CPS 2022 RFP – FINAL PROJECT REPORT – Year 2

Project Title:

Flexible risk process models to quantify residual risks and the impact of interventions

Project Period:

January 1, 2024 – December 31, 2024

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Objectives:

Year 1. Build a supply chain risk model (SCRM) for Shiga toxin–producing *Escherichia coli* (STEC) and *Listeria monocytogenes* (LM) simultaneously in leafy greens to identify important risk factors and the impact of interventions on those risks. [Completed in Y1 of 3-year renewable project.]

Year 2. Improve the STEC and LM model with feedback from CPS stakeholders, and adapt the SCRM to accommodate additional pathogens and commodities.

Funding for this project was provided partly through the CPS Campaign for Research.

FINAL REPORT

Summary of Findings and Recommendations

Summary of Findings

- Modeling inadequate process wash water control (maintaining adequate free chlorine only about half the time rather than nearly all the time) increased both the public health risk and recall risk, even when initial contamination variability was low.
- Modeling small-scale failures in food safety practices, such as one irrigation water treatment failure, small animal intrusion, or an inadequate harvest sanitation between harvests, may result in small changes to public health risk and recall risk, though we need to add capabilities to model non-homogenous contamination to fully address these scenarios.
- Highly effective downstream processing (e.g., pathogen reductions achieved by process wash) can reduce the public health risk of rare, high-level contamination events.

Recommendations

From the project to date we recommend risk assessment in the produce industry clearly differentiate work to identify best practices from work to assess unintended deviations from those best practices, as these have very different implications for proactive and reactive management.

Abstract

The fresh produce industry uses pre- and post-harvest assessments to monitor food safety systems and identify deviations from standard food safety protocols. Yet, there are limited quantitative tools that have modeled deviations to support decision-making around response. We used our peer-reviewed supply chain risk model (SCRM) to evaluate the impact of industry-relevant scenarios representing small-scale failures introducing contamination or reduced control over treatments. Four scenarios were parametrized to represent (i) discovering a nonfunctioning irrigation treatment system after irrigation, (ii) ineffective harvester equipment sanitation before harvest, (iii) small animal fecal contamination in a field, and (iv) inadequate process wash control (free chlorine is maintained only about half the time). Each scenario was reviewed by domain-specific experts to critically evaluate the input parameters for modeling. The scenarios were applied to leafy green contamination with Shiga-toxin-producing *Escherichia coli*, with high and low variability. Lots were categorized by the risk of producing a positive test at retail. Under high contamination variability, inadequate process wash control resulted in a 9-fold increase in the overall risk of a positive test at retail (recall risk) compared to the baseline, and a meaningful increase in the number of highest public health risk lots (from 16 to 433). Under low variability, inadequate process wash control likewise resulted in a 10-fold increase in recall risk, but no highest public health risk lots were identified. Discovering a nonfunctioning irrigation treatment system, ineffective harvester equipment sanitation, and small animal fecal contamination each resulted in less than 2-fold increases in recall risk and negligible changes in the number of highest public health risk lots across both contamination scenarios. Where good data and reasonable simplifying assumptions support scenario parametrization, these findings can help the produce industry with risk-based decisions on response, such as product disposition, following deviations from standard food safety protocols.

Background

Project need and challenge

In the first year of this project, we successfully developed the framework of the Supply Chain Risk Model (SCRM); a tool initially designed to help the produce industry guide decision-making about best food safety practices (Pinto et al., 2025). In our published model, we presented the results of two leafy green contamination scenarios (with low or high variability initial contamination) with Shiga-toxin-producing *Escherichia coli* (STEC). We show that rare, high-level contamination events ultimately drive risk when good agricultural practices, standard food safety processes, and cold chain temperatures are otherwise well-managed. We further evaluated the tradeoffs between two, industry-relevant food safety practices of additional process wash water lethality and additional finished product testing. These tradeoffs demonstrated how our tool could inform decision-making about prioritizing resources to make the greatest food safety gains. While the previous scenarios can help with proactive decision-making around where to invest in best practices, conversations with our CPS Advisory Council identified an unmet need for scenario development to support reactive decision-making, such as what to do if one discovers a short-term problem in a field.

Additionally, our Advisory Council identified the need for a better dissemination plan for getting our model to the produce industry. In the first year of this project, we developed the framework of this model in a software program that required a license. Thus, we needed to transition the existing SCRM to a more user-friendly and accessible platform to overcome the potential cost and technical barriers. It was also important to define the appropriate users of the SCRM in the produce industry, while still providing a means for any interested user to explore the functions of the SCRM.

Current barriers in adopting computational tools in food safety risk assessment and management

Models and risk assessments such as the Food and Drug Administration Leafy Greens Risk Assessment Model (FDA-LGRAM), FDA iRisk, among others (Chen et al., 2013; FDA CFSAN & JIFSAN and RSI, 2021; Mokhtari et al., 2022; Zoellner et al., 2018), have demonstrated the potential utility of these models to the fresh produce industry. However, these tools may require technical expertise, accessing code, and an advanced understanding of risk assessment. Purposeful design of new computational tools and revisions to existing tools, defining an audience, and developing simplified versions for interested users could ultimately promote the broader adoption of these tools in the produce industry.

Solution, transition the SCRM to a more user-friendly and accessible platform

To overcome potential barriers to adoptions in the SCRM's original framework, we transitioned to a free platform, R via shiny (Chang et al., 2024; R Core Team, 2024b). We also put significant effort into developing user guides, installation and use tutorials, results viewers, and results download options.

Solution, define different model users to target for different tools

It was also important to consider who would be the SCRM users and their various needs. Through discussions with our Advisory Council, we ended up with two different types of users. One type of user was a technical expert with some training in risk assessment, who could eventually use the model to answer new industry-relevant questions by generating new model results and interpreting them accurately. Another type of user was one who might want to explore the results of the published work in a different way than reading the published paper. For this type of user we developed a results viewer to allow interested users to explore the results of our published leafy green scenarios (Pinto et al., 2025).

