peer-reviewed research on risk level calculations can be found here: [6, 7].)

In addition to the PRRS and PEDV models, the third and arguably most critical model is **a transmission model for African swine fever (ASF)** [10]. Tracking the spread of this major infectious disease threat as soon as the first case is detected on U.S. soil is a prominent goal of the RABapp™ project. By leveraging the integration of comprehensive swine industry biosecurity and movement datasets within RABapp™, **the main outcomes of this ASF model** include:

1. Predictions of the initial disease spread and expected numbers of infected farms and pigs across the country.
2. Projected disease spread within different time frames after the initial outbreak is detected (e.g. weekly projections).
3. Identification of the transmission route that is most likely to cause the highest number of new cases (e.g. between-farm movement of pigs).

5.1.6 Tab 6: Import movements

This tab serves as a separate data sharing option for both **small and large independent swine producers** that wish to share movement data via RABapp™ instead of setting direct connection with the RABapp™ cyberinfrastructure. Using a basic upload function and a template provided by the RABapp™ team, independent producers can upload their movement data directly to the app.

There are simple requirements for ensuring data is uploaded successfully. If the movement data matches the list of farms already stored within RABapp™ the upload will be successful, and the team will proceed with data integration. If movement data is provided for sites (either origin or destination farms) that have not yet been added to RABapp™, the user simply needs to submit the missing information to the RABapp™ team, who can update the farm list. Once the farm is added to RABapp™, the independent producer can proceed with uploading their movement data.

Chapter 6 Final remarks

RABapp™ is a unique, state-of-the-art tool designed to enhance U.S. swine industry resilience against major infectious disease threats. By helping stakeholders work together across multiple states and sectors, RABapp™ ensures government officials, swine companies, independent producers and academic scholars can harmonize their preparation for foreign animal disease emergencies. Importantly, this not only enhances protection against future threats, but also helps reduce the heavy economic burden of existing endemic diseases such as PRRS and PEDV by reinforcing on-farm biosecurity.

The unparalleled strength of RABapp™ derives from cutting edge software development, mathematical models and outbreak simulations performed by leading academic experts in livestock infectious disease transmission. Rigorous quality control analysis of large, comprehensive datasets ensures RABapp™ provides the extraordinary precision needed for rapid decision-making before and during emergencies. Additionally, by fully integrating movement data with on-farm biosecurity information, RABapp™ provides in-depth insight into which farms are at greatest risk based on existing farm defenses and the likely path and magnitude of an outbreak.

With these capabilities, RABapp™ substantially enhances swine industry resilience against endemic and anticipated disease threats by:

- **Minimizing business disruption:** By running continuous models of disease outbreaks, RABapp™ allows users to develop and deploy highly targeted outbreak response and control strategies.
- **Reducing the major economic burden of endemic diseases:** By using past cases and predictive models to identify how, why and when farms will become infected, RABapp™ lets users more rapidly control an outbreak.
- **Limiting damage inflicted by ASF:** By leveraging models of endemic diseases to predict the path of damage, RABapp™ will help users proactively deploy outbreak responses to farms that are most likely to become infected with ASF.
- **Advancing outbreak mitigation:** Using state-of-the-art mathematical modeling, network analysis and outbreak simulations, RABapp™ provides users with highly effective contact-tracing tools to detect and quarantine infected farms.
- **Expediting state and national responses:** By equipping animal health officials with easily accessible online tools and high quality data, RABapp™ helps governments respond quickly and efficiently to foreign animal disease outbreaks.

Chapter 7 List of symbols and abbreviations

Item	Description
Pre-approved SPS plan status	The status awarded to farms in RABapp™ when the team has received the information needed to complete and submit the SPS plan (written and map view components) to animal health officials. At this stage, government approval is pending but SPS plans are loaded into RABapp™ to expedite information access.
Approved SPS plan status	The status awarded to farms in RABapp™ after animal health officials have completed their review of pre-approved farms (see above) and approved all plan components.
GIS	Geographic information system
ASF	African swine fever
SPS	Secure Pork Supply
NADPRP	National Animal Disease Preparedness and Response Program
EMRS	Emergency Management Response System
NASAHO	National Assembly of State Animal Health Officials
RABapp™	Rapid Access Biosecurity (RAB) app
SAHO	State animal health official
FFAR	Foundation for Food and Agriculture Research
USDA	U.S. Department of Agriculture
APHIS	Animal and Plant Health Inspection Service
FAD PReP	Foreign Animal Disease Preparedness Response Plan
GWCC	Giant Weakly Connected Component
PRRS	Porcine Reproductive and Respiratory Syndrome
PED	Porcine Epidemic Diarrhea

