CPS 2023 RFP – FINAL PROJECT REPORT

Project Title:

Developing a user-friendly risk assessment tool to assess the food safety risks of fresh produce production and landscape use

Project Period:

January 1, 2024 – December 31, 2025 (extended to January 31, 2026)

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Objectives:

1. Conduct focus groups to collect and discuss inputs for quantitative risk assessment model.
2. Conduct quantitative risk assessment to evaluate the risk of fresh produce contamination under various agricultural, climatic, and environmental system scenarios.
3. Develop decision support tool: online user-friendly platform.

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FINAL REPORT

Summary of Findings and Recommendations

We developed a framework for risk assessment under various agricultural settings, climatic, and environmental scenarios in the Salinas Valley, CA, that integrated multiple sources of information, including evidence from the current body of literature, expert opinion, and public databases using a hybrid stochastic and spatially explicit risk assessment model approach. This framework was integrated into a user-friendly interface dashboard that is publicly available to help growers, the produce industry, and other stakeholders manage risks associated with contamination of leafy greens with pathogenic *E. coli* via different pathways. These pathways include: 1) wildlife intrusion, 2) animal feeding operations (AFOs) and concentrated animal feeding operations (CAFOs), 3) grazing cattle, 4) other sources (proximity to compost facilities, diversified small-scale farms [DSSF], and hobby farms), 5) irrigation water, and 6) flood events.

We established on-going partnerships with the industry that led to a series of discussions that helped shape the model through a participatory modeling approach. Moreover, these interactions developed into a fully structured expert opinion elicitation process to generate data to populate some of the parameters for the risk assessment for which only scarce data were available. By following a participatory modeling approach, not only were we able to use the stakeholders' feedback to improve the risk assessment model and its assumptions, as we also increased the usefulness of the tool and the engagement of its potential users. In other words, stakeholders were active participants in the co-design and beta-testing of the tool, which will directly increase usability and operational value of the developed risk assessment.

Future work focused on data collection and integration of relevant data sources would further strengthen the model, increase its quantitative rigor, and support continued refinement for industry use. Potential improvements include individual model customization using grower-specific data, without compromising data ownership, liability, or confidentiality. The sensitivity analysis indicated that the initial probability of contamination is the parameter with the greatest influence on model outcomes. Incorporating additional data, such as baseline contamination data from on-farm testing, would help reduce uncertainty and enable more precise risk estimates. Furthermore, as new evidence becomes available in the scientific literature, continued model refinement will be possible using the current framework. Regardless of these limitations, the model represents an important step towards improving food safety and provides a valuable decision-support tool for farmers, stakeholders, and the produce industry overall.

Abstract

Despite improvements in food safety standards and evolving changes in farming practices, foodborne disease outbreaks, including those caused by pathogenic *E. coli*, continue to occur in the fresh produce industry. Despite much scientific effort, it is difficult to determine the route of pathogenic *E. coli* contamination in fresh produce. To address these gaps, this project aimed at 1) conducting a series of stakeholder meetings, including focus groups and an expert opinion elicitation, to define the priorities in risk management and parameterization in a risk assessment model, coupled with a literature review of the evidence regarding risk factors involved in fresh produce contamination, 2) developing a framework for risk assessment that integrates different sources of information, such as literature, expert opinion, and publicly available data to assess the food safety risk of pathogenic *E. coli* contaminating fresh produce in the Salinas Valley, CA, and 3) developing a user-friendly interface that integrates the risk

assessment model to evaluate where and when the risk of a contamination event is increased. Data from 18 experts were used to populate model parameters and were integrated into the model, along with data retrieved from the literature and public databases. Results highlight the areas of concern according to the environmental and farm management scenarios being evaluated, which are spatially explicit, and provide guidance for prioritizing risk mitigation decisions. The model framework is fully open source and developed in R with an interactive user interface using R shiny for accessibility. The developed framework allows for integration of new information as it becomes available and updating and adapting the risk assessment model as needed. The developed tool is available to help growers be more proactive in managing risk from foodborne pathogen contamination into their fields, contributing to a safe supply of the produce and leafy green products grown in California.

Background

Contamination of produce and leafy greens with Shiga toxin–producing *Escherichia coli* (STEC) has first been identified as a public health issue in 1991 and repeated outbreaks have been reported since then in the US (Bottichio et al., 2020). The strain most commonly associated with outbreaks where severe disease occurs is *E. coli* O157:H7 (Marshall et al., 2020). According to a study using surveillance data from FoodNet (the CDC's Foodborne Diseases Active Surveillance Network), there were 357,000 (90% Credible Interval: 159,000–648,000) estimated cases of domestically acquired foodborne illnesses caused by STEC in 2019 in the US (Walter et al., 2025). Symptoms associated with STEC infection include gastro-intestinal disease (e.g., bloody diarrhea), anemia, hemolytic uremic syndrome, and kidney failure, which can lead to death, especially in children under five years old (Pennington, 2010).

California and Arizona are the top producers of leafy greens in the US, producing approximately 90% of leafy greens grown in the country (California Leafy Greens Marketing Agreement, 2025). As such, in the last decades the fresh produce industry has been working towards the improvement of safe leafy greens and other fresh produce production. Good Agricultural Practices for farming operations have been developed and are detailed in the California Leafy Greens Marketing Agreement, including standards for growing, harvesting, packing, and holding produce for human consumption (California Leafy Greens Marketing Agreement, 2024). In 2011, the Food Safety Modernization Act (FSMA) was created and regulations have been outlined by the Food and Drug Administration (FDA) to harmonize practices along the production continuum and in response to the outbreaks (Lacombe et al., 2022). These standards and regulations entail the collaboration between public stakeholders and private sectors within an agricultural ecosystem in which knowledge gaps in food safety associated with the production of leafy greens are tackled together.

Contamination of leafy greens and fresh produce with pathogenic *E. coli* can occur via different pathways, including application of contaminated soil amendments, contaminated soil or irrigation water, wildlife intrusion, contaminated equipment, and workers (Alegbeleye et al., 2018). The co-existence of animal and land use, as occurs with cattle grazing in lands that are adjacent to crop fields, and the interaction of weather patterns and presence of wildlife make it possible for transmission to happen in a complex and dynamic system (Dogan et al., 2023). Moreover, the survival of pathogenic *E. coli* in soil depends on many spatiotemporal factors, including site, year, season, soil characteristics, as well as agricultural practices (e.g., application of soil amendments, their type and depth of application) and weather factors (e.g., average daily temperature, precipitation), which adds to the complexity of STEC transmission dynamics (Sharma et al., 2019).

Cattle are a known reservoir for *E. coli* O157:H7 (Borczyk et al., 1987; Montenegro et al., 1990; Gyles, 2007; Persad & Lejeune, 2014). Fecal shedding of the pathogen may directly (e.g., airborne through contaminated fugitive dust particles, soil amendments) or indirectly (e.g., through water runoff that reaches irrigation systems, wildlife) contribute to the contamination of leafy greens in a dynamic process in which different environmental factors interplay (Yanamala et al., 2011; Persad & Lejeune, 2014; Benjamin et al., 2015; Berry et al., 2015; Marshall et al., 2020). In fact, FDA outbreak investigations during 2018-2020 have found patterns associated with certain geographical regions in California's central coast and activities associated with adjacent land use, which included cattle grazing and the presence of migratory birds (Lacombe et al., 2022).

The overarching goal of this project is to understand the risks associated with landscape use and environmental factors on the transmission and contamination dynamics of STEC in California fresh produce, considering the interaction of spatiotemporal, agricultural, weather, and environmental factors, to ultimately support risk mitigation decision-making under different scenarios, which can be explored using this tool. To achieve this, the first objective was to conduct focus groups discussions to understand risk factors and inputs for a quantitative risk assessment model, coupled with a literature search. These discussions developed into an expert opinion elicitation process, which resulted in the generation of data used to populate the risk assessment model in objective 2. The second objective was to develop a quantitative risk assessment to evaluate the risk of fresh produce contamination in the Salinas Valley, CA, under various agricultural, climatic, and environmental system scenarios, using data generated through the expert opinion elicitation from objective 1, public data, and data retrieved from the literature. The third objective was to develop a decision support tool integrating and translating the model developed in objective 2 into an online user-friendly dashboard, representing a useful aid for growers and other food safety managers to proactively manage contamination risks in leafy greens.

Research Methods and Results

Objective 1—To understand the current evidence regarding pathways of contamination and risk factors associated with the contamination of fresh produce and leafy greens with foodborne pathogens (in general) and pathogenic *E. coli* (in particular), we conducted an informal literature search and review from the body of literature available from lab resources, and further retrieval of related published papers was accomplished by checking the reference list of initial papers included in the review. Additional literature was reviewed as per stakeholders' suggestions.

Two hundred and twenty (n=220) publications (including scientific papers, whitepapers, reports, and guidelines from fresh produce associations) were gathered and reviewed. Papers were organized using an online citation management tool designed to organize, annotate, and format references (Sciwheel, now Lean Library Workspace) using tags pertaining to the following categories: wildlife, adjacent land use, soil amendments, climate/weather, livestock proximity, water, soil, airborne contamination, vectors, risk perception, mitigation, handling, biological soil amendments of animal origin (BSAAO), manure, compost, and organic. Key information that was considered important for later parameterization was collected in an Excel spreadsheet. The information in each tab varied depending on factors that may influence the risk of fresh produce contamination. **Table 1** provides a sample of references that are relevant to the wildlife and adjacent land use pathways.

Following the literature review, we conducted two focus groups: 1) fresh produce–related stakeholder meeting (June 28, 2024; seven participants) and 2) beef cattle stakeholder meeting (May 13, 2024; five participants). The research team presented the project objectives, outcomes and dashboard demo (objective 3).

From the stakeholder meetings (total of 12 stakeholders) and available industry risk assessments (LGMA and CCOF) and white paper (CAN) we identified the main pathways considered by the industry and stakeholders as 1) wildlife, 2) landscape use, 3) soil amendments, 4) AFOs and CAFOs, 5) hobby farms, 6) proximity to cow-calf operations, 7) water, and 8) climate/ extreme weather events. In identifying the pathways of most concern among stakeholders and industry guidelines, those cited at least three times were considered as the main pathways of interest. The use of soil amendments was not further considered in this project, because the Principal Investigator is conducting a separate project exclusively investigating soil amendments.

For wildlife, the most cited aspects related to contamination through this pathway were seasonality, fecal shedding, and neighboring wildlife habitat, with feral pigs and birds being the animal species of most concern. For all animal-related operations (AFOs/CAFOs, hobby farms, and cow-calf operations) and soil amendments, proximity to fields and water sources, wind speed and direction, and water runoff were the most cited aspects of concern, as well as dust for hobby farms and cow-calf operations and compost application for soil amendments. Within the land use pathway, the adjacent crop production timeline and crop-specific distance were reported as important. As for the water pathway, surface water contamination was the most cited as concerning. Lastly, weather-related seasonal patterns (such as precipitation) and extreme weather events (such as flooding) were cited across the different sources as aspects to consider when assessing risk of contamination.