Current limitations in produce model scenario analyses

Others have reported produce models and risk assessments to identify which interventions have the greatest impact on pathogen concentration, or other measures of risk (Bozkurt et al., 2021; Mokhtari et al., 2022; Pang et al., 2017; Sant'Ana et al., 2014; Zoellner et al., 2018). While many of these models and risk assessments include scenario analyses to compare the relative risk reduction from implementing food safety interventions, e.g., chlorinated washes (most common) and ionizing radiation of finished product (uncommon), few report parametrization of scenarios that could represent small-scale failures. Yet, previous recalls and outbreak investigations, often of leafy greens, have reported the suspected or confirmed source of contamination resulting from deviations in standard food safety protocols or findings during routine assessments (FDA, 2019, 2021; USDA-FSIS, 2023). Suspected or confirmed contamination sources in these reports have included harvester equipment, the sediment of an agricultural water reservoir, and animal feces. Further, use of models such as the Food and Drug Administration Leafy Greens Risk Assessment Model (FDA-LGRAM) have demonstrated the importance of controlling wash water parameters, such as free chlorine, during processing (Mokhtari et al., 2022). These findings prompt a need to conduct new scenario analyses and build upon previous ones to equip the produce industry with a resource to guide decision-making.

Solution, develop scenarios representing deviations from standard food safety protocols and use the SCRM to evaluate impact

To better help the produce industry characterize risk associated with deviations from standard food safety protocols, we parametrized four industry-relevant scenarios using the SCRM. We used our existing leafy green STEC contamination scenario, as leafy greens represent many of the traceback investigations of the FDA and this scenario was used in previous model development. This contamination scenario allowed for relatively quicker comparison (than for a new commodity-hazard combination) of the impact of deviations, using the SCRM in a way that addressed Advisory Council priorities and demonstrated an additional function of the tool.

Taking steps to adapt the SCRM to new hazard-commodity combinations

Discussions with our Advisory Council for this project also helped us identify a new hazard-commodity combination to focus on: *Salmonella* and cantaloupes. To this end, members of our team toured cantaloupe farms in central Indiana in September of 2024 to facilitate an understanding of cantaloupe production. However, in this report, we will primarily focus on the transition of the SCRM to a new platform, and presenting the results and analysis of the new scenarios.

Research Methods and Results

Methods – Transitioning the SCRM Platform

We selected the new platform for the SCRM as R 4.3.3., using shiny to create a guided user interface (Chang et al., 2024; R Core Team, 2024b). The original framework of the SCRM in @Risk for Excel was translated to R by two team members. Additional packages used include "parallel", "lhs", "mc2d", "bslib", "bsicons", "shinyalert", "shinyBS", "shinyjs", "shinyWidgets", and "DT" (Attali, 2021a, 2021b; Bailey, 2022; Carnell, 2022; Perrier et al., 2024; Pouillot et al., 2023; R Core Team, 2024a; Sievert et al., 2024; Sievert et al., 2023; Xie et al., 2024). All codes are accessible at https://github.com/foodsafetylab/PintoReyes-2024-SCRM.git.

Results – SCRM Platform Transition with Integrated User Guide

The new platform for the SCRM is shown in **Figure 1**. We created a guided user interface with three main tabs: Model, Results Comparisons, and User Guide. To facilitate easy initial download of our tool, user instructions for downloading the tool are present on the GitHub (https://github.com/foodsafetylab/PintoReyes-2024-SCRM.git).

The *Model* tab (shown in **Figure 1A**) is the location where the SCRM can be run. The user would define the parameters for their supply chain prior to use and enter them into the fields of the model steps (**Figure 1B**). Up to 10 steps are possible. Once model steps are entered and named (optional), the user would navigate to the side panel, enter the desired number of iterations, name the scenario (optional), and select “run” to run the model. The results are summarized into three tables (one overall summary, one for risk categories, one for testing), and can be saved to the *Results Comparisons* tab. Users can also select a preset scenario from the drop-down menu, which include the scenarios we published. Instructions on how to run the scenarios are described on the main page of our GitHub (https://github.com/foodsafetylab/PintoReyes-2024-SCRM.git).

The *Results Comparisons* tab is the location where the results can be stored. From the *Model* tab, the user would select a slot number to save the results to, and by hitting "save" would automatically populate the results into 2 tables: one for risk categories and one for test results. These tables can be downloaded to local desktops as CSV files.

The *User Guide* tab is the location where the terms used in the model are explained (**Figure 1C**). The glossary presented describes every term that appears on the *Model* tab.

Methods – Defining SCRM Users and Development of Exploratory Version of the SCRM

After the interactive session held at the 2024 CPS Research Symposium, we developed a plan for users of the SCRM. This process consisted of conceptualizing a process flow for SCRM model use, i.e., trained specialists work with stakeholders in their network to use the tool. A 1-hour virtual meeting with our Advisory Council was held in July 2024 to discuss our proposed process flow and receive feedback.

Results – Defining SCRM Users and Development of the SCRM-Lite

Discussion with our Advisory Council resulted in alignment of our plan for intended users of the SCRM. The user of the SCRM was defined as any person on our current team, or an experienced individual in risk assessment. These individuals would ideally be positioned in networks in the produce industry that can reach growers, producers, and buyers (for example, food safety personnel in trade associations). This will be a primary focus of the third year of this project.

To facilitate engagement with future interested users, we further developed a tool to explore the types of results the SCRM generates, the SCRM-Lite (see **Figure 2**). This tool has one *Model* tab, which gives users access to sliding bars that can be moved. The results of the selections made appear in two graphs, which highlight the results of the published scenarios (Pinto et al., 2025). The instructions for downloading the SCRM-Lite can be found on our GitHub (https://github.com/foodsafetylab/PintoReyes-2024-SCRM.git).

