Comprehensive Assessment of Flood Risk and Community Impact of Concentrated Animal Feeding Operations in Iowa

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Abstract

Flooding presents a significant risk to Concentrated Animal Feeding Operations (CAFOs), especially in regions increasingly affected by extreme weather events. This study uses advanced geospatial analysis techniques to assess the environmental and economic vulnerabilities of 12,703 CAFOs across Iowa, United States. We focused on the exposure of CAFOS to 100-year and 500-year floodplains, integrating floodplain maps with location data operational characteristics, and livestock types (cattle, swine, poultry) to assess flood risk. The analysis also considered the size and construction year of each CAFO, offering insights into how older and larger operations are disproportionately vulnerable. The results indicate that over 1.9 million animal units (13.35% of total), are located within the 100-year floodplain. In the 500-year flood floodplain, it increases to 2.05 million animal units, representing 14.37% of the state's total. Sioux, Lyon, and Hancock counties were identified as particularly high-risk, with over 16% of animal units in Sioux County exposed to 100-year flood risks, rising to 17.4% under the 500-year floodplain. The study reveals that larger CAFOs, particularly those constructed before 2004, are at greater risk due to their location in flood-prone areas and the challenges posed by their operational scale. These risks not only threaten livestock but also have far-reaching economic consequences, including significant operational disruptions, infrastructure damage, and cascading effects on supply chains and market stability. As extreme weather events become more frequent due to climate change, these findings highlight the need for heightened awareness of CAFO vulnerabilities and call for further research into adaptive strategies to protect Iowa's agricultural sector.

Keywords: CAFO, Flood Risk Assessment, Floodplain Vulnerability, Geospatial Analysis, Iowa, Livestock Vulnerability

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Highlights

- The study reveals that over 1.9 million animal units are located within the 100-year floodplain, increasing to 2.05 million under the 500-year floodplain, indicating substantial flood risks to Iowa's livestock industry.
- Counties such as Sioux, Lyon, and Hancock are identified as particularly vulnerable, with large concentrations of animal units exposed to both 100-year and 500-year floodplains.
- CAFOs constructed before 2004 are disproportionately at risk, especially larger operations, due to their location in flood-prone areas.
- Flooding poses not only environmental risks but also significant economic disruptions, including damage to infrastructure, interruptions in livestock production, and cascading effects on supply chains and market stability.
- The findings underscore the importance of developing flood mitigation strategies to safeguard Iowa's agricultural operations from the increasing frequency and severity of flood events driven by climate change.

1. Introduction

The increasing frequency and severity of flood events due to climate change have profound impacts on agriculture and infrastructure globally (Kundzewicz et al., 2014; Rojas-Downing et al., 2017; IPCC, 2022). Floods are driven by several factors, including rainfall quantity and distribution, topography, land cover, and soil moisture, and are considered among the most dangerous natural disasters (Paprotny et al., 2018; Sadler et al., 2018). These climate-induced hazards can cause extensive damage to crops, infrastructure (Grant et al., 2024), and livestock, disrupting food supply chains and leading to significant economic losses (FAO, 2018; U.S. GCRP, 2018; Gaviglio et al., 2021). The economic and social impacts of floods are particularly significant in regions where agriculture plays a significant role in the economy (Islam et al., 2024). In areas with intensive livestock farming, such as Iowa, the risks are especially pronounced due to the high density of CAFOs located in flood-prone areas (Throgmorton, 2012; Carrel et al., 2016; Gaviglio et al., 2022).

For example, the 2008 flood in the Midwest United States, particularly in Iowa, illustrates the devastating potential of these events. This flood was even more destructive than the "Great Flood of 1993" (Mutel, 2010; Throgmorton, 2012; Connerly et al., 2017), causing widespread damage to infrastructure and agricultural systems, including substantial livestock and crop losses. Such impacts underscore the vulnerability of these systems to extreme weather events (Eash & Koppensteiner, 2008; Gilles, 2010). Given the potential for severe and long-lasting consequences, effective flood management and mitigation strategies are essential to safeguard agricultural productivity and sustainability (Cikmaz et al., 2023). These strategies involve a combination of preventative and corrective measures, such as planning and preparation, to reduce flood damage (FAO, 2018; Crist et al., 2020; Alabbad et al., 2023; Gaviglio et al., 2022).