Building on these discussions, and given that the ongoing literature review revealed a lack of quantitative data suitable for parameterizing the risk assessment model (objective 2), an expert opinion elicitation process was undertaken. This process served a dual purpose: first, to gather expert-derived data to inform model parameters (objective 2); and second, to provide an open forum for feedback on the model's framework and assumptions, as well as on the practicability of the tool itself (objective 3), while fostering continued stakeholder engagement and active participation through a participatory modeling approach.

We organized a series of stakeholder meetings (scheduled on March 21, 26, and 28, and April 2, 2025) in an online format. A total number of 34 experts (representing industry, research, governmental agencies and extension) were invited and 18 agreed to participate. This series of meetings were designed to be conducted in small groups to present the process of expert opinion elicitation and took place between March and April 2025. A protocol for the expert opinion elicitation process was developed and was based on the IDEA approach (Investigate, Discuss, Estimate, Aggregate) (Hanea et al., 2017), as applied by Estevez et al. (2019), and is an adaptation of the Delphi method (European Food Safety Authority, 2014; Estévez et al., 2019). The expert elicitation process was divided into three steps: 1) Pre-elicitation, 2) Elicitation, and 3) Post-elicitation.

Pre-elicitation: A group of experts was identified from a network of stakeholders relevant to the industry, including researchers, extension specialists, food safety experts, representatives of the industry (both produce and beef cattle), and governmental agencies. Factors contributing to the risk of contamination of leafy greens with STEC were reviewed and identified from the literature and interactions with the stakeholders. These risk factors were associated with environmental characteristics (e.g., soil pH), meteorological factors (e.g., wind) or on-farm food safety mitigation practices (e.g., wildlife protective barriers).

The event of interest was contamination of leafy greens with pathogenic *E. coli*, and experts were asked to provide a risk score based on their experience and considering all potential sources of information and knowledge (peer-reviewed papers and grey literature, empirical knowledge, observed data, previous experiences, conversations with growers or other stakeholders, etc.). The answer (Likert-type) scale was:

1. the factor highly reduces the risk; it is beneficial
2. the factor reduces the risk; may be beneficial
3. the factor is neutral; no risk modification
4. the factor increases the risk; may be detrimental
5. the factor highly increases the risk; it is detrimental

Elicitation: Expert opinion elicitation (18 subject matter experts) consisted of a series of two Zoom meetings with two rounds of data collection in-between, using a survey comprised of 13 questions. The survey also included boxes where participants could enter comments that they deemed relevant. While only the responses collected in the 13 questions were used as our model inputs, comments were considered for interpretation and discussion purposes.

Questions pertained to assessing how risk factors or interventions (e.g., wildlife mitigation practices, movement of cattle, proximity to CAFOs, etc.) modified the risk of contamination of leafy greens with pathogenic *E. coli*, according to experts. The same survey was sent out twice to allow experts to reconsider their answers from round 1 and have a chance to discuss potential ambiguities in the second meeting, which took place before round 2 of data collection (please refer to **Figure 1** for a flowchart depicting the expert opinion elicitation process). The meetings after round 1 took place in June 2025, via Zoom. Experts were encouraged to name other factors to be included in the questionnaire.

Post-elicitation: The 1-5 scale was transformed using a 0.8-1.2 odds ratio (OR) scale, such as that a 3 corresponded to an OR of 1 (no change in risk), and the remaining values corresponded at most to a 20% change in OR (either by reducing or increasing it, so that OR of 0.8 = score 1, OR of 0.9 = score 2, OR of 1 = score 3, OR of 1.1 = score 4, and OR of 1.2 = score 5). A 20% change in OR is assumed as a meaningful cutoff in risk assessment models and comprises a model assumption.

For parameterization purposes (objective 2), expert opinion was elicited as minimum, most likely, and maximum values. Generated data were aggregated (**Figure 2**) and used to populate the risk assessment model (objective 2) by fitting a pert distribution using the values provided by the experts for the minimum, most likely, and maximum values, which correspond to the parameters of the pert distribution.

A final meeting with the stakeholders/experts took place in October (October 21 and 24, 2025). In this meeting, we presented the results from round 2 of expert opinion data collection, as well as explained how data were integrated into the risk assessment model, and how the tool works (including sensitivity analysis). A sample of comments provided by stakeholders (pertaining to removal of non-crop vegetation, movement of cattle, and proximity to compost facilities) is summarized in **Table 2**. Some questions generated more variability (i.e., disagreement) in the expert responses. Those pertained mainly to questions about wildlife deterrence methods, which is aligned with the discussions that had previously taken place during the focus groups meetings. Comments from stakeholders highlighted the importance of more granularity in the assessments, as context matters, i.e., the impact of wildlife intrusion or, conversely, of implementing wildlife barriers, depends on farm conditions, other management practices, and weather. On the other hand, responses for other questions (e.g., the impact of wind) seemed to provide more precise estimates among experts.

Objective 2—To develop a framework for risk assessment under various production, climatic, and environmental scenarios in the Salinas Valley, CA, that integrated different sources of information, including literature, expert opinion, and public databases, we used a hybrid stochastic and spatially explicit risk assessment model approach. The premises for objective 2 were that: 1) the risk of contamination of leafy greens depends on many agricultural, spatiotemporal, weather, and environmental factors that interact with each other to generate different risk profiles that could be described using a risk assessment framework, and 2) the contribution of each factor or intervention (and each option within a factor) can be described using this approach to help inform the implementation of best practices for risk mitigation under different scenarios (e.g., proximity to grazing cattle versus CAFOs).

The different risk factors or interventions (input parameters) were assessed/populated by incorporating data retrieved from the literature, expert opinion, and public databases, using the quantrra package in R

(Gomez-Vazquez, 2024). The final outcome of interest was probability of contamination of leafy greens with pathogenic *E. coli*.

Risk factors and interventions were identified in the literature and from interactions with relevant stakeholders and built into a framework representing the different pathways of contamination that informed the risk assessment model. Factors/interventions were mostly agricultural and related to landscape use, but meteorological and environmental factors were also integrated in the model. Sources of data include literature and expert opinion (objective 1) for informing parameter values, and public databases (for spatiotemporal components, such as temperature or abundance of feral pigs) and user-input choices (for interventions) for calculating the final outcome using a user interface.

Parameters were modeled in the OR scale. For parameters modeled according to evidence from the available body of literature, a uniform distribution was fitted, e.g., uniform(1,1.2). For parameters modeled using expert opinion, a pert distribution was fitted, using a minimum, most likely, and maximum values. These parameters feed into each other to generate a final risk of *E. coli* survival in soil (in OR), which is then multiplied to the initial probability (**Figure 3**).

Table 3 describes model input parameters, assumptions, and sources of data either informing the assumption or populating the model parameter, **Table 4** describes the key parameter estimates and key information for risk assessment, and **Table 5** contains the formulae for calculating the final output.

Due to the uncertainty associated with the parameters included in the model and to understand their impact on the output, we conducted a sensitivity analysis. Sensitivity analysis consisted of running a number of iterations of the model (e.g., 1,000), randomly selecting different options, and then plotting the options associated with specific risk factors or interventions of interest to visually inspect the mean output (i.e., probability of contamination of leafy greens with pathogenic *E. coli*) and confidence intervals. Sensitivity analyses plots are provided in **Figure 4**.

Running a scenario in a random location in the month of January – where the user selected a medium initial probability of contamination (1 in 100 batches would be contaminated) and the following options for farm characteristics: 1) not removing (i.e., keeping) non-crop vegetation around crop fields, 2) no fences being used as a food safety practice, 3) proximity to a CAFO, 4) with more than 5,000 head of cattle, and 5) located uphill in relation to their farm, 6) proximity to grazing cattle located uphill in relation to their farm, 7) existing movement of cattle from both CAFOs and 8) grazing cattle around their farm in the week prior to the assessment, 9) no proximity to a diversified small-scale farms (DSSF) or hobby farm, and 10) no proximity to a compost facility, 11) using the public water supply, and 12) subsurface drip as the method of irrigation, 13) no flood events occurring in the two month-period prior to the assessment, 14) a predominantly sandy type of soil, 15) with an alkaline pH – yielded a medium (1 in 100 batches would be contaminated) probability of contamination of leafy greens with pathogenic *E. coli* (final output). This is an example of a scenario where the farm being evaluated is close to cattle (both CAFOs and grazing cattle) and there is movement of cattle around the farm (**Figure 5**).

Because the hypothetical user selected a medium initial probability of contamination (1 in 100 batches would be contaminated), which is the variable that contributes the most to the final probability, we do not see the influence of proximity and movement of cattle in changing the final output. Please bear in mind that other variables (not user-defined) that relate to abundance of wildlife and soil type in that region, as well as weather factors for the month of January in the region (a different month could have been selected), including temperature, wind conditions, hours of sunlight, and precipitation (which are spatially-explicit) are being informed by datasets running in the background and these also influence the final output.

Objective 3—To integrate the model into a user-friendly web-based platform that facilitates the use of this risk assessment (i.e., dashboards that facilitate the visualization of the risk estimates, risk maps and sensitivity analyses interactively) by stakeholders, industry, and growers, a tool/dashboard was developed on the programming language R and R package Shiny.

The collected data from publicly available sources was processed for the study region (Salinas Valley, CA) and summarized to be integrated in the dashboard. This process included: 1) downloading the data from the publicly accessible databases, 2) reducing the data for the study area and variables of interest, 3) making any necessary data transformation to interpret the data in the context of the model, 4) aggregating the data for generalizability, and 5) exporting the data in an efficient format for cloud storage and integration in the platform. These standards for processing and managing the spatiotemporal data that feeds into the model take into account the efficiency in storage and processing of the information.

The raw data were obtained from publicly available extensive spatiotemporal databases, then the data were processed and aggregated into 12 rasters representing the expected values for each of the months through the year for each variable (i.e., presence of different wildlife species, precipitation, hours of sunlight, among others). Abundance of wildlife data were retrieved from the Global Biodiversity Information Facility (GBIF), an international network and data infrastructure, weather conditions (e.g., wind speed, hours of sunlight, temperature, soil type, and precipitation data) were retrieved from Copernicus Climate Data (ERA5). Please refer to Table 3 for more information on input parameters, assumptions, sources of data, and references.

The current framework allows the user to select a specific time frame and location in the Salinas Valley region in CA (individual field(s) or ranches) for which they want to assess the risk of contamination (i.e., the tool is spatially and temporally specific), as well as other inputs pertaining to farm characteristics (farm interventions or risk factors), that are selected from different possible options. The initial probability of contamination to be considered (low, medium, or high) must also be selected by the user. A low probability of contamination is defined to range from 0.00001 to 0.001, medium from 0.001, 0.01, and high from 0.01,0.05 (Cooley et al., 2014; Zhang et al., 2018).

All the information incorporated in the model is publicly available and the tool does not collect the input information from the user.

The tool incorporating the model and the spatiotemporal data has been deployed on a cloud-based server for easy access and can be accessed following this link: https://ucdcadms.shinyapps.io/cps-app/.

A documentation package is integrated into the platform, as well as a pdf manual for its distribution and easy access by its users. These include an example of a scenario and its interpretation, a description of what is risk and risk assessment, a general background information section to contextualize the issue and the application of the tool, a glossary of terms, and a reference list, by topic.