Methods – Scenario Development

We finalized four new industry-relevant "what-if" scenarios for modeling contamination with STEC in leafy greens. This process consisted of (i) first selecting contamination scenarios based on a technical meeting we hosted at Illinois in November 2023 (project Year 1) with industry partners, (ii) individual 1.5-hour ideation sessions to determine the necessary parameters for a modellable input, and (iii) an internal team review of parametrization for each scenario. After internal team review, each scenario was discussed with a respective domain-specific expert in produce safety, and the parametrization approach or parameter values were modified accordingly. The four scenarios chosen each involved the introduction of additional STEC contamination to the baseline system, which are defined here:

1. **Small Animal Fecal Contamination (in a Field):** Contamination is introduced at the preharvest supply chain stage, representing finding a dead rodent during a preharvest assessment. The STEC contamination is the result of the rodent defecating in the field prior to discovering it. Some fraction of the feces is transferred to the produce. The key assumptions and parameters can be found in **Table 1**.
2. **Ineffective Harvester Sanitation:** Contamination is introduced at the preharvest supply chain stage from a food-contact (Zone 1) surface of a harvester not being sanitized after a harvest. The contamination is from leftover STEC cells (i) on a Zone 1 surface of the harvester, (ii) in the soil

left on equipment, or (iii) on the lettuce debris left on equipment. STEC levels can increase (grow) or not, between harvests. The key assumptions and parameters are listed in **Table 2**.

3. **Discovering a Non-Functioning Irrigation Water Treatment System:** Contamination is introduced at the preharvest supply chain stage when irrigation with water that does not meet Type A requirements per the LGMA occurs 2 days before harvest. Specifically, this scenario represents irrigating with Type B water where treatment failed (see Type B→A Requirements; LGMA, 2023). This would result from discovering a non-functioning irrigation water treatment system during a preharvest assessment. The key assumptions and parameters are listed in **Table 3**.
4. **Inadequate Process Wash Control:** Here new contamination is not reduced adequately when a process wash step is not well-controlled in a processing facility, i.e., >10 ppm free chlorine is not maintained. Thus, there is a lower probability of occurrence of the expected reduction achieved through a chlorinated wash step. The key assumptions are parameters are listed in **Table 4**.

Methods – Using the SCRM to evaluate the impact of defined scenarios

We built upon our published high and low STEC contamination variability scenarios for leafy greens (Pinto et al., 2025). The two baseline contamination scenarios were differentiated by changing the standard deviation of the normal distribution for initial contamination while leaving the mean as 1 CFU/lb. (-2.65 Log (CFU/g)). The baseline contamination scenarios were calculated as having a random contamination event occur at the preharvest stage.

For the *high variability contamination system*, the standard deviation (σ) was 0.8 Log (CFU/g), as this was the 'high variability' standard deviation used by the International Commission on Microbiological Specifications for Foods (ICMSF) to determine the stringency of sampling plans. This standard deviation was also used in the produce case studies for food safety objectives (International Commission on Microbiological Specifications for Foods (ICMSF), 2018; Zwietering et al., 2010). For the *low variability contamination system*, we changed the standard deviation (σ) of the initial contamination to 0.2 Log (CFU/g). This represents the low variability system as used by ICMSF through their system analysis.

The developed scenarios either resulted in additional STEC contamination being introduced into the supply chain, or smaller reductions to existing contamination achieved by a food safety process already present in the supply chain. For the Small Animal Fecal Contamination, Ineffective Harvester Sanitation, and Discovering a Non-functioning Irrigation Treatment Pump (in a Field) scenarios, a "Contamination" model step type was added at the appropriate point in the supply chain (see definitions on SCRM platform; https://github.com/foodsafetylab/PintoReyes-2024-SCRM.git). For the Inadequate Process Wash Control scenario, the processing step was broken into two model steps: a "Reduction" model step type for the reduction achieved by (i) water alone (100% probability of occurrence) and (ii) water with >10 ppm chlorine maintained (42.3% probability of occurrence).

The main output of the model is the probability of a positive test at retail. To better communicate the results, we categorized the likelihood of a positive test into two main bins, highest risk, defined by > 1 in 10 chance of a positive test, and lowest risk being non-contaminated. The overall risk was used as a proxy for 'recall risk' and the number of highest-risk lots was used as a proxy for 'public health risk'.

Results – Scenario Evaluation in the SCRM

Deviations or small-scale failures that result in contamination do not meaningfully change to public health risk or recall risk.

Small animal fecal contamination, discovering a non-functioning irrigation water treatment system, and inadequate harvester sanitation all do not meaningfully change public health risk or overall recall risk, under both high and low variability contamination scenarios (**Table 5**). While adding these contamination events to the system does increase lots with relatively low-level contamination, the downstream effects of processing manage the added risk enough such that the recall (overall) risk remains low. Basically, good processing manages the risk of small preharvest and harvest problems.

Inadequate process wash meaningfully increases recall risk under both contamination scenarios. However, public health risk only increases under high variability contamination.

Inadequate process controls (free chlorine only adequately maintained about 42% of the of the time rather than 99%) increased the recall risk by 9- and 10-fold for high variability and low variability contamination, respectively. Under high variability, the recall risk increased from 1 in 4,500 under the baseline scenario to 1 in 500. Under low variability, the recall risk increased from 1 in 20,000 to 1 in 2,000.

Under high variability contamination, inadequate process controls had a meaningful impact on public health risk, where the number of highest-risk lots increased from 16 to 433 (see **Table 5**), showing a meaningful (97%) increase. Under low variability contamination, inadequate process controls had negligible impact on public health risk, where no change was observed in lots of public health risk.