Livestock farming, a critical part of many agricultural economies, is particularly susceptible to flooding. CAFOs, which confine large numbers of animals in relatively small areas, face heightened risks due to their operational scale and waste management practices. The distinction between Animal Feeding Operations (AFOs) and CAFOs is significant when assessing the environmental and public health risks posed by these operations. An AFO is defined as an agricultural facility where animals are confined for at least 45 days within a 12-month period, during which time the confinement area lacks vegetation typical of the normal growing season (U.S. EPA, 2024). This definition covers various confined environments, such as feedlots and cow yards, but typically excludes pastures.

A CAFO is a specialized category of AFO, distinguished by its larger scale and more stringent regulatory criteria, particularly in terms of animal numbers and waste disposal practices. For example, a large CAFO houses more than 1,000 beef cattle, 700 mature dairy cows, or 2,500 swine. Medium CAFOs have smaller capacities—300 to 999 beef cattle, 200 to 699 mature dairy cows, or 750 to 2,499 swine—along with specific pollutant discharge conditions. A small CAFO, meanwhile, houses fewer animals than those specified for Medium CAFO but is classified as a CAFO by the permitting authority if it is determined to be a significant contributor to pollution (EPA, 2023). This classification highlights that environmental and public health impacts are determined not just by scale but by how well waste is managed in proximity to natural water sources.

Flooding exacerbates the risks posed by CAFOs. Floods can damage the physical infrastructure of CAFOs and severely affect livestock health, leading to operational disruptions and economic losses (Wing et al., 2002; Hribar, 2010; Gaviglio et al., 2022; Fierros, 2023). Beyond these immediate impacts, floods can result in the contamination of local water supplies through the overflow of manure storage facilities, which pose serious environmental and public health risks (EPA, 2001; FAO, 2006; Hribar, 2010). Historical flood events, such as those in North Carolina following Hurricane Floyd in 1999, demonstrated these risks. In that case, satellite-based flood estimates identified that 241 CAFOs—including swine, poultry, and cattle operations—were located within the flooded area (Wing et al., 2002). Similarly, Inchaisri et al. (2013) examined the 2011 catastrophic flood in Thailand, where farms in river-adjacent areas experienced high livestock mortality, particularly among poultry and swine.

In regions with dense industrial farming, the risks associated with flooding are further compounded by the effects of natural and technological (Natech) disasters (Ramthun, 2020). During floods, such as those caused by hurricanes Matthew (2016) and Florence (2018) in North Carolina, manure storage systems were overwhelmed, contaminating local water sources and resulting in severe environmental damage (Ramthun, 2020; Hamilton et al., 2023). These disasters led to the deaths of thousands of pigs and millions of chickens, underscoring the vulnerability of CAFOs to extreme weather events and highlighting the importance of implementing robust emergency preparedness plans, insurance coverage, and coordinated response efforts (Heath & Linnabary, 2015; Beeson, 2018; Bissett et al., 2018; Maness, 2019).

Iowa serves as an ideal case study for examining the impacts of flooding on CAFOs, given the high density of these operations and frequent flood events in the state (Throgmorton, 2012; DNR, 2022; IEC, 2023). Iowa is home to more than 12,000 CAFOs, which include facilities for cattle, swine, and poultry. Major flood events can cause extensive damage to livestock operations in Iowa, particularly in flood-prone areas where large CAFOs are clustered (DNR, 2022). Additionally, the placement of CAFOs in low-income and minority communities has raised environmental justice concerns, as these populations are disproportionately affected by the environmental and economic impacts of floods (Nicole, 2013; Son & Bell, 2022). These factors underscore the need for a detailed geospatial analysis to better understand and mitigate the risks of future floods on CAFOs (Ramthun, 2020).