Chapter 8 Frequently Asked Questions (FAQs)

8.0.1 What is the Rapid Access Biosecurity application (RABapp™?

- ***Answer***: RABapp™ is a web-based software tool that allows swine producers and animal health officials to easily and continuously store, review and update Secure Pork Supply (SPS) biosecurity plans and movement information for animals and products (e.g. semen, germplasm). Developed by infectious disease experts at North Carolina State University, RABapp™ systematically integrates biosecurity information with movement data to generate cutting edge insights into livestock infectious disease transmission, and enhance preparedness for and responses to outbreak emergencies.

8.0.2 Does RABapp™ collect the minimum data fields required to enroll a site in the US Swine Health-Improvement Plan (US-SHIP)?

- ***Answer***: Yes, RABapp™ collects and processes data fields required by US-SHIP enrollment and certification, for more information please send us an email at machado-lab@ncsu.edu or call (919) 513-0781.

8.0.3 Why it is important to standardize SPS on-farm biosecurity plans?

- ***Answer***: During outbreaks of major infectious disease threats such as African swine fever (ASF), animal health officials need rapid access to compliant, accurate SPS plans to help businesses resume standard operations, including animal transportation between farms, as quickly as possible. Working closely with swine producers, veterinarians and animal health officials, the RABapp™ team provides a streamlined process for producing, reviewing and approving SPS plans to ensure all plans are not only up to date, but also adhere to national requirements [4]. This helps maintain business continuity during an outbreak emergency, and thereby enhances industry resilience.

8.0.4 Who should enroll and use RABapp™?

- ***Answer***: Personnel from any entity that sends or receives pigs from a site - from contract growers to company representatives to independent pig producers - are encouraged to participate in the RABapp™ project. To take part and use RABapp™, there are a few simple steps to follow:

  1. Request a National Premises Identification Number (PremID or PIN) from the office of your State Animal Health Official.
  2. Visit the Secure Pork Supply (SPS) Plan for Continuity of Business website to learn how to start building your biosecurity plans SPS plans.
  3. Once steps 1 and 2 have been completed, contact the RABapp™ team via email (machado-lab@ncsu.edu) or phone (919-513-0781). You can also contact the team for guidance and data collection tools if you are unfamiliar with SPS plans and would like additional assistance.

Chapter 9 Version history

This handbook is revised whenever RABapp™ functionalities are updated, new features are added, and new participants and partnerships are established. To help keep all stakeholders informed, this chapter serves as a living timeline of the entire RABapp™ project.

12/21/2019 *Updates:Project starts*

① The RABapp™ project starts by collecting SPS and movement data from one swine company in NC.

② NC State Animal Health Officials (SAHO) express support for the project and start to approve SPS plans within the app.

01/10/2021 *Updates:More swine companies join*

① **! Big Milestone**: All six pork producing companies with at least one farm in NC join the project. SPS plans and pig movement data collection begins.

② **! Big Milestone**: The first RABapp™ version (v1.0.0) is developed and deployed.

③ **Release of v1.0.0.** In this first version of RABapp™, users are only allowed to view SPS plans.

07/12/2021 *Updates:New version, v1.2.0.*

① RABapp™ allows animal movement contact tracing.

② RABapp™ allows SPS plans to be exported directly from the application.

③ Animal health officials (SAHOs) from additional states approve SPS plans within RABapp™.

01/21/2021 *Updates:USDA funding (NADPRP program) enables RABapp™ extension to OK and TX .*

① **! Big Change**: OK and TC State Departments of Agriculture join RABapp™.

② **! Big Change**: 10 new swine companies join RABapp™.

04/21/2021 *Updates:New SAHOs join RABapp™, reaching a total of eight state departments.*

① RABapp™ is presented to the National NASAHO ASF Working Group for the first time.