These results suggest that under a system where rare, high-level contamination events can occur (i.e., the high variability system) that the downstream effects of processing are important to controlling public health risk. Since the processing step was broken up into the reduction achieved from water (1.0 Log_{10} reduction, 100% of the time) and the reduction achieved from chlorine (1.25 Log_{10} reduction, 42.3% of the time), water alone is not sufficient to manage lots with initially high levels of contamination. The similar shifts in recall risk under both contamination variability scenarios provide support for the importance of having a consistent, high-quality wash.

Considerations for Risk Management Decision-Making

Here, we showed the potential value of the SCRM in guiding reactive decision-making, a reality which the industry may face when growing and processing produce. It is important to consider the assumptions of the parametrized scenarios, contamination distribution, and the data that are available for parametrization, as these may limit the conclusions which may be drawn. Where good data and reasonable simplifying assumptions exist, such as with process wash controls and irrigation water treatment system, these scenarios may have immediate value to the produce industry. Nuance remains important in these scenarios. Produce industry members should still evaluate the scenario descriptions and parameter values used. For example, discovering a non-functioning irrigation water treatment system and receiving a water sample test result of 10 MPN/ml vs. 10,000 MPN/ml could prompt very different action with respect to product disposition (result not yet modeled). Where data were less available and required assumptions about spread of contamination, such as with the inadequate harvester sanitation and small animal fecal contamination, more research to collect better data or revisions to the SCRM (i.e., to make cross-contamination possible) may be required before supporting risk management decisions. Nonetheless, we have demonstrated a new function of the SCRM, taking four industry-relevant scenarios representing deviations from food safety protocols or small-scale failures, and characterizing their risk.

Outcomes and Accomplishments

SCRM Guided User Interface

- We advanced the accessibility of the SCRM by moving it to a free platform and providing detailed instructions for launching the tool.
- Conversations with our Advisory Council helped identify the most appropriate users for the SCRM and helped us identify a priority area for the third year of this project: intentional roll out of the SCRM to targeted users in the produce industry.
- A "lite" version of the tool can be accessed by any interested user to explore the results of running scenarios in the SCRM.

SCRM Scenario Evaluation

- We successfully developed four new industry-relevant scenarios and applied them to our leafy green contamination scenarios previous published.
- The results indicate that inadequate process controls increased both the public health risk and recall risk, even when initial contamination variability was low.
- The results suggest that deviations or small-scale failures may result in small changes to public health risk and recall risk, though building in the functionality for non-homogenous contamination in the model or better data could support alternative conclusions.
- Where good data and reasonable simplifying assumptions exist, these scenario analyses may support risk management decisions.

Other

- We identified our new hazard-commodity combination and *Salmonella* and cantaloupe and went on a site visit to cantaloupe farms in Indiana to help our team understand whole-cantaloupe production.
- Manuscript writing (see Publications section)
    - Successfully published the SCRM and initial scenario analyses in the *Journal of Food Protection*
    - Submitted the literature review to the *Journal of Food Protection*. We are currently responding to reviewer comments.

APPENDICES

Publications and Presentations

Publications

- Pinto, G., Reyes, G.A., Barnett-Neefs, C., Jung, Y., Qian, C., Wiedmann, M., & Stasiewicz, M.J. (2025). Development of a flexible produce supply chain food safety risk model: Comparing tradeoffs between improved process controls and additional product testing for leafy greens as a test case. *Journal of Food Protection* 88:100393. https://doi.org/10.1016/j.jfp.2024.100393
- Jung, Y., Pinto, G., Reyes, G., Qian, C., Wiedmann, M., & Stasiewicz, M.J. (2025). A critical review of parameters relevant for Shiga toxin-producing *Escherichia coli* and *Listeria monocytogenes* risk assessments of leafy greens. *Journal of Food Protection* 88:100497. https://doi.org/10.1016/j.jfp.2025.100497

Additionally, a manuscript detailing the work done in Year 2 will be submitted to the *Journal of Food Protection*, with the working title of: Using a Fresh Produce Supply Chain Risk Model to Assess the Impact of Deviations from Standard Food Safety Protocols.

Presentations

- Stasiewicz, M. J., Wiedmann, M., Pinto, G., Barnett-Neefs, C., Jung, Y., Qian, C. (2024, April 24). Year 2 Kickoff: Development of "what-if" scenarios to guide stakeholder discussion [PowerPoint Presentation]. Virtual.
- Stasiewicz, M. J. (2024, June 18-19). Flexible risk process models to quantify residual risks and the impact of interventions [Oral Presentation]. Center for Produce Safety Research Symposium. Denver, CO, United States.
- Stasiewicz, M. J. (2024, June 18-19). Flexible risk process models to quantify residual risks and the impact of interventions [Poster Presentation]. Center for Produce Safety Research Symposium. Denver, CO, United States.
- Stasiewicz, M. Wiedmann, M. (2024, July 10). CPS Research Symposium Takeaways, Moving Forward with Industry Access to The Tool [PowerPoint Presentation]. Virtual.
- Pinto, G., Reyes, G.A., Jung, Y., Qian, C., Wiedmann, M., & Stasiewicz, M.J. (2024, July 16). Using a Flexible Supply Chain Risk Model for Leafy Greens to Compare Tradeoffs between Contamination Variability, Finished Product Testing, and Improved Process Controls [Poster Presentation]. Long Beach, CA, United States.
- Stasiewicz, M.J., Wiedmann, M. (2024, November 20). Flexible risk process models can be used to quantify residual risks and the impact of interventions on residual risks - CPS Site Visit & Update [PowerPoint Presentation]. Virtual.