Research has shown that floods in the past have led to significant livestock losses and infrastructure damage, underscoring the urgency for comprehensive flood risk assessments (Eash & Koppensteiner, 2008; Merz et al., 2010; FAO, 2018; GCRP, 2018; Alabbad et al., 2024). Proactive vulnerability assessments and mitigation strategies, supported by government agencies like Federal Emergency Management Agency (Yildirim et al., 2022), are crucial for improving the resilience of CAFOs and protecting vulnerable communities. Previous studies have focused primarily on flood impacts on agricultural systems, particularly crop damage (Gilles, 2010; Tanir et al., 2024). However, research specifically examining the vulnerability of CAFOs remains limited, particularly in Iowa, where livestock farming plays a central role in the state's economy.

This paper presents a detailed analysis of the impacts of flooding on CAFOs in Iowa. The study integrates flood inundation maps, CAFO location data, and tax parcel information to assess the exposure and vulnerability of these operations to flood events. By identifying the areas and facilities most at risk, the research provides policy-relevant and operational insights into the potential impacts of flooding on livestock health and economic losses. The study's findings aim to contribute to the development of more effective flood management and mitigation strategies for CAFOs in Iowa and similar regions.

The paper is organized as follows: Section 2 outlines the materials and methods used, including data collection and processing techniques. Section 3 presents the results of the spatial analysis, highlighting the areas and types of CAFOs most vulnerable to flooding. Section 4 discusses the implications of these findings for flood management and mitigation strategies. Finally, Section 5 provides conclusions and recommendations for future research. Each section builds on the previous one, providing a cumulative understanding of the flood risks to CAFOs and leading to actionable recommendations in the closing section.

2. Methodology

This section outlines the datasets and methodologies used to assess flood impacts on CAFOs in Iowa, utilizing advanced spatial techniques to perform a comprehensive analysis.

2.1. Study Area

Iowa, located in the Midwestern United States, consists of 99 counties bordered by the Missouri River to the west and the Mississippi River to the east. Due to its geographic positioning, Iowa is highly susceptible to recurrent flood events (Yildirim et al., 2023), which have caused considerable damage to infrastructure, livestock, crops, and human life over the past three decades (Alabbad &

Demir, 2024). These factors make Iowa an ideal case for studying the impact of floods on agricultural infrastructure, particularly CAFOs, which play a vital role in the state's economy. Figure 1 illustrates the spatial distribution of CAFOs in Iowa, categorized by size, highlighting the prevalence of small, medium, and large operations throughout the state.

Iowa's agricultural sector is critical to both state and national food supplies, particularly in pork, egg, and cattle production. Iowa's pork industry, which accounts for over one-third of all pork produced in the United States, generates approximately $40 billion in annual economic activity and supports over 120,000 jobs (Iowa Pork Producers Association, 2024). Iowa also leads the nation in egg production, producing 16.4 billion eggs in 2018, which represents 17% of the nation's table egg supply (Ibarburu, 2019).