② RABapp™ is also presented to the National Pork Board, Illinois Department of Agriculture, Minnesota Department of Agriculture, Michigan Department of Agriculture, Virginia Department of Agriculture, South Carolina Department of Agriculture, Nebraska Department of Agriculture, South Dakota Department of Agriculture, Wyoming Department of Agriculture, Arkansas Department of Agriculture and Pennsylvania Department of Agriculture.

③ New pig producing companies and veterinarians join the project, reaching a new total of 15 companies and three mixed animal clinics.

07/21/2021 *Updates:RABapp™ incorporates animal movement data quality check reports and movement data observatory*

① Computer codes are developed to analyze the quality of movement data shared (see Appendix A for details).

11/23/2021 *Updates:Release of RABapp™ v2.0.0*

① ! **Big Change**: New functionality for collecting animal movement from small or mid-size producers is included.

② ! **Big Change**: ASF transmission model is incorporated into the disease transmission tab.

12/05/2021 *Updates:RABapp™ project receives additional funding from the Foundation for Food and Agricultural Research*

02/01/2022 *Updates:ASF transmission model available*

04/01/2022 *Updates:EMRS integration via API*

2022/07/06 *Updates:release of v2.4.0,* ***LAST*** *version of 2.4.0.*

08/08/2022 *Updates:release of v2.4.5,* ***LAST*** *version of 2.4.5.*

① ! **Big Change**: New SAHOs joined.

② ! **Big Change**: New SPS approval functionality.

③ ! **Big Change**: Semen networks available.

11/27/2022 *Updates:release of v2.5,* ***LAST*** *version of 2.5.*

① ! **Big Change**: New design and account "Manager User" now available.

Appendix A Additional information

A.1 Summary of published work and additional outreach tools

A.1.1 RABapp™ manuscripts

2022– Sykes, A.L. Galvis, J.A., OHara, K.C., Corzo,C., **Machado, G.** Estimating the effectiveness of control and eradication actions on African swine fever transmission in commercial swine populations in the United States. Link **–>biorxiv**

2022– Galvis, J.A., Corzo, C, Prada, J.M., **Machado, G.** Modeling between-farm transmission dynamics of porcine epidemic diarrhea virus: characterizing the dominant transmission routes. Link **–>Preventive Veterinary Medicine**

2022– Galvis, J.A., Corzo, C, Prada, J.M., **Machado, G.** Modelling and assessing additional transmission routes for porcine reproductive and respiratory syndrome virus: vehicle movements and feed ingredients. Link **–>Transboundary and Emerging Diseases**

2021– Sykes,A.L., Silva,S.G., Holtkamp,J.D., Mauch,W.B., Osemeke,O., Linhares,C.L.D., **Machado, Gustavo.** Interpretable machine learning applied to on-farm biosecurity and porcine reproductive and respiratory syndrome virus. Link **–>Transboundary and Emerging Diseases**

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[6] Jason A Galvis et al. "Modelling the transmission and vaccination strategy for porcine reproductive and respiratory syndrome virus". In: *Transboundary and Emerging Diseases* (2021). DOI: 10.1111/tbed.14007.

[7] Jason A Galvis et al. "The between-farm transmission dynamics of porcine epidemic diarrhoea virus: A short-term forecast modelling comparison and the effectiveness of control strategies". In: *Transboundary and Emerging Diseases* (2021). DOI: 10.1111/tbed.13997.

[8] Jason A. Galvis, Cesar A. Corzo, and Gustavo Machado. "Modelling and assessing additional transmission routes for porcine reproductive and respiratory syndrome virus: vehicle movements and feed ingredients". In: *bioRxiv* (2022). DOI: 10.1101/2021.07.26.453902.

[9] Jason A. Galvis et al. *Modeling between-farm transmission dynamics of porcine epidemic diarrhea virus: characterizing the dominant transmission routes*. 2022. arXiv: 2201.04983 [q-bio.PE].

[10] Gustavo Machado et al. "Modelling the role of mortality-based response triggers on the effectiveness of African swine fever control strategies". In: *Transboundary and Emerging Diseases* (). DOI: 10.1111/tbed.13841.

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