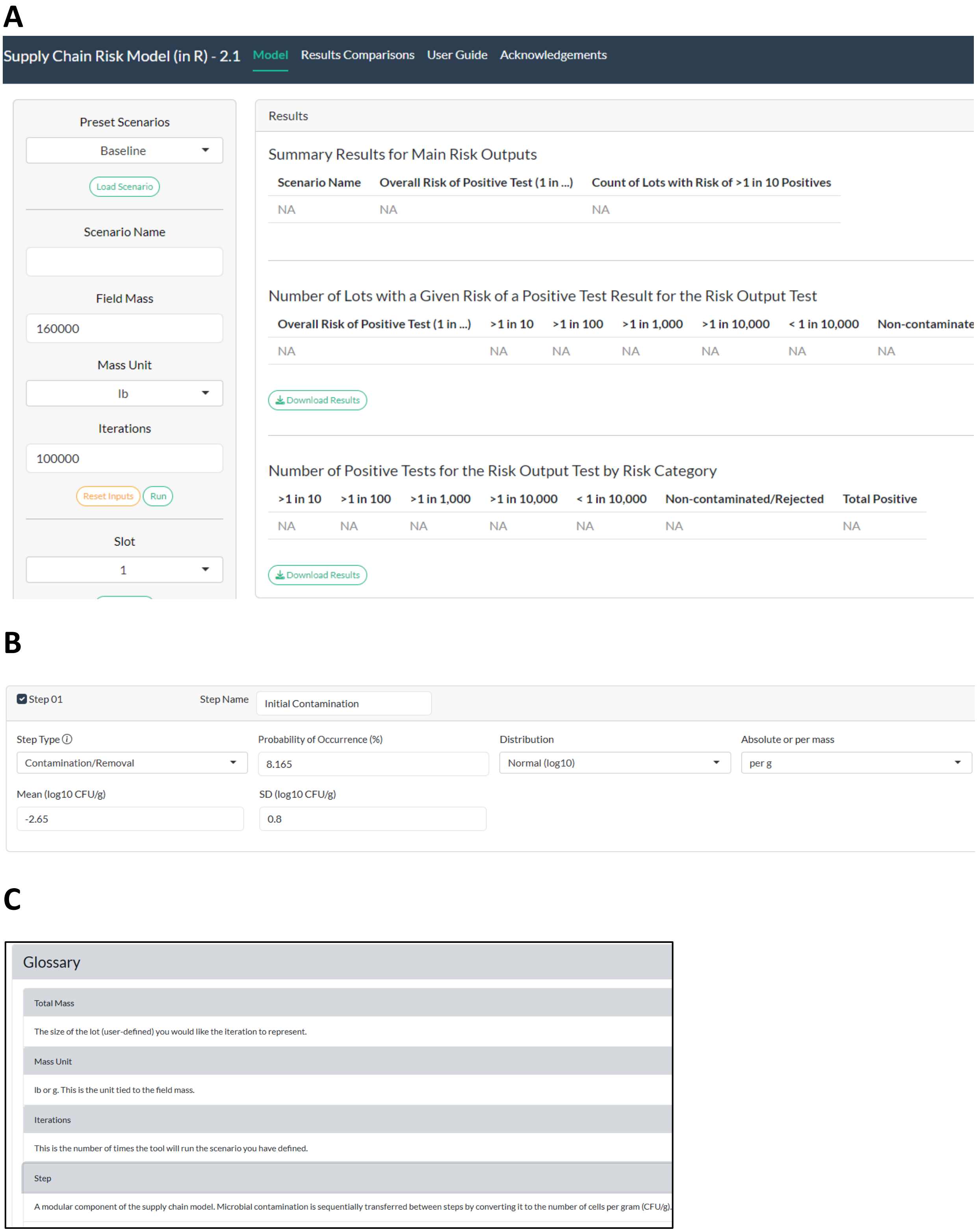
Budget Summary

We spent a total of $277,000 of the $298,000 budgeted though the Year 2 performance period ending December 31, 2024. The $21,000 unspent carryover to Year 3 was split approximately $8,000 to Illinois and $13,000 as subaward to Cornell. In addition, the total award to date for the project included $10,000 in Year 3 for travel to the CPS Research Symposium and publication fees, which brings the total budget to date to $308,000.

We did have the necessary funds to fully implement the project goals to date. The unspent Year 2 funds will carry over to Year 3.

Figures and Tables (see below)

***Figure 1:** SCRM guided user interface in R via shiny. Main page to run the model (**A**), an example model step with values populated (**B**), and glossary of terms used in the SCRM, found in the User Guide tab (**C**).*



Preset Scenarios
Baseline

Scenario Name

Field Mass
160000

Mass Unit
lb

Iterations
100000

Slot
1

Results

Summary Results for Main Risk Outputs

Scenario Name	Overall Risk of Positive Test (1 in ...)	Count of Lots with Risk of >1 in 10 Positives
NA	NA	NA

Number of Lots with a Given Risk of a Positive Test Result for the Risk Output Test

Overall Risk of Positive Test (1 in ...)	>1 in 10	>1 in 100	>1 in 1,000	>1 in 10,000	< 1 in 10,000	Non-contaminate
NA	NA	NA	NA	NA	NA	NA

Number of Positive Tests for the Risk Output Test by Risk Category

>1 in 10	>1 in 100	>1 in 1,000	>1 in 10,000	< 1 in 10,000	Non-contaminated/Rejected	Total Positive
NA	NA	NA	NA	NA	NA	NA