Figure 5 depicts a section of the dashboard and how the results are shown to the user.

Outcomes and Accomplishments

Objective 1—The first objective of this project was to understand and review the current body of evidence for the pathways of contamination of leafy greens with pathogenic *E. coli* and related risk factors.

To address this objective, we conducted an informal literature search and review, focus group discussions, and an expert opinion elicitation. The literature search yielded 220 publications that were organized and reviewed to inform the framework for the risk assessment (objective 2) and for parameterization purposes. Focus group discussions were essential for establishing an enduring partnership with the stakeholders, engaging them in the process of model building and tool development (participatory modeling approach). We identified the main pathways of contamination from both the interactions with stakeholders and the evidence from the literature. These were: 1) wildlife intrusion, 2) landscape use, 3) soil amendments, 4) AFOs and CAFOs, 5) hobby farms, 6) proximity to cow-calf operations, 7) water, and 8) climate/extreme weather events. Soil amendments were not considered as a pathway in this model.

The interactions and discussions with the stakeholders led to an expert opinion elicitation process that helped foster stakeholder engagement and participation, and allowed to generate data for parameters for which little data were available in the literature. The expert opinion elicitation process was comprised of three steps – pre-elicitation, elicitation, and post-elicitation – and resulted in the generation of data for 13 inputs in the risk assessment model.

Objective 2—The second objective of this project was to develop a risk assessment model to evaluate the risk of contamination of leafy greens with pathogenic *E. coli* (outcome of interest) using the quantrra package in R (Gomez-Vazquez, 2024). A framework informing the model was developed based on information gathered in objective 1, that included the different pathways previously identified. The different model inputs were populated using data retrieved from the literature (objective 1), publicly available databases, and expert opinion (objective 1). The model is spatially and time specific, as users can select a geographic location in the Salinas Valley region in CA and timeframe for which they wish to perform the assessment, possible through the development of an online interface (objective 3) that allows users to choose their model specifications before running the model. Time- and space-dependent parameters include wildlife abundance, number of hours of sunlight, environmental temperature, soil type, wind speed, and precipitation.

A sensitivity analysis was performed, consisting of running a number of iterations of the model, randomly selecting different options, and then plotting the options associated with specific risk factors or interventions of interest to visually inspect the mean output (i.e., probability of contamination of leafy greens with pathogenic *E. coli*) and confidence intervals associated with the different choices. The variable that contributes the most in terms of relative important to the final probability, is the initial probability of contamination (a user-defined parameter). In practice, this may imply an over or underestimation of initial contamination levels, depending on how precise the user's assessment of their initial risk is. This limitation can be addressed by incorporating additional data, such as baseline contamination data from on-farm testing, which would help reduce uncertainty and enable more precise risk estimates.

Objective 3—The third objective of this project was to integrate the model developed in objective 2 into a user-friendly interface to be used as a decision tool aiding in the implementation of best practices for risk mitigation in fresh produce fields under different agricultural, climatic and environmental system scenarios. This was achieved by building an online dashboard using R and R package Shiny.

This tool allows the user to select a specific time frame and location in the Salinas Valley region in CA, and inputs pertaining to farm characteristics (farm interventions or risk factors), as well as the initial probability of contamination to be considered as baseline in the assessment (low, medium, or high). The results provide the output values in the OR scale, and the final outcome (probability of contamination). All data are publicly available and the tool does not collect the input information from the user.

Overall, a major accomplishment of this project was the active engagement, feedback, interest, and participation of all stakeholders involved. With the literature search yielding few quantitative estimates that could be used for parameterization in the hybrid model we had envisioned, ongoing conversations and focus group discussions led to the development of a structured expert opinion elicitation process to address those data gaps. The process resulted not only in data generation, but in the establishment and continuation of industry relationships that helped shape the model and the dashboard and were participatory in nature. The suggestions and comments of participating experts were integrated in the framework and helped us tailor the tool to industry needs. Moreover, throughout our interactions several of the participating industry representatives have expressed their interest in using the tool with their growers. Finally, this framework has been applied in additional grant proposals to support future research.

APPENDICES

Publications and Presentations

Publications:

Two manuscripts will be submitted: (i) a research paper describing the expert opinion elicitation process and (ii) a research paper describing the framework and findings of the model.

Presentations:

1. Alda Pires#, José Pablo Gómez-Vázquez, Beatriz Martinez-López, Gabriele Maier Risk Assessment: Balancing Food Safety & Co-Management; workshop: Co-management: Balancing food safety risks for biodiverse practices, 2025 EcoFarm, January 23, 2025 Asilomar CA. Oral presentation & Poster, #presenter.
2. Alda Pires #, Ana R.S. Oliveira, José Pablo Gómez-Vázquez, Beatriz Martinez-López, Gabriele Maier Developing a user-friendly risk assessment tool to assess the food safety risks of fresh produce production and landscape use 2025 CPS Research Symposium, June 17- 18, 2024 La Jolla, California. Oral presentation & Poster, #presenter.
3. Ana R.S. Oliveira, José Pablo Gómez-Vázquez, Beatriz Martinez-López, Gabriele Maier, Kefang Nie, Maria Luisa Klobongona, Alda F. A. Pires#. Developing a user-friendly risk assessment tool to assess the food safety risks of fresh produce production and landscape use. 13th International Conference on Predictive Modelling in Food Meeting (ICPMF), Sept. 1-3, 2025, Athens, Greece. Oral presentation, #presenter.
4. Ana R.S. Oliveira, José Pablo Gómez-Vázquez, Beatriz Martinez-López, Gabriele Maier, Alda F. A. Pires. Assessing the risk of contamination of leafy greens and landscape use in California farmland: a participatory modeling approach and user-friendly tool. 2026 Annual IAFP Meeting, July 26-29, 2026, New Orleans, Louisiana. Submitted.

Budget Summary

This project was awarded $337,701 in research funds. Throughout the project period, the project team utilized funds to support students and research staff salaries and benefits at the University of California, Davis. Personnel and travel funds were used to conduct focus groups for the collection and discussion of model inputs. Personnel funds were used to develop a risk assessment model designed to estimate the probability of the presence or absence of pathogenic *E. coli* under diverse epidemiological scenarios. In addition, personnel funds were used to build a platform incorporating the findings of both the focus groups and risk assessment model. Travel funds were used to support the project PI and project personnel to attend the annual Center for Produce Safety Research Symposium in 2024 and 2025.

Tables 1–5 and Figures 1–5 (see below)

Table 1. Sample of publications reviewed during the literature search and pertaining to the wildlife and adjacent land use pathways of contamination of leafy and fresh produce with foodborne pathogens.

Pathway	Number of articles	Authors
Wildlife	25	Sargeant et al. (1999); Fischer et al. (2001); Jay et al. (2007); Fonseca et al. (2011); Strawn et al. (2013); Jay-Russell et al. (2014); Szymczak et al. (2014); Atwill et al. (2015); Bell et al. (2015); Karp, Baur, et al. (2015); Karp, Gennet, et al. (2015); Singh et al. (2015); Karp et al. (2016); Wild Farm Alliance (2016); Mishra et al. (2017); Weller et al. (2017); Jeamsripong et al. (2019); Jones et al. (2019); Pradhan et al. (2019); Navarro-Gonzalez et al. (2020); Topalcengiz et al. (2020); Weller et al. (2020); California Leafy Greens Marketing Agreement (2023); Smith et al. (2023); Olimpi et al. (2024)
Adjacent land use	6	Strawn et al. (2013); Wild Farm Alliance (2016); Weller et al. (2020); Weller et al. (2022); Devarajan et al. (2023); Murphy et al. (2023)

Table 2. Sample of comments provided by stakeholders during the expert elicitation process (in open-ended boxes in survey), as they pertain to removal of non-crop vegetation, movement of cattle, and proximity to compost facilities.

	Comments related to removal of non-crop vegetation
Beneficial	Physical barriers are needed to prevent or deter wildlife. Bare ground buffers may reduce rodent and amphibian excursions into crops from non-crop vegetation. Non-crop vegetation in vegetated ditches brings in greater rodent biodiversity.
Detrimental	Literature shows that habitat removal is not effective and may even increase food safety risks. Non-crop vegetation like grasses can filter polluted sheet flow during rainstorms. Windbreaks intercept dust from CAFOs. Trees provide raptors with perches to hunt rodents that may have come in contact with cattle feces. Wild pigs are coming to eat the crop and are not attracted to habitat; they mostly travel at night when they don't need cover.
Depends	Depends upon the environmental factors, timing, location, local factors. Perception of buyers will probably drive this requirement, rather than the science. In many scenarios, this would not reduce risk and may be neutral. In certain scenarios, non-crop vegetation may be detrimental. Depends on the crop being grown and the types of vegetation surrounding crop fields, type of wildlife intrusion and fresh produce or soil contamination. May reduce the likelihood of large wildlife (e.g., deer, feral swine) entering produce fields but overall impact on *E. coli* contamination risk is likely limited. Scientific evidence remains inconclusive.
	Comments related to movement of cattle (CAFOs)
Detrimental	Can increase the risk of *E. coli* contamination due to the potential for airborne transmission of dust particles containing fecal matter, increased vector activity (e.g., flies, birds), and runoff or surface water contamination. While not all cattle movement events lead to contamination, studies have demonstrated that proximity to CAFOs and associated activities like transportation or loading can be significant contributors to *E. coli* presence in produce fields. The risk is particularly elevated under dry, windy conditions or if mitigation measures (e.g., buffer zones, dust control) are not in place.
Depends/unknown	Personal experience indicates that this is an unknown and uncontrolled risk. Depends on several factors such as the age and type of crop (new or close to harvest) and other topography and weather conditions factors, wind, dust abatement measures. Depends on wind direction/gustiness/ speed during cattle movement operations, along with the surface moisture/dryness (dustiness) of the soil at cattle operations and position of trees and tall vegetative areas between cattle operations and crop area, which may serve as particulate catchment of wind/airborne particulates.

	Within a mile is a tough thing, is it 20 feet or 5200 feet? Also, is this near water? Or in a windy location. We know the cattle can be a source of pathogenic *E. coli*, but the potential for spread hinges on other things.
Comments related to movement of cattle (grazing cattle)	
Detrimental	Depending on how much dust is created, there is the potential for increased risk.
Depends	Less risky than CAFOs but can still increase the risk through dust, water runoff, or vectors like flies and birds. Seasonality and proximity of transloading facilities of the cattle must be factored. Compared to stationary grazing, movement-related activities create dynamic contamination pathways. Well-managed rotational grazing with effective buffers and drainage mitigate the risk. Other variables such as weather, wind direction, UV index, water runoff, etc. could increase or decrease the level of risk. Cattle staging locations, movement type and human management modify the risk.
Comments related to proximity to compost facilities	
	Depends on weather and stage of the composting operation. If the raw compost ingredients are away from the field versus close. It is about the exposure to the untreated/unfinished compost of the operation. Depends on the compost management practices, size of yard, physical barriers for wind, etc. Not all composting operations are the same with consistent raw materials coming in over the year. This may be a seasonal concern too. DEPENDS: there are many distinct operations to a compost facility. E.g., incoming material, does it go into a containment area or is it outside and released by dumping from delivery trucks and visible particulate dust/debris released into the air; what is the prevailing wind direction relative to time of day deliveries into the compost facility are made; what operation steps are completely outdoors, e.g. compost piles and turning operations, screening of finished product, delivery of bulking materials; loading of finished product into trucks; bagging operations etc. All outdoor, non-enclosed operations particularly of unprocessed/non-composted materials (inputs) and compost piles are potential sources for airborne particulate release into air and transport off-site. May increase the risk of *E. coli* contamination if compost is improperly treated, stored, or managed especially if it includes animal waste. Risks include wind-blown particulates, compost leachate runoff, and vector transmission. Also, this close proximity can cause cross-contamination during transport of raw material to the composting facility. However, well-managed compost facilities may not pose a significant risk justifying a lower minimum value. Depends on type of feedstock, prevailing winds, and type of compost facility. My big concern would be the transportation and turning steps of the compost production, causing potential dust and particulates to reach the leafy greens field. 400 feet is pretty far and should serve to minimize risk.