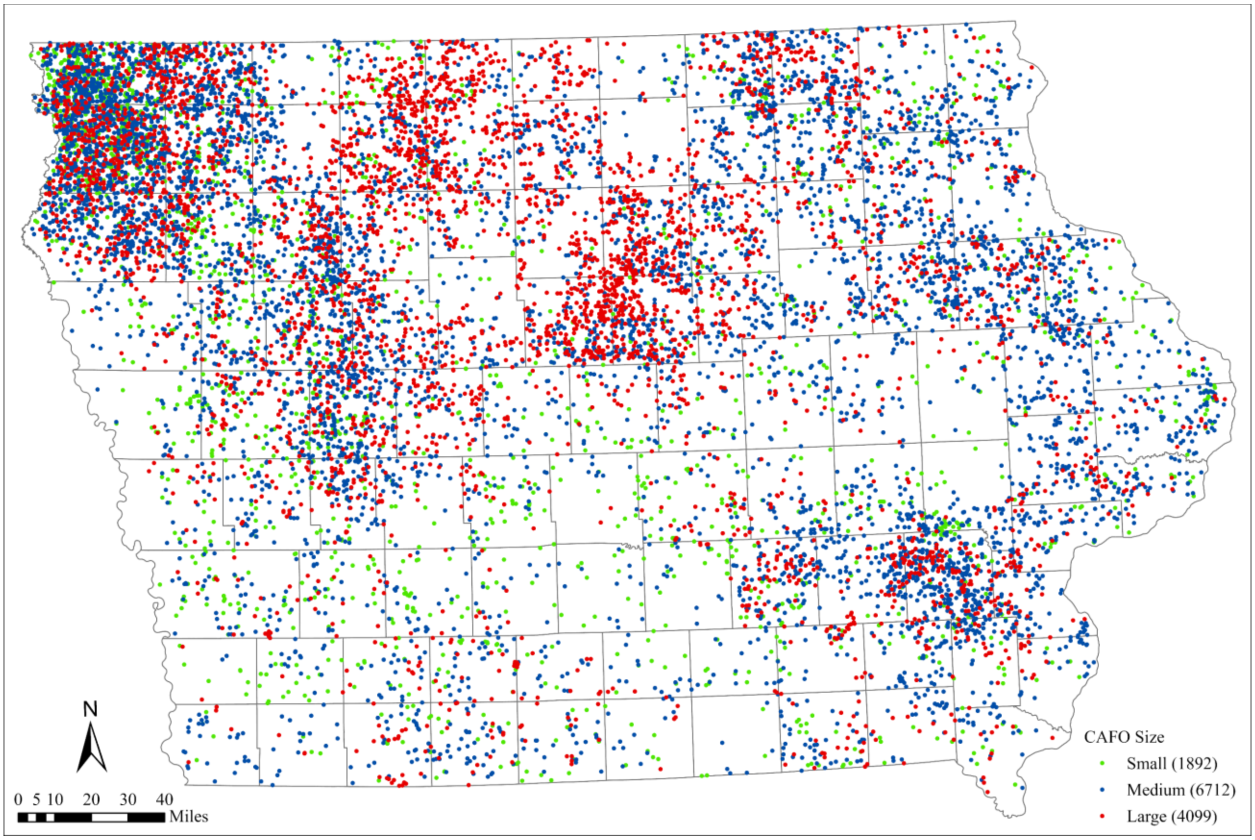

Figure 1. Spatial distribution of CAFOs by size in Iowa

Cattle production is another key pillar of Iowa's agricultural economy. In 2021, Iowa housed over 3.85 million cattle and calves, ranking it among the top ten cattle-producing states (U.S. Department of Agriculture, 2022). This industry not only generates direct income for farmers but also stimulates related sectors such as feed production, processing, and transportation, creating a broad economic ripple effect across the state.

While the economic contributions of Iowa's swine, poultry, and cattle industries are substantial, these sectors remain highly vulnerable to disruptions, particularly from flooding events. Floods can cause widespread damage to CAFOs, resulting in significant economic losses due to reduced livestock productivity, facility damage, and operational downtime. These impacts extend beyond the CAFOs themselves, affecting job markets, feed supply chains, and potentially raising food prices, thereby amplifying economic consequences at both the state and national levels.

Given the critical role of CAFOs in Iowa's economy and their susceptibility to flood hazards, assessing their flood risk is essential. Understanding these risks is crucial to protect Iowa's agricultural productivity and prevent broader economic disruptions. Evaluating the flood risks for CAFOs is key to ensuring Iowa maintains its leadership in national and global food production, especially as extreme weather events become more frequent.

Flood inundation maps are fundamental tools for managing and communicating flood risks (Sermet and Demir, 2022), particularly in agricultural sectors like CAFOs. These maps allow for a detailed evaluation of exposure and vulnerability across multiple factors, including populations, properties, and agricultural areas. By providing critical information, flood inundation maps support informed decision-making for flood preparedness and mitigation efforts. For CAFOs, these maps are particularly valuable in ensuring that resources are efficiently allocated to protect facilities from flood-related disruptions, minimizing both economic losses and potential environmental impacts.

Flood inundation maps are created by integrating diverse data sources, such as hydrological, topographical (Li and Demir, 2022), and infrastructure data, combined with advanced flood forecasting (Sit et al., 2021) and mapping techniques. This approach enhances their accuracy and reliability. These maps are indispensable for safeguarding CAFO infrastructure and surrounding communities from the detrimental effects of flooding. In this context, flood inundation maps play a vital role in developing more resilient and adaptive flood management strategies (Yesilkoy et al., 2024), tailored to protect critical agricultural operations.