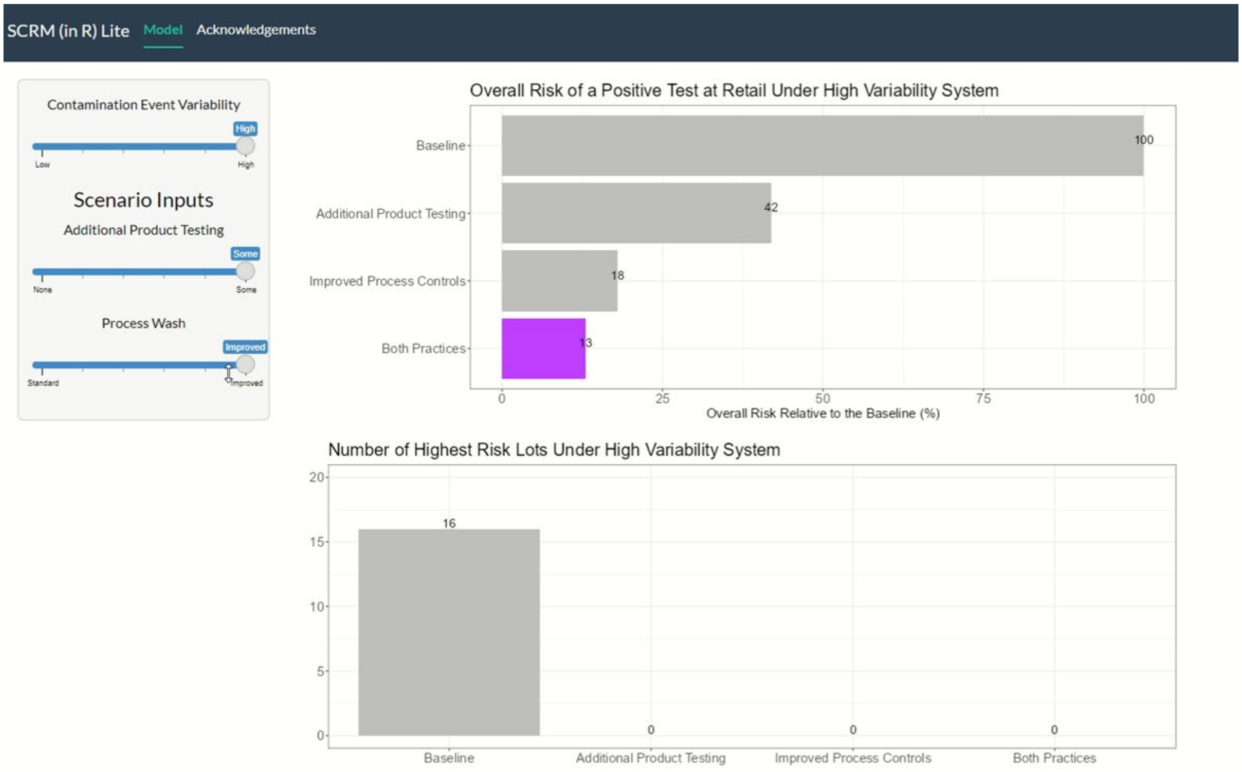
☑ Step 01
Step Name: Initial Contamination

Step Type: Contamination/Removal
Probability of Occurrence (%): 8.165
Distribution: Normal (log10)
Absolute or per mass: per g
Mean (log10 CFU/g): -2.65
SD (log10 CFU/g): 0.8

Glossary

Total Mass	The size of the lot (user-defined) you would like the iteration to represent.
Mass Unit	lb or g. This is the unit tied to the field mass.
Iterations	This is the number of times the tool will run the scenario you have defined.
Step	A modular component of the supply chain model. Microbial contamination is sequentially transferred between steps by converting it to the number of cells per gram (CFU/g).

Figure 2: *SCRM-Lite guided user interface in R via shiny.*



Contamination Event Variability: High

Scenario Inputs

Additional Product Testing: Some

Process Wash: Improved

Table 1: *Scenario parametrization of small animal fecal contamination*

Parameter	Symbol	Value	Unit	Source
General Description: We estimate the effect that would be expected from a small animal (e.g., rodent) defecating a field before it is found at the next preharvest assessment.				
Key Assumptions: • The fecal pellets are not centralized in one location in the field • The probability of discovering an infected rodent is the same as the prevalence of infected rodents captured in Kilonzo et al. (2013)				
Total lb of leafy greens produced in field	*m*	160,000	lb.	Calculated
Probability of discovering an infected rodent	*IR*	3.4	%	Kilonzo et al. (2013)
Rodents discovered /day	*Rc*	1	Rodents/day	Assumed value
STEC concentration in feces	*Cont_fc*	230000	CFU/g	Jahan et al. (2021)
Fecal pellet mass	*fpm*	0.1	g/pellet	Calculated
STEC concentration in pellet	*Cont_p*	*Cont_fc* fpm*	CFU/pellet	Calculated
Rodent fecal production per day	*Rfd*	100	Pellets/day	Assumed value
Pathogen cells in infected feces per day	*Cont_IRf*	*Cont_p* Rfd*	CFU/day	Calculated
Transfer coefficient from feces to product	*Cont_Tr*	0.01	unitless	Jeamsripong et al. (2019)
Cells transferred to crop/day	*Cont_lettuce*	*Cont_IRf* Cont_Tr*	CFU/day	Calculated
Concentration of STEC in field	*Cont_field*	*(Cont_lettuce/m)*454*	CFU/g	Calculated
Log concentration of STEC in field	*Cont_final*	Log_{10}*(Cont_field)*	Log_{10}(CFU/g)	Calculated