Table 3. Risk assessment input parameters, their assumptions, source of data for parameterization, and references.

Parameter	Assumption	Input type	Source of data	Supporting literature
Presence of wildlife (and prevalence of STEC in wildlife) (wl_b, wl_c, wl_p)	Presence of wildlife increases the risk of contamination of leafy greens with STEC.	dataset	Global Biodiversity Information Facility (GBIF)	Kullas et al. (2002); Gordus et al. (2011); Kilonzo et al. (2013); Jay-Russell et al. (2014); Navarro-Gonzalez et al. (2020); Smith et al. (2023); Karp (2024)
Controlling biodiversity as a wildlife mitigation practice (i1)	Removal of non-crop vegetation, putting up fences or creating bare-ground buffers around crop fields are detrimental to biodiversity and thus counterproductive as wildlife mitigation practices.	User-defined	Expert opinion	Sellers et al. (2018); Shariat et al. (2020); Weller et al. (2022); Olimpi et al. (2024)
Hours of sunlight (e_s)	Increased hours of daylight reduce STEC survival in soil.	dataset	Copernicus Climate Data (ERA5)	Yaun et al. (2003, 2004)
Environmental temperature (e_t)	STEC survival decreases as temperature increases (< 10°C; 10-20° C; > 20° C).	dataset	Copernicus Climate Data (ERA5)	Tran et al. (2020)
Soil type (i13)	Clay soil increases STEC survival, compared to silty and sandy soil types.	dataset	Copernicus Climate Data (ERA5)	Franz et al. (2014)
Soil pH (i14)	Ideal pH: 6.5–7.5; can grow in acidic pH:4.5-6.5; Limited growth > 7.5.	User-defined	Literature	Balamurugan et al. (2015)
Soil moisture (i15)	Higher soil moisture increases STEC survival	User-defined	Literature	Tate (1978); Chandler and Craven (1980); Rochelle-Newall et al. (2016); Underthun et al. (2018)
Movement of cattle (i2)	Movement of cattle around the farms increases the risk of	User-defined	Expert opinion	Berry and Wells (2010); Bright et al. (2020); Wei, Aggrawal, Bond and Atwill (2023)

	STEC airborne contamination			
Proximity to a concentrated animal feeding operation (CAFO) (i3)	Proximity to a CAFO increases the risk of STEC contamination (airborne and via water runoff)	User-defined	Expert opinion	Berry and Wells (2010); Bright et al. (2020); Wei, Aggrawal, Bond and Atwill (2023)
Size of CAFO if farm close to CAFO (i4_1)	The larger the CAFO, the higher the risk of contamination	User-defined	Expert opinion	California Leafy Greens Marketing Agreement (2023)
Location of CAFO if farm close to CAFO (i4_2)	CAFOs located uphill to the farm increase the risk of contamination via water runoff	User-defined	Expert opinion	assumption
Proximity to grazing cattle (i5)	Proximity to grazing cattle increase the risk of STEC contamination (airborne and via water runoff)	User-defined	Expert opinion	Hoar and Atwill (2011); California Leafy Greens Marketing Agreement (2023).
Location of grazing cattle if farm close to grazing cattle (i6)	Grazing cattle located uphill to the farm increase the risk of contamination via water runoff	User-defined	Expert opinion	assumption
Proximity to diversified small-scale farms (DSSF)/hobby farms (i7)	Proximity to diversified small-scale farms (DSSF)/hobby farms increases the risk of STEC contamination (airborne and via water runoff)	User-defined	Expert opinion	Patterson et al. (2022); Di Francesco et al. (2025)
Location of DSSF/hobby farm if farm close to DSSF/hobby farm (i8)	DSSF/hobby farms located uphill to the farm increase the risk of contamination via water runoff	User-defined	Expert opinion	Patterson et al. (2022); Di Francesco et al. (2025)
Proximity to compost facility (i9)	Proximity to compost facility increases the risk of airborne STEC contamination	User-defined	Expert opinion	California Leafy Greens Marketing Agreement (2023).

Occurrence of flood events (i10)	Occurrence of flood events increases the risk of STEC contamination	User-defined	Literature	Bergholz et al. (2016); Sharma et al. (2024)
Wind speed (e_w)	The lower the wind speed, the higher the risk of STEC contamination if farm close to CAFO, grazing cattle, DSSF/hobby farm, or compost facility (assuming worst-case scenario of wind direction towards the farm)	dataset	Copernicus Climate Data (ERA5) and expert opinion	Berry and Wells (2010); Berry et al. (2015); Devarajan et al. (2023); Wei, Aggrawal, Bond and Atwill (2023); Wei, Aggrawal, Bond, Latack, et al. (2023)
Agricultural water source (i11_1)	The order of increasing risk for different types of water supply is public water supply, groundwater from deep wells, groundwater from shallow wells, surface water, and wastewater	User-defined	Literature	Leifert et al. (2008); Pachepsky et al. (2011); Devarajan et al. (2023)
Method of irrigation (i11_2)	Increased risk of STEC contamination when using overhead sprinkler irrigation, followed by furrow irrigation and subsurface irrigation	User-defined	Literature	Fonseca et al. (2011)
Precipitation (e_p)	Heavy precipitation increases the risk of STEC contamination	dataset	Copernicus Climate Data (ERA5)	Ivanek et al. (2009); Strawn et al. (2013).
Initial probability of contamination (i0)	Assumed initial probability of contamination	User-defined	Literature	Cooley et al. (2014); Zhang et al. (2018)

Table 4. Key parameter estimates and key information for risk assessment.

Id	Parameter	Input	Value (in OR)	Assumption
i1_1	Do you remove non-crop vegetation or create bare-ground buffers around crop fields as a food safety practice?	yes	pert(0.96, 0.98, 1.04)	Removal of non-crop vegetation to create bare-ground buffers around crop fields is detrimental to biodiversity and thus counterproductive as a wildlife mitigation practice.
i1_1		no	1	
i1_2	Do you put up fences around crop fields as a food safety practice?	yes	pert(0.92, 0.92, 0.94)	Putting up fences around crop fields is detrimental to biodiversity and thus counterproductive as a wildlife mitigation practice.
i1_2		no	1	
p_b	Abundance of birds	low abundance of birds	uniform(0.0, .2)	Low abundance of birds = low risk of contamination
p_b		medium abundance of birds	uniform(0.2, 0.6)	Medium abundance of birds = medium risk of contamination
p_b		high abundance of birds	uniform(0.6, 1.0)	High abundance of birds = high risk of contamination
p_c	Abundance of cervids	low abundance of cervids	uniform(0.0, .2)	Low abundance of cervids = low risk of contamination
p_c		medium abundance of cervids	uniform(0.2, 0.6)	Medium abundance of cervids = medium risk of contamination
p_c		high abundance of cervids	uniform(0.6, 1.0)	High abundance of cervids = high risk of contamination
p_p	Abundance of feral pigs	low abundance of feral pigs	uniform(0.0, .2)	Low abundance of feral pigs = low risk of contamination
p_p		medium abundance of feral pigs	uniform(0.2, 0.6)	Medium abundance of feral pigs = medium risk of contamination
p_p		high abundance of feral pigs	uniform(0.6, 1.0)	High abundance of feral pigs = high risk of contamination
i2_1	Was there movement of cattle from CAFOs (e.g., transportation, roundups) around your farm (within a mile) in the past week?	yes	pert(1.01, 1.09, 1.17)	Movement of cattle around the farms increases the risk of STEC airborne contamination.
i2_1		no	1	

i2_2	Was there movement of grazing cattle (e.g., transportation, roundups) around your farm (within a mile) in the past week?	yes	pert(0.99, 1.05, 1.13)	Movement of cattle around the farms increases the risk of STEC airborne contamination.
i2_2		no	1	
i3	Is your farm close to a concentrated animal feeding operation (CAFO) (<1,200 feet if 1,000-5,000 head of cattle or <1 mile if >5,000 head of cattle)?	yes	pert(1.02, 1.08, 1.13)	Proximity to a CAFO increases the risk of STEC contamination (airborne and via water runoff).
i3		no	1	
i4_1	If YES to i3: how many head of cattle are there in nearby CAFO?	between 1,000-5,000	1	The more animals, the higher the risk of contamination.
i4_1		>5,000 head of cattle	pert(1.02, 1.08, 1.13)	
i4_2	If YES to i3: is it located uphill or downhill?	uphill (runoff)	pert(0.99, 1.06, 1.11)	CAFOs located uphill to the farm increase the risk of contamination via water runoff.
i4_2		downhill	1	
i5	Is your farm close to grazing cattle (less than 30 ft)?	yes	pert(1, 1.05, 1.12)	Proximity to grazing cattle increases the risk of STEC contamination (airborne and via water runoff).
i5		no	1	
i6	If YES to i5: is it located uphill or downhill?	uphill (runoff)	pert(0.96, 1.06, 1.12)	Grazing cattle located uphill to the farm increases the risk of contamination via water runoff.
i6		downhill	1	
i7	Is your farm close to a DSSF/hobby farm (less than 30 ft)?	yes	pert(0.96, 1.03, 1.1)	Proximity to diversified small-scale farms (DSSF)/hobby farms increases the risk of STEC contamination (airborne and via water runoff).
i7		no	1	
i8	If YES to i7: is it located uphill or downhill?	uphill	pert(0.98, 1.04, 1.11)	DSSF/hobby farms located uphill to the farm increase the risk of contamination via water runoff.
i8		downhill	1	
i9	Is your farm close to a compost facility (< 400 feet)?	yes	pert(0.99, 1.06, 1.14)	Proximity to compost facility increases the risk of airborne STEC contamination.