2.2. Data Collection and Analysis

This study analyzed data from 12,703 CAFOs, housing approximately 14.25 million animals, sourced from the Iowa Department of Natural Resources (DNR) Geospatial Data, online data repository offering detailed geospatial datasets (DNR, 2024). These CAFOs are distributed across all 99 counties, making Iowa a key contributor to national livestock production, particularly in the swine, poultry, and cattle industries. Understanding the economic implications of flood risks to these operations is essential for developing strategies that safeguard Iowa's agricultural backbone.

Following the record-breaking Iowa flood of 2008, which caused extensive damage and highlighted the state's vulnerability, the Iowa Flood Center was established in 2009 to improve flood preparedness. One of its primary initiatives was the development of comprehensive floodplain maps, accessible through the Iowa Flood Information System (Demir and Krajewski, 2013).

Flood inundation maps, which are central to this analysis, were developed using a combination of flow gauge data, topographical information, and hydraulic modeling (Li et al., 2023; Hu and Demir, 2021). These maps analyzed the hydrologic and hydraulic characteristics of basins and streams, incorporating high-resolution data, such as a 1-meter digital elevation model enhanced with data-driven methods (Demiray et al., 2021). Sophisticated modeling software, including MIKE FLOOD and HEC-RAS, was used to simulate various flood return period floodplains, ranging from 2-year to 500-year events (Gilles, 2010). For this study, flood maps for the 100-year (1% annual chance) and 500-year (0.2% annual chance) flood events were used to assess flood exposure and risk for CAFOs across Iowa.

The DNR AFO Siting Atlas provided a comprehensive dataset on CAFOs, including geographic locations, operational details, species, animal units, and operation types (e.g., confinement, open feedlot, and combined operations). Construction date values were extracted using a Python script to better understand CAFO vulnerability based on facility age and design. Figure 2 illustrates the spatial distribution of CAFOs in Iowa, categorized by construction year, highlighting variations in establishment periods across the state.

Additionally, tax parcel data, comprising 2,450,589 digitally created parcels represented as polygon-geometry layers in shapefile format, was used. This dataset includes information on deedholders and parcel classifications (e.g., agricultural, commercial, residential, exempt), which are essential for understanding land ownership and usage patterns. These data are critical for accurately assessing flood risk and informing strategies to protect CAFOs from flooding.