Table 2: *Scenario parametrization of ineffective harvester sanitation*

Parameter	Symbol	Value	Unit	Source
General Description: Harvester equipment may pose a meaningful food safety risk for leafy greens. We estimate the effect of not sanitizing a mechanical harvester Zone 1 surface between harvests: (i) Contaminated lettuce transfers STEC to conveyor belt, STEC multiplies between harvests, and a fraction of these get transferred to the next harvest. (ii) Contaminated lettuce transfers STEC to conveyor belt, STEC does *not* grow between harvests, and a fraction of these get transferred to the next harvest. (iii) 2 pounds of contaminated lettuce are left on the conveyor belt, STEC multiplies between harvests, and all the lettuce is picked up during conveying of the next harvest. (iv) 2 pounds of contaminated soil are added to the conveyor belt, STEC in soil multiplies between harvests, and all the soil is picked up during conveying of the next harvest. Examples in blue				
Key Assumptions: • The field (lettuce), conveyor belt, and soil are all homogenously contaminated • All harvests are of the same size (160,000 lb.) • STEC growth in lettuce, on equipment and in soil are all the same • Temperature between harvests is assumed to be constant				
General Harvesting Parameters				
Total lb. of leafy greens produced in 5-acre field	m_{field}	160,000	lb.	Assumed value
Baseline contamination in field	$Cont_i$	1	CFU/lb.	Assumed value
Total cells on leafy greens per field	$Cont_{field,\ i}$	160,000	CFU	Calculated
Transfer coefficient from lettuce to conveyor belt	$Tr_{L\text{-}C}$	Triangular(0,0.62,1.39)	%	Mokhtari et al. (2018)
Transfer coefficient from conveyor belt to lettuce	$Tr_{C\text{-}L}$	Triangular(15,28,22)	%	Mokhtari et al. (2018)
Total lb. of lettuce left on harvester	$m_{lettuce}$	2 (908)	lb. (g)	Assumed value
Total lb. of soil left on harvester	m_{soil}	2 (908)	lb. (g)	Assumed value
Contamination from lettuce				
No. of cells transferred from lettuce to conveyor belt	$Cont_{L\text{-}C,\ i}$	160,000 × 0.0062 = 992	CFU	Calculated
No. of cells transferred from conveyor belt to lettuce	$Cont_{C\text{-}L,\ i}$	160,000 × 0.22 = 218	CFU	Calculated
No. of cells on lettuce after harvest *i*	$Cont_{Lettuce,\ i}$	159,226	CFU	Calculated
New lettuce contamination level	$STEC_{Lettuce}$	$\text{Log}_{10}((Cont_{Lettuce,\ i}/160{,}000)/454)$ $\text{Log}_{10}((159{,}226/160{,}000)/454)$ = -2.66	Log_{10} (CFU/g)	Calculated
Contamination level on equipment after harvest *i*	$Cont_{Equip,\ i}$	160,000 – 159,226 = 774	CFUs	Calculated

Parameter	Symbol	Value	Unit	Source
Contamination from soil				
E. coli level in soil	EC_{soil}	Norm(0.549, 0.816) 1.37	Log$_{10}$ (CFU/g)	Allende et al. (2017)
Ratio of *E. coli* to STEC	R	$10^{-1.3}$ = 0.05	unitless	Ottoson et al. (2011)
STEC level in soil	$STEC_{soil}$	Log$_{10}$(10^{ECsoil} x R) Log$_{10}$(23.17 x 0.05) = 0.065	Log$_{10}$(CFU/g)	Calculated
Growth between harvests				
Time between harvests	t_{next}	12	h	Assumed value
Temperature between harvests	T_{next}	20	°C	Assumed value
Doubling time	dt	1.09	h	Koseki and Isobe (2005)
Maximum growth rate	μ	0.276	Log$_{10}$ (CFU/g/h)	Koseki and Isobe (2005)
Lag time	lag	5.04	h	Koseki and Isobe (2005)
No. of doublings	n	$2^{((tnext-lag)/dt)}$ $2^{((12-5.04)/1.09)}$ = 83.6	unitless	Calculated from Buchanan et al. (1997)
Change in STEC cells between harvests	$\Delta STEC$	Log$_{10}$(n) Log$_{10}$(83.6) = 1.92	Log$_{10}$ units	Calculated
Final STEC Levels				
Scenario (i)				
STEC levels on equipment next day	$STEC_{Final}$	83.6 × 774 = 64,681	CFUs	Calculated
STEC levels available to be transferred	$STEC_{Trans}$	64,681 × 0.22 = 14,230	CFUs	Calculated
STEC transferred to next harvest	$STEC_{Next}$	Log$_{10}$((STEC$_{Trans}$/m$_{field}$)/454) log$_{10}$((14,230/160,000)/454) = -3.7	Log$_{10}$ (CFU/g)	Calculated
Scenario (ii)				
STEC levels on equipment next day	$STEC_{Final}$	774	CFUs	Calculated
STEC levels available to be transferred	$STEC_{Trans}$	774 × 0.22 = 170	CFUs	Calculated
STEC transferred to next harvest	$STEC_{Next}$	Log$_{10}$((STEC$_{Trans}$/m$_{field}$)/454) Log$_{10}$((170/160,000)/454) = -5.6	Log$_{10}$ (CFU/g)	Calculated
Scenario (iii)				
STEC levels in soil next day	$STEC_{New}$	1.92 + 0.065 = 1.99	Log$_{10}$ (CFU/g)	Calculated
STEC levels in soil next day	$STEC_{Final}$	$10^{1.99}$ × (2 × 454) = 88,157	CFUs	Calculated
STEC transferred to next harvest	$STEC_{Next}$	Log$_{10}$((STEC$_{Final}$/m$_{field}$)/454) Log$_{10}$((88,157/160,000)/454) = -2.9	Log$_{10}$ (CFU/g)	Calculated

Parameter	Symbol	Value	Unit	Source
Scenario (iv)				
STEC levels in lettuce next day	$STEC_{New}$	1.92 + -2.66 = -0.74	Log_{10} (CFU/g)	Calculated
STEC levels in lettuce next day	$STEC_{Final}$	$10^{-0.74} \times (2 \times 454) = 166$	CFUs	Calculated
STEC transferred to next harvest	$STEC_{Next}$	$Log_{10}((STEC_{Final}/m_{field})/454)$ $Log_{10}((166/160{,}000)/454) = -5.6$	Log_{10} (CFU/g)	Calculated