i9		no	1	
i10	Has your farm experienced flooding in the past 2 months (LGMA metric)?	yes	uniform(0.75,1)	Occurrence of flood events increases the risk of STEC contamination.
i10		no	1	
e_w	Wind speed	milder (<25 mph) to no-wind	1	The lower the wind speed, the higher the risk of STEC contamination if farm close to CAFO, grazing cattle, DSSF/hobby farm, or compost facility (assuming worst-case scenario of wind direction towards the farm).
e_w		stronger wind (>25mph)	pert(1.02, 1.09, 1.16)	
i11_1	What water source supply do you use in your farm?	public water supply	uniform(0.0,0.2)	The order of increasing risk for different types of water supply is public water supply, groundwater from deep wells, groundwater from shallow wells, surface water, and wastewater.
i11_1		groundwater from deep wells	uniform(0.2,0.4)	
i11_1		groundwater from shallow wells	uniform(0.4,0.6)	
i11_1		surface water	uniform(0.6,0.8)	
i11_1		wastewater	uniform(0.8,1.0)	
i11_2	What method of irrigation is used in your farm?	overhead sprinkler	uniform(0.66,1)	Increased risk of STEC contamination when using overhead sprinkler irrigation, followed by furrow irrigation and subsurface irrigation.
i11_2		furrow irrigation	uniform(0.33,0.66)	
i11_2		subsurface drip	uniform(0.0,0.33)	
e_s	Average daily number of hours of sunlight	low sunlight (<9.5h)	uniform(0.5,1)	More daylight = less STEC, so less risk
e_s		high sunlight (>9.5h)	uniform(0.0,0.5)	
e_t	Average daily temperature	low temperature (<10°C)	uniform(0.66,1)	STEC survival decreases as temperature increases.
e_t		medium temperature (10 to 20°C)	uniform(0.33,0.66)	
e_t		high temperature (> 20°C)	uniform(0.0,0.33)	

i13	What soil type does your farm predominantly have?	clay	uniform(0.66,1)	Clay soil increases STEC survival, compared to silty and sandy soil types.
i13		silty	uniform(0.0,0.33)	
i13		sandy	uniform(0.0,0.33)	
i13		mixed (loam)	uniform(0.33,0.66)	
i14	What pH does the soil in your farm have?	alkaline (>7.5)	uniform(0.0,0.33)	STEC growth is limited in alkaline pH.
i14		neutral (6.5-7.5)	uniform(0.66,1)	Ideal pH for STEC: 6.5–7.5.
i14		acid (4.5-6.5)	uniform(0.33,0.66)	STEC can grow in acidic conditions.
e_p	Average daily precipitation	low precipitation (<5mm per hour or accumulates to more than 25mm in a 24-hour period)	uniform(0.0,0.5)	Heavy precipitation increases the risk of STEC contamination.
e_p		high precipitation (>5mm per hour or accumulates to more than 25mm in a 24-hour period)	uniform(0.5,1)	
i0	What initial probability of contamination do you want to consider (low, medium, high)?	low	uniform(0.00001,0.001)	Assumed initial probability of contamination
i0		med	uniform(0.001, 0.01)	
i0		high	uniform(0.01,0.05)	

Table 5. Output parameters included in the risk assessment model and their calculation from input parameters.

Output variables	**Formulae**
Risk of contamination of wildlife[†] (o1) in OR	Mean of (wl_b*prevalence), (wl_c* prevalence), (wl_p* prevalence), non-crop vegetation, fences
Risk of contamination via CAFOs (o_cafo) in OR	Proximity to CAFO*mean of size CAFO, location CAFO
Risk of contamination via grazing cattle (o_gc) in OR	Proximity to grazing cattle*location of grazing cattle
Risk of contamination via other sources (o_o) in OR	Mean of movement cattle, proximity DSSF[††], location DSSF, proximity compost facility
Risk of airborne contamination (o2) in OR	Mean of (o_cafo, o_gc, o_o)*wind speed
Risk of contamination via water (o3) in OR	Mean of water source, method of irrigation, location CAFO, location grazing cattle, location DSSF
Risk of *E. coli* survival in soil (o4) in OR	Mean of o1, o2, o3, hours sunlight, temperature, soil type, soil pH, precipitation, flood events
Final probability	Initial probability*o4

[†] wl_b: abundance of birds; wl_c: abundance of cervids; wl_p: abundance of feral pigs; [††]DSSF: Diversified Small-Scale Farm

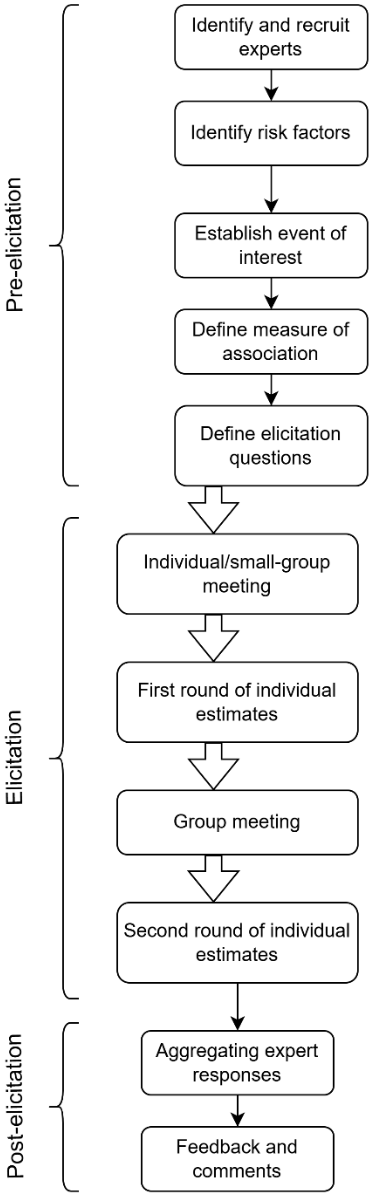


Figure 1. Flowchart describing the three steps of the expert opinion elicitation process. Adapted from Estévez et al. (2019).

Figure 2. Aggregated results from rounds 1 (in red) and 2 (in green) of data collection from expert opinion. Green area of the plot indicates beneficial interventions/factors and red area indicates detrimental interventions/factors. Dots represent median responses of all 18 participating experts. Data from round 2 only were used to populate the risk assessment model.

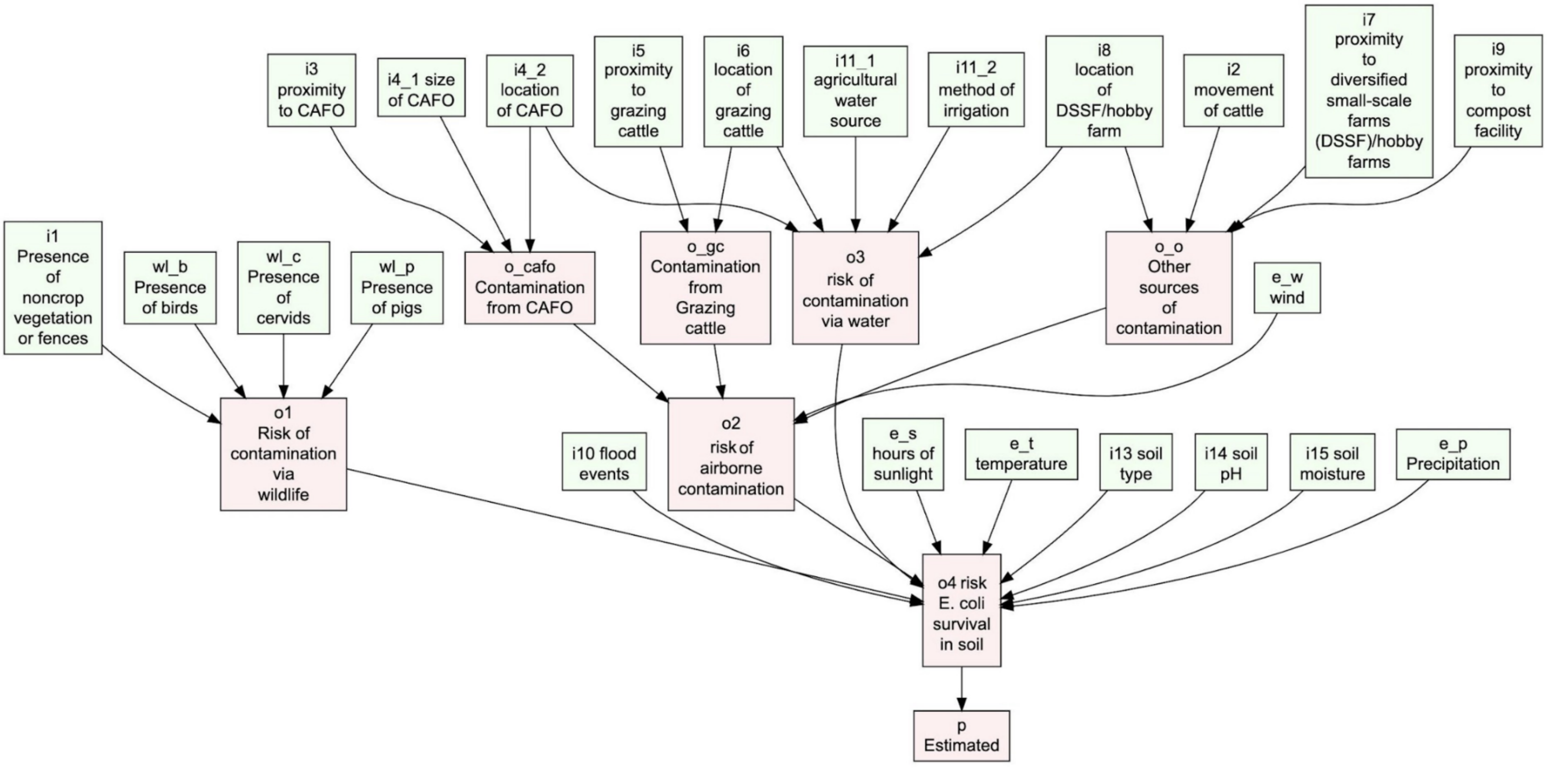


Figure 3. Conceptual risk pathway used to inform the risk assessment model (inputs in green; outputs in red).