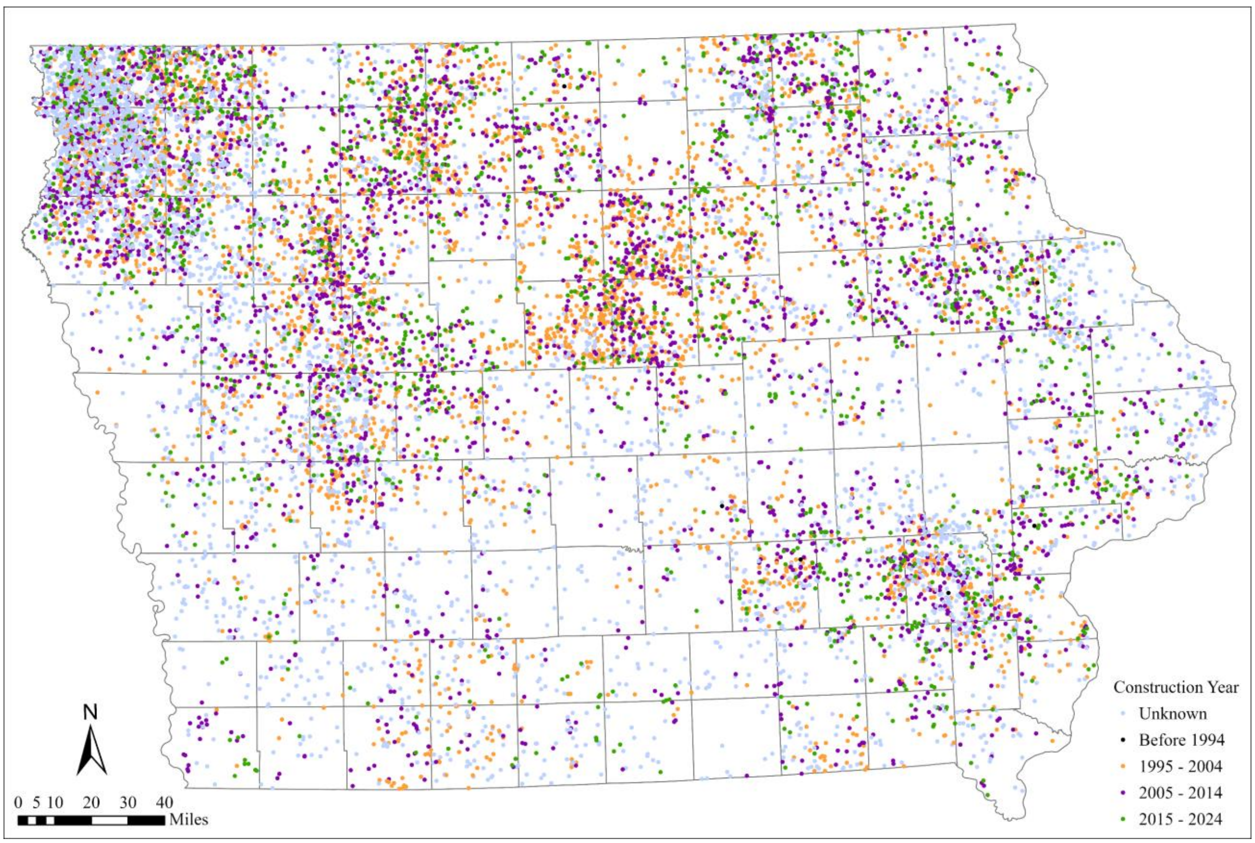

Figure 2. Spatial distribution of CAFOs by construction year in Iowa

2.3. Floodplain Analysis and Mapping

A county-level analysis of CAFO inundation during 100-year and 500-year flood events was conducted using ArcGIS Pro (ESRI). The study was grounded in several critical assumptions to ensure robust and consistent modeling outcomes. One key assumption was the persistence of flooding effects from those observed in smaller flood extents to larger ones. Specifically, this assumption proposed that CAFO inundated during a 100-year flood event would also be at risk during more severe scenarios, such as 500-year flood events, consistent with patterns documented in historical flood data. This approach facilitated a conservative and comprehensive evaluation of long-term risks associated with extreme flood events. Another fundamental assumption concerned the accuracy and precision of the input datasets employed in the spatial analysis.

This encompassed elements such as the reliability of hydrological and topographical data used to delineate floodplains and their intersections with CAFO locations. The assumption of persistent flooding effects was instrumental in assessing long-term risks to CAFOs. Wing et al., (2002) has demonstrated that even partial inundation of CAFO facilities can result in significant operational disruptions and environmental contamination, including the release of hazardous pollutants into surrounding ecosystems. Consequently, this study identified any CAFO intersecting with a floodplain as being at risk, thereby adopting a conservative and environmentally precautionary approach to flood risk assessment.

The spatial analysis incorporated flood inundation maps (polygon geometry), CAFO locations (point geometry), and tax parcel data (polygon geometry). Flood impacts on CAFOs were identified by intersecting floodplain data with CAFO locations using a 2D set intersection. Since CAFOs consist of multiple interconnected components—including shelters, storage areas, silos, and waste disposal sites—partial inundation of any component was assumed to impact the entire operation. This assumption is supported by systems theory, which emphasizes the interdependence between elements within a system. In this context, the functionality of the whole system depends on the proper operation of its individual parts. Disruption in one component can therefore affect the performance of the entire system. Figure 3 shows the spatial distribution of CAFOs in Iowa, categorized by operation types such as open feedlot, confinement, and combined operations.

A more comprehensive understanding of flood risks was achieved by intersecting tax parcel data with CAFO point data. Since CAFOs often comprise multiple interconnected structures spread across large areas, parcel data provided a more detailed and accurate representation compared