***Table 3:** Scenario parametrization of discovering a non-functioning irrigation water treatment system*

Parameter	Symbol	Value	Unit	Source
General Description: We estimate the effect of irrigating with Treated Type B→A water at the threshold for failure per the LGMA 2 days prior to harvest. Such as discovering a non-functioning irrigation water treatment system (so no chlorine delivered) during a preharvest assessment.				
Key Assumptions: • Treated Type B→A water system had two, 100 ml samples of water test at the threshold for failure (10 MPN/100 ml, expressed as CFU/100 ml units below) • Irrigation with this water occurs 2 days prior to harvest (worst-case scenario) • Sun hours per day are assumed to be the same over the 2 days before harvest, resulting in the same STEC die-off on both days				
Failure MPN Generic *E. coli* in Type A irrigation water	EC_{fail}	10	CFU/100mL	LGMA (2023)
Days prior to harvest that irrigation occurred	IR	2	days	Assumed value
Transfer coefficient for *E. coli* via sprinkler irrigation	Tr_{IW}	0.011	unitless	Rock et al. (2012)
E. coli concentration in irrigation water transferred to leafy greens	EC_{IW}	$EC_{fail}*Tr_{IW}$	CFU/mL	Calculated
Ratio STEC to *E. coli* in irrigation water	R	20	%	Expert opinion
STEC concentration in irrigation water transferred to leafy greens	$STEC_{IW}$	$EC_{IW} * R$	CFU/mL	Calculated
Amount of irrigation water transferred via sprinkler irrigation	v_{IW}	Uniform(1.8, 21.6) $\mu = 11.7$	ml/g produce	Allende et al. (2017)
STEC concentration on leafy greens after irrigation	$STEC_{LG}$	$Log_{10}(STEC_{IW} * v_{IW})$	Log_{10} (CFU/g)	Calculated
Sun hours per day	h_{sun}	Pert(5, 10.4, 12)	h	Allende et al. (2017)
STEC decay in plant per day	$STEC_{decay}$	$-0.52* (h_{sun}/24)$	Log_{10} units	Allende et al. (2017); Ottoson et al. (2011)
STEC concentration on leafy greens at harvest	$STEC_{final}$	$STEC_{LG} + (STEC_{decay}*IR)$	Log_{10} (CFU/g)	Calculated

Table 4: *Scenario parametrization of inadequate process wash control, where adequate chlorine treatment is maintained either 99% or 42% of the time*

<table>
<tr><th>Parameter</th><th>Symbol</th><th>Value</th><th>Unit</th><th>Source</th></tr>
<tr><td colspan="5">General Description: We estimated the reduction (Log$_{10}$ change) in STEC concentration on leafy greens after washing in chlorinated (>10 ppm) wash water during the processing supply chain stage. The reduction achieved was calculated by subtracting the STEC concentration after processing from the initial STEC concentration before washing. The probability that the process wash achieved the reduction using chlorinated water was varied to represent a consistent, high-quality wash and a standard wash with limited controls</td></tr>
<tr><td colspan="5">Key Assumptions:
• The reduction of <i>E. coli</i> found in peer-reviewed literature was assumed to be 1:1 with the reduction of STEC
• No cross-contamination occurs during the wash (model limitation)
• A reduction of STEC from washing leafy greens with water always occurs</td></tr>
<tr><td>Log reduction in STEC concentration from water only</td><td>$\Delta STEC_{AW}$</td><td>-1.0</td><td>Log$_{10}$ (CFU/g)</td><td>Expert opinion; most likely value from pert distribution in Pang et al. (2017)</td></tr>
<tr><td>Log$_{10}$ reduction in STEC concentration from water with chlorine maintained at > 10 ppm</td><td>$\Delta STEC_{AW}$</td><td>-1.25</td><td>Log$_{10}$ (CFU/g)</td><td>Expert opinion; adapted from Pinto et al. (2025)</td></tr>
<tr><td>Probability of reduction from water alone</td><td>Pr_w</td><td>100</td><td>%</td><td>Assumed value</td></tr>
<tr><td>Probability of reduction from water with chlorine maintained at >10 ppm</td><td>Pr_{cw}</td><td></td><td></td><td></td></tr>
<tr><td>Consistent High-quality wash</td><td></td><td>98.8</td><td>%</td><td>Expert opinion</td></tr>
<tr><td>Standard wash with limited controls</td><td></td><td>42.3</td><td>%</td><td>Expert opinion</td></tr>
</table>

Table 5: *Scenario analysis results for risk of a positive product test at retail for each baseline scenario with high and low contamination variability, small-scale failure scenarios, and less well managed processing*

What-if Scenario	Number of lots categorized by risk of positive test at retail		The overall risk of a positive test
	Highest 1 in 10 lots	*Lowest* Non-contaminated	
High Variability Contamination (μ = -2.65 log_{10} CFU/g, σ = 0.8, Probability of Occurrence = 8.2%)			
Baseline	16	91,835	1 in 4,500
Irrigation Treatment Pump Failure	16	84,309	1 in 4,100
Ineffective Harvester Sanitation	16	84,309	1 in 4,400
Small Animal Fecal Contamination	16	88,711	1 in 4,400
Inadequate Process Wash Control	433	91,835	1 in 500
Low Variability Contamination (μ = -2.65 log_{10} CFU/g, σ = 0.2, Probability of Occurrence = 8.2%)			
Baseline	< 1	91,835	1 in 20,000
Irrigation Treatment Pump Failure	<1	84,309	1 in 14,600
Ineffective Harvester Sanitation	<1	84,309	1 in 18,500
Small Animal Fecal Contamination	<1	88,711	1 in 19,000
Inadequate Process Wash Control	<1	91,835	1 in 2,000

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