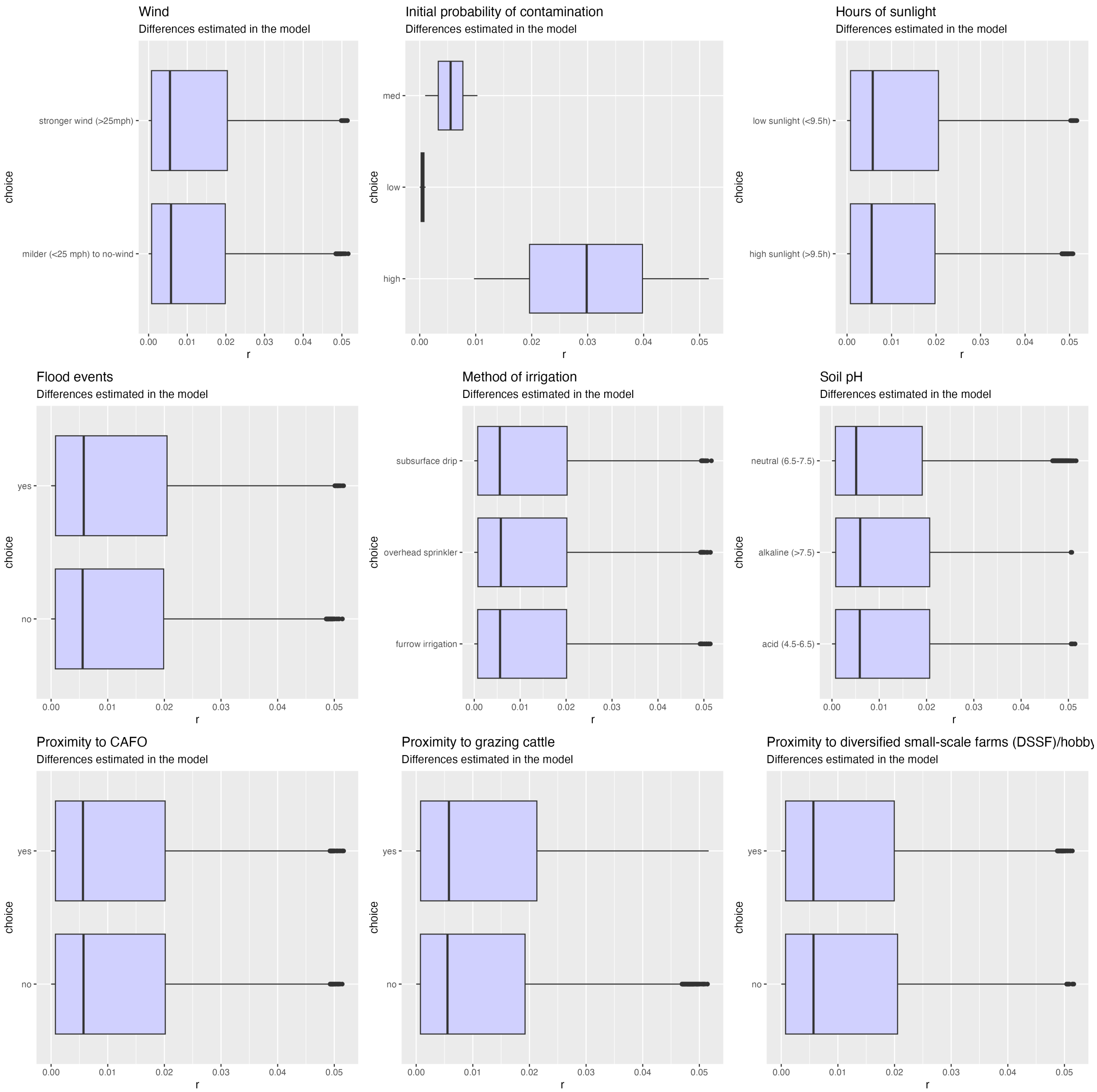
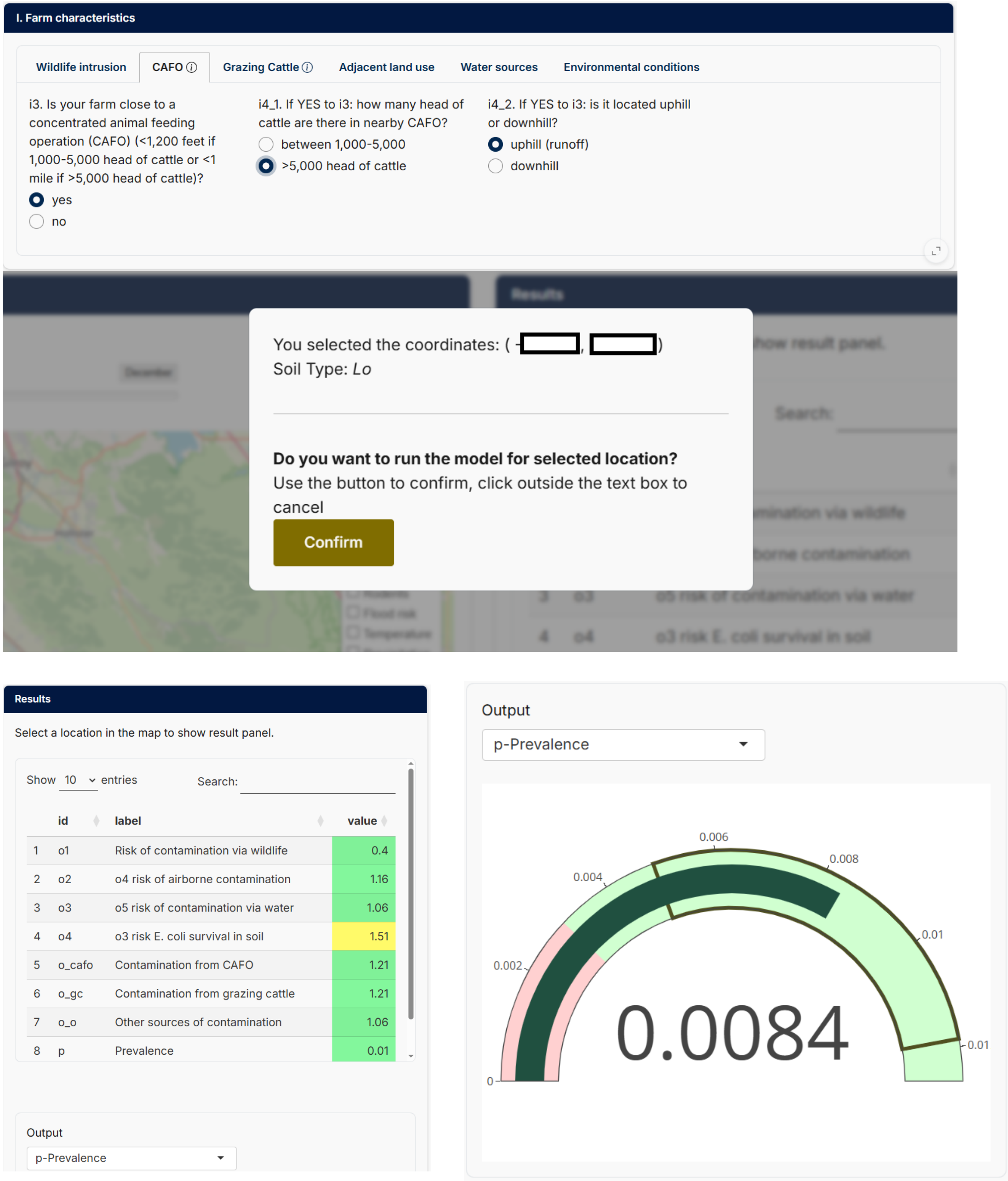


Figure 4. Sensitivity analysis plots showing the probability of a contamination event (x axis) depending on the user choices (y axis) for the user-input parameters.



i3. Is your farm close to a concentrated animal feeding operation (CAFO) (<1,200 feet if 1,000-5,000 head of cattle or <1 mile if >5,000 head of cattle)?

● yes
○ no

i4_1. If YES to i3: how many head of cattle are there in nearby CAFO?

○ between 1,000-5,000
● >5,000 head of cattle

i4_2. If YES to i3: is it located uphill or downhill?

● uphill (runoff)
○ downhill

You selected the coordinates: ([redacted], [redacted])
Soil Type: *Lo*

Do you want to run the model for selected location?
Use the button to confirm, click outside the text box to cancel

Select a location in the map to show result panel.

Show 10 entries Search:

	id	label	value
1	o1	Risk of contamination via wildlife	0.4
2	o2	o4 risk of airborne contamination	1.16
3	o3	o5 risk of contamination via water	1.06
4	o4	o3 risk E. coli survival in soil	1.51
5	o_cafo	Contamination from CAFO	1.21
6	o_gc	Contamination from grazing cattle	1.21
7	o_o	Other sources of contamination	1.06
8	p	Prevalence	0.01

Output: p-Prevalence

Figure 5. Screenshot of the web-based, user-friendly platform for assessing the risk of contamination of leafy greens with pathogenic *E. coli*.

References

Alegbeleye, O. O., Singleton, I., & Sant'Ana, A. S. (2018). Sources and contamination routes of microbial pathogens to fresh produce during field cultivation: A review. *Food Microbiology*, *73*, 177-208. https://doi.org/10.1016/j.fm.2018.01.003

Atwill, E. R., Chase, J. A., Oryang, D., Bond, R. F., Koike, S. T., Cahn, M. D., Anderson, M., Mokhtari, A., & Dennis, S. (2015). Transfer of O157:H7 from simulated wildlife scat onto romaine lettuce during foliar irrigation. *Journal of Food Protection*, *78*(2), 240-247. https://doi.org/10.4315/0362-028x.Jfp-14-277

Balamurugan, S., Ahmed, R., & Gao, A. (2015). Survival of Shiga toxin-producing Escherichia coli in broth as influenced by pH, water activity and temperature. *Letters in Applied Microbiology*, *60*(4), 341-346. https://doi.org/10.1111/lam.12375

Bell, R. L., Zheng, J., Burrows, E., Allard, S., Wang, C. Y., Keys, C. E., Melka, D. C., Strain, E., Luo, Y., Allard, M. W., Rideout, S., & Brown, E. W. (2015). Ecological prevalence, genetic diversity, and epidemiological aspects of isolated from tomato agricultural regions of the Virginia Eastern Shore. *Frontiers in Microbiology*, *6*. https://doi.org/10.3389/fmicp.2015.00415

Benjamin, L. A., Jay-Russell, M. T., Atwill, E. R., Cooley, M. B., Carychao, D., Larsen, R. E., & Mandrell, R. E. (2015). Risk factors for Escherichia coli O157 on beef cattle ranches located near a major produce production region. *Epidemiology and Infection*, *143*(1), 81-93. https://doi.org/10.1017/S0950268814000521

Bergholz, P. W., Strawn, L. K., Ryan, G. T., Warchocki, S., & Wiedmann, M. (2016). Spatiotemporal analysis of microbiological contamination in New York State produce fields following extensive flooding from hurricane Irene, August 2011. *Journal of Food Protection*, *79*(3), 384-391. https://doi.org/10.4315/0362-028x.Jfp-15-334

Berry, E. D., & Wells, J. E. (2010). *Escherichia coli O157:H7 in bioaerosols from cattle production areas: evaluation of proximity and airborne transport on leafy green crop contamination*.

Berry, E. D., Wells, J. E., Bono, J. L., Woodbury, B. L., Kalchayanand, N., Norman, K. N., Suslow, T. V., Lopez-Velasco, G., & Millner, P. D. (2015). Effect of proximity to a cattle feedlot on Escherichia coli O157:H7 contamination of leafy greens and evaluation of the potential for airborne transmission. *Applied and Environmental Microbiology*, *81*(3), 1101-1110. https://doi.org/10.1128/AEM.02998-14

Borczyk, A. A., Karmali, M. A., Lior, H., & Duncan, L. M. (1987). Bovine reservoir for verotoxin-producing Escherichia coli O157:H7. *Lancet*, *1*(8524), 98. https://doi.org/10.1016/s0140-6736(87)91928-3

Bottichio, L., Keaton, A., Thomas, D., Fulton, T., Tiffany, A., Frick, A., Mattioli, M., Kahler, A., Murphy, J., Otto, M., Tesfai, A., Fields, A., Kline, K., Fiddner, J., Higa, J., Barnes, A., Arroyo, F., Salvatierra, A., Holland, A., . . . Gieraltowski, L. (2020). Shiga Toxin-producing Escherichia coli infections associated with Romaine lettuce - United States, 2018. *Clinical Infectious Diseases*, *71*(8), e323-e330. https://doi.org/10.1093/cid/ciz1182

Bright, K. R., Betancourt, W. Q., Gerba, C. P., Kumar, G. D., & Dunn, L. (2020). *When the E. coli hits the fan! Evaluating the risks of dust-associated produce cross-contamination*.

California Leafy Greens Marketing Agreement. (2023). *Commodity specific food safety guidelines*. https://sciwheel.com/work/item/16311468/resources/19014968/pdf

California Leafy Greens Marketing Agreement. (2024). *Commodity specific food safety guidelines*. https://assets.lgma.ca.gov/downloads/CA-LGMA-Metrics_2024.08.21-FINAL.pdf

California Leafy Greens Marketing Agreement. (2025). *About us*. https://lgma.ca.gov/about-us

Chandler, D., & Craven, J. (1980). Relationship of soil moisture to survival of Escherichia coli and Salmonella Typhimurium in soils. *Crop and Pasture Science*, *31*, 547-555.

Cooley, M. B., Quiñones, B., Oryang, D., Mandrell, R. E., & Gorski, L. (2014). Prevalence of shiga toxin producing Escherichia coli, Salmonella enterica and Listeria monocytogenes at public access watershed sites in a California Central Coast agricultural region. *Frontiers in Cellular and Infection Microbiology*, *4*. https://doi.org/10.3389/fcimb.2014.00030

Devarajan, N., Weller, D. L., Jones, M., Adell, A. D., Adhikari, A., Allende, A., Arnold, N. L., Baur, P., Beno, S. M., Clements, D., Olimpi, E. M., Critzer, F., Green, H., Gorski, L., Gruber, A. F., Kovac, J., McGarvey, J., Murphy, C. M., Murphy, S. I., . . . Karp, D. S. (2023). Evidence for the efficacy of pre-harvest agricultural practices in mitigating food-safety risks to fresh produce in North America. *Frontiers in Sustainable Food Systems*, *7*. https://doi.org/10.3389/fsufs.2023.1101435

Di Francesco, J., Isenhower, E., Fausak, E. D., Silva-Del-Rio, N., & Pires, A. F. A. (2025). A scoping review of studies reporting biosecurity practices in small and backyard farms raising livestock or poultry in developed countries, 2000-2022. *Preventive Veterinary Medicine*, *236*. https://doi.org/10.1016/j.prevetmed.2025.106423

Dogan, O. B., Flach, M. G., Miller, M. F., & Brashears, M. M. (2023). Understanding potential cattle contribution to leafy green outbreaks: A scoping review of the literature and public health reports. *Comprehensive Reviews in Food Science and Food Safety*, *22*(5), 3506-3530. https://doi.org/10.1111/1541-4337.13200

Estévez, R. A., Mardones, F. O., Alamos, F., Arriagada, G., Carey, J., Corre, C., Escobar-Dodero, J., Gaete, A., Gallardo, A., Ibarra, R., Ortiz, C., Rozas-Serri, M., Sandoval, O., Santana, J., & Gelcich, S. (2019). Eliciting expert judgements to estimate risk and protective factors for Piscirickettsiosis in Chilean salmon farming. *Aquaculture*, *507*, 402-410. https://doi.org/10.1016/j.aquaculture.2019.04.028

European Food Safety Authority. (2014). Guidance on expert knowledge elicitation in food and feed safety risk assessment. *EFSA Journal*, *12*(6). https://doi.org/10.2903/j.efsa.2014.3734

Fischer, J. R., Zhao, T., Doyle, M. P., Goldberg, M. R., Brown, C. A., Sewell, C. T., Kavanaugh, D. M., & Bauman, C. D. (2001). Experimental and field studies of O157:H7 in white-tailed deer. *Applied and Environmental Microbiology*, *67*(3), 1218-1224. https://doi.org/Doi 10.1128/Aem.67.3.1218-1224.2001

Fonseca, J. M., Fallon, S. D., Sanchez, C. A., & Nolte, K. D. (2011). Survival in lettuce fields following its introduction through different irrigation systems. *Journal of Applied Microbiology*, *110*(4), 893-902. https://doi.org/10.1111/j.1365-2672.2011.04942.x

Franz, E., Schijven, J., Husman, A. M. D., & Blaak, H. (2014). Meta-regression analysis of commensal and pathogenic Escherichia coli survival in soil and water. *Environmental Science & Technology*, *48*(12), 6763-6771. https://doi.org/10.1021/es501677c

Gomez-Vazquez, J. P. (2024). *quantrra: reproducible risk assessment with R.* In (Version 0.1) Zenodo.

Gordus, A. G., Mandrell, R., & Atwill, E. R. (2011). *Wildlife survey for E. coli O157:H7 and Salmonella in the Central Coastal counties of California*.

Gyles, C. L. (2007). Shiga toxin-producing Escherichia coli: an overview. *Journal of Animal Science*, *85*(13 Suppl), E45-62. https://doi.org/10.2527/jas.2006-508

Hanea, A. M., McBride, M. F., Burgman, M. A., Wintle, B. C., Fidler, F., Flander, L., Twardy, C. R., Manning, B., & Mascaro, S. (2017). InvestigateDiscussEstimateAggregate for structured expert judgement. *International Journal of Forecasting*, *33*(1), 267-279. https://doi.org/10.1016/j.ijforecast.2016.02.008

Hoar, B., & Atwill, E. R. (2011). *Developing buffer zone distances between sheep grazing operations and vegetable crops to maximize food safety*.

Ivanek, R., Gröhn, Y. T., Wells, M. T., Lembo, A., Sauders, B. D., & Wiedmann, M. (2009). Modeling of spatially referenced environmental and meteorological factors influencing the probability of Listeria species isolation from natural environments. *Applied and Environmental Microbiology*, *75*(18), 5893-5909. https://doi.org/10.1128/Aem.02757-08

Jay-Russell, M. T., Hake, A. F., Rivadeneira, P., Virchow, D. R., & Bergman, D. L. (2014). *Enteric human pathogens of wild boar, feral swine, and Javelina (Order: Artiodactyla)* Proceedings of the 26th Vertebrate Pest Conference,

Jay, M. T., Cooley, M., Carychao, D., Wiscomb, G. W., Sweitzer, R. A., Crawford-Miksza, L., Farrar, J. A., Lau, D. K., O'Connell, J., Millington, A., Asmundson, R. V., Atwill, E. R., & Mandrell, R. E. (2007). Escherichia coli O157:H7 in feral swine near spinach fields and cattle, central California coast. *Emerging Infectious Diseases*, *13*(12), 1908-1911. https://doi.org/10.3201/eid1312.070763

Jeamsripong, S., Chase, J. A., Jay-Russell, M. T., Buchanan, R. L., & Atwill, E. R. (2019). Experimental in-field transfer and survival of Escherichia coli from animal feces to Romaine lettuce in Salinas Valley, California. *Microorganisms*, *7*(10). https://doi.org/10.3390/microorganisms7100408

Jones, M. S., Fu, Z., Reganold, J. P., Karp, D. S., Besser, T. E., Tylianakis, J. M., & Snyder, W. E. (2019). Organic farming promotes biotic resistance to foodborne human pathogens. *Journal of Applied Ecology*, *56*(5), 1117-1127. https://doi.org/10.1111/1365-2664.13365

Karp, D. S. (2024). *Towards a holistic assessment of the food-safety risks imposed by wild birds*.

Karp, D. S., Baur, P., Atwill, E. R., De Master, K., Gennet, S., Iles, A., Nelson, J. L., Sciligo, A. R., & Kremen, C. (2015). The unintended ecological and social impacts of food safety regulations in California's Central Coast region. *Bioscience*, *65*(12), 1173-1183. https://doi.org/10.1093/biosci/biv152

Karp, D. S., Gennet, S., Kilonzo, C., Partyka, M., Chaumont, N., Atwill, E. R., & Kremen, C. (2015). Comanaging fresh produce for nature conservation and food safety. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(35), 11126-11131. https://doi.org/10.1073/pnas.1508435112

Karp, D. S., Moses, R., Gennet, S., Jones, M. S., Joseph, S., M'Gonigle, L. K., Ponisio, L. C., Snyder, W. E., & Kremen, C. (2016). Agricultural practices for food safety threaten pest control services for fresh produce. *Journal of Applied Ecology*, *53*(5), 1402-1412. https://doi.org/10.1111/1365-2664.12707

Kilonzo, C., Li, X. D., Vivas, E. J., Jay-Russell, M. T., Fernandez, K. L., & Atwill, E. R. (2013). Fecal shedding of zoonotic food-borne pathogens by wild rodents in a major agricultural region of the Central California Coast. *Applied and Environmental Microbiology*, *79*(20), 6337-6344. https://doi.org/10.1128/Aem.01503-13

Kullas, H., Coles, M., Rhyan, J., & Clark, L. (2002). Prevalence of Escherichia coli serogroups and human virulence factors in faeces of urban Canada geese (Branta canadensis). *International Journal of Environmental Health Research*, *12*(2), 153-162. https://doi.org/10.1080/09603120220129319

Lacombe, A., Quintela, I., Liao, Y.-T., & Wu, V. (2022). Shiga toxin-producing Escherichia coli outbreaks in California’s leafy greens production continuum. *Frontiers in Food Science and Technology*, *2*. https://doi.org/10.3389/frfst.2022.1068690

Leifert, C., Ball, K., Volakakis, N., & Cooper, J. M. (2008). Control of enteric pathogens in ready-to-eat vegetable crops in organic and 'low input' production systems: a HACCP-based approach. *Journal of Applied Microbiology*, *105*(4), 931-950. https://doi.org/10.1111/j.1365-2672.2008.03794.x

Marshall, K. E., Hexemer, A., Seelman, S. L., Fatica, M. K., Blessington, T., Hajmeer, M., Kisselburgh, H., Atkinson, R., Hill, K., Sharma, D., Needham, M., Peralta, V., Higa, J., Blickenstaff, K., Williams, I. T., Jhung, M. A., Wise, M., & Gieraltowski, L. (2020). Lessons learned from a decade of investigations of Shiga toxin-producing Escherichia coli outbreaks linked to leafy greens, United States and Canada. *Emerging Infectious Diseases*, *26*(10), 2319-2328. https://doi.org/10.3201/eid2610.191418

Mishra, A., Guo, M., Buchanan, R. L., Schaffner, D. W., & Pradhan, A. K. (2017). Prediction of Escherichia coli O157:H7, Salmonella, and Listeria monocytogenes growth in leafy greens without temperature control. *Journal of Food Protection*, *80*(1), 68-73. https://doi.org/10.4315/0362-028x.Jfp-16-153

Montenegro, M. A., Bulte, M., Trumpf, T., Aleksic, S., Reuter, G., Bulling, E., & Helmuth, R. (1990). Detection and characterization of fecal verotoxin-producing Escherichia coli from healthy cattle. *Journal of Clinical Microbiology*, *28*(6), 1417-1421. https://doi.org/10.1128/Jcm.28.6.1417-1421.1990

Murphy, C. M., Weller, D. L., & Strawn, L. K. (2023). Salmonella prevalence is strongly associated with spatial factors while Listeria monocytogenes prevalence is strongly associated with temporal factors on Virginia produce farms. *Applied and Environmental Microbiology*, *89*(2). https://doi.org/10.1128/aem.01529-22

Navarro-Gonzalez, N., Wright, S., Aminabadi, P., Gwinn, A., Suslow, T., & Jay-Russell, M. T. (2020). Carriage and subtypes of foodborne pathogens identified in wild birds residing near agricultural lands in California: a repeated cross-sectional study. *Applied and Environmental Microbiology*, *86*(3). https://doi.org/10.1128/AEM.01678-19

Olimpi, E. M., Ke, A. L. S., Baur, P., Carlisle, L., Esquivel, K. E., Glaser, T., Snyder, W. E., Waterhouse, H., Bowles, T. M., Kremen, C., & Karp, D. S. (2024). Ungrazed seminatural habitats around farms benefit bird conservation without enhancing foodborne pathogen risks. *Landscape Ecology*, *39*(7). https://doi.org/10.1007/s10980-024-01907-y

Pachepsky, Y., Shelton, D. R., McLain, J. E. T., Patel, J., & Mandrell, R. E. (2011). Irrigation waters as a source of pathogenic microorganisms in produce: a review. In Elsevier (Ed.), *Advances in Agronomy* (Vol. 113, pp. 75-141). https://doi.org/10.1016/B978-0-12-386473-4.00002-6

Patterson, L., Navarro-Gonzalez, N., Jay-Russell, M. T., Aminabadi, P., & Pires, A. F. A. (2022). Risk factors of Shiga toxin-producing Escherichia coli in livestock raised on diversified small-scale farms in California. *Epidemiology & Infection*, *150*. https://doi.org/10.1017/S0950268822001005

Pennington, H. (2010). Escherichia coli O157. *Lancet*, *376*(9750), 1428-1435. https://doi.org/Doi 10.1016/S0140-6736(10)60963-4

Persad, A. K., & Lejeune, J. T. (2014). Animal reservoirs of Shiga Toxin-producing Escherichia coli. *Microbiology Spectrum*, *2*(4). https://doi.org/10.1128/microbiolspec.EHEC-0027-2014

Pradhan, A. K., Pang, H., & Mishra, A. (2019). Foodborne disease outbreaks associated with organic foods: animal and plant products. *Safety and Practice for Organic Food*, 135-150. https://doi.org/10.1016/B978-0-12-812060-6.00006-4

Rochelle-Newall, E. J., Ribolzi, O., Viguier, M., Thammahacksa, C., Silvera, N., Latsachack, K., Dinh, R. P., Naporn, P., Sy, H. T., Soulileuth, B., Hmaimum, N., Sisouvanh, P., Robain, H., Janeau, J. L., Valentin, C., Boithias, L., & Pierret, A. (2016). Effect of land use and hydrological processes on Escherichia coli concentrations in streams of tropical, humid headwater catchments. *Scientific Reports*, *6*. https://doi.org/10.1038/srep32974

Sargeant, J. M., Hafer, D. J., Gillespie, J. R., Oberst, R. D., & Flood, S. J. A. (1999). Prevalence of Escherichia coli O157:H7 in white-tailed deer sharing rangeland with cattle. *Journal of the American Veterinary Medical Association*, *215*(6), 792-794. <Go to ISI>://WOS:000082471400011

Sellers, L. A., Long, R. F., Jay-Russell, M. T., Li, X., Atwill, E. R., Engeman, R. M., & Baldwin, R. A. (2018). Impact of field-edge habitat on mammalian wildlife abundance, distribution, and vectored foodborne pathogens in adjacent crops. *Crop Protection*, *108*. https://doi.org/0.1016/j.cropro.2018.02.005

Shariat, N., Snyder, W., & Dunn, L. (2020). *Understanding and predicting food safety risks posed by wild birds*

Sharma, D., Kraft, A. L., Owade, J. O., Milicevic, M., Yi, J. Y., & Bergholz, T. M. (2024). Impact of biotic and abiotic factors on Listeria monocytogenes, Salmonella enterica, and enterohemorrhagic Escherichia coli in agricultural soil extracts. *Microorganisms*, *12*(7). https://doi.org/10.3390/microorganisms12071498

Sharma, M., Millner, P. D., Hashem, F., Vinyard, B. T., East, C. L., Handy, E. T., White, K., Stonebraker, R., & Cotton, C. P. (2019). Survival of in manure-amended soils is affected by spatiotemporal, agricultural, and weather factors in the Mid-Atlantic United States. *Applied and Environmental Microbiology*, *85*(5). https://doi.org/10.1128/AEM.02392-18

Singh, P., Sha, Q., Lacher, D. W., Del Valle, J., Mosci, R. E., Moore, J. A., Scribner, K. T., & Manning, S. D. (2015). Characterization of enteropathogenic and Shiga toxin-producing Escherichia coli in cattle and deer in a shared agroecosystem. *Front Cell Infect Microbiol*, *5*, 29. https://doi.org/10.3389/fcimb.2015.00029

Smith, J. C., Varriano, S., Roach, K., Snipes, Z., Dawson, J. L., Shealy, J., Dunn, L. L., Snyder, W. E., & Shariat, N. W. (2023). Prevalence and molecular characterization of Salmonella isolated from wild birds in fresh produce environments. *Frontiers in Microbiology*, *14*. https://doi.org/10.3389/fmicb.2023.1272916

Strawn, L. K., Fortes, E. D., Bihn, E. A., Nightingale, K. K., Gröhn, Y. T., Worobo, R. W., Wiedmann, M., & Bergholz, P. W. (2013). Landscape and meteorological factors affecting prevalence of three food-borne pathogens in fruit and vegetable farms. *Applied and Environmental Microbiology*, *79*(2), 588-600. https://doi.org/10.1128/Aem.02491-12

Szymczak, B., Szymczak, M., Sawicki, W., & Dabrowski, W. (2014). Anthropogenic impact on the presence of L. monocytogenes in soil, fruits, and vegetables. *Folia Microbiologica*, *59*(1), 23-29. https://doi.org/10.1007/s12223-013-0260-8

Tate, R. L. (1978). Cultural and environmental factors affecting the longevity of Escherichia coli in histosols. *Applied and Environmental Microbiology*, *35*, 925-929.

Topalcengiz, Z., Jeamsripong, S., Spanninger, P. M., Persad, A. K., Wang, F., Buchanan, R. L., LeJeune, J., Kniel, K. E., Jay-Russell, M. T., & Danyluk, M. D. (2020). Survival of Shiga Toxin-Producing Escherichia coli in various wild animal feces that may contaminate produce. *Journal of Food Protection*, *83*(8), 1420-1429. https://doi.org/10.4315/Jfp-20-046

Tran, D. T. Q., Bradbury, M. I., Van Ogtrop, F. F., Bozkurt, H., Jones, B. J., & McConchie, R. (2020). Environmental drivers for persistence of Escherichia coli and Salmonella in manure-amended soils: a meta-analysis. *Journal of Food Protection*, *83*(7), 1268-1277. https://doi.org/10.4315/0362-028x.Jfp-19-460

Underthun, K., De, J., Gutierrez, A., Silverberg, R., & Schneider, K. R. (2018). Survival of Salmonella and Escherichia coli in two different soil types at various moisture levels and temperatures. *Journal of Food Protection*, *81*(1), 150-157. https://doi.org/10.4315/0362-028x.Jfp-17-226

Walter, E. J. S., Cui, Z., Tierney, R., Griffin, P. M., Hoekstra, R. M., Payne, D. C., Rose, E. B., Devine, C., Namwase, A. S., Mirza, S. A., Kambhampati, A. K., Straily, A., & Bruce, B. B. (2025). Foodborne Illness Acquired in the United States-Major Pathogens, 2019. *Emerg Infect Dis*, *31*(4), 669-677. https://doi.org/10.3201/eid3104.240913

Wei, X. H., Aggrawal, A., Bond, R. F., & Atwill, E. R. (2023). Low to zero concentrations of airborne bacterial pathogens and indicator E. coli in proximity to beef cattle feedlots in Imperial Valley, California. *Microorganisms*, *11*(2). https://doi.org/10.3390/microorganisms11020411

Wei, X. H., Aggrawal, A., Bond, R. F., Latack, B. C., & Atwill, E. R. (2023). Dispersal and risk factors for airborne Escherichia coli in the proximity to beef cattle feedlots. *Journal of Food Protection*, *86*(6). https://doi.org/10.1016/j.jfp.2023.100099

Weller, D., Brassill, N., Rock, C., Ivanek, R., Mudrak, E., Roof, S., Ganda, E., & Wiedmann, M. (2020). Complex interactions between weather, and microbial and physicochemical water quality impact the likelihood of detecting foodborne pathogens in agricultural water. *Frontiers in Microbiology*, *11*. https://doi.org/10.3389/fmicb.2020.00134

Weller, D. L., Kovac, J., Roof, S., Kent, D. J., Tokman, J. I., Kowalcyk, B., Oryang, D., Ivanek, R., Aceituno, A., Sroka, C., & Wiedmann, M. (2017). Survival of Escherichia coli on lettuce under field conditions encountered in the Northeastern United States. *Journal of Food Protection*, *80*(7), 1214-1221. https://doi.org/10.4315/0362-028X.JFP-16-419

Weller, D. L., Love, T. M. T., Weller, D. E., Murphy, C. M., Rahm, B. G., & Wiedmann, M. (2022). Structural equation models suggest that on-farm noncrop vegetation removal is not associated with improved food safety outcomes but is linked to impaired water quality. *Applied and Environmental Microbiology*, *88*(23), e0160022. https://doi.org/10.1128/aem.01600-22

Wild Farm Alliance. (2016). *Co-managing farm stewardship with food safety GAPs and conservation practices: A grower's and conservationist's handbook*.

Yanamala, S., Miller, M. F., Loneragan, G. H., Gragg, S. E., & Brashears, M. M. (2011). Potential for microbial contamination of spinach through feedyard air/dust growing in close proximity to cattle feedyard operations. *Journal of Food Safety*, *31*(4), 525-529. https://doi.org/10.1111/j.1745-4565.2011.00330.x

Yaun, B. R., Sumner, S. S., Eifert, J. D., & Marcy, J. E. (2003). Response of Salmonella and Escherichia coli O157:H7 to UV energy. *Journal of Food Protection*, *66*(6), 1071-1073. https://doi.org/10.4315/0362-028x-66.6.1071

Yaun, B. R., Sumner, S. S., Eifert, J. D., & Marcy, J. E. (2004). Inhibition of pathogens on fresh produce by ultraviolet energy. *International Journal of Food Microbiology*, *90*(1), 1-8. https://doi.org/10.1016/S0168-1605(03)00158-2

Zhang, G. D., Chen, Y., Hu, L. J., Melka, D., Wang, H., Laasri, A., Brown, E. W., Strain, E., Allard, M., Bunning, V. K., Parish, M., Musser, S. M., & Hammack, T. S. (2018). Survey of foodborne pathogens, aerobic plate counts, total coliform counts, and counts in leafy greens, sprouts, and melons marketed in the United States. *Journal of Food Protection*, *81*(3), 400-411. https://doi.org/10.4315/0362-028x.Jfp-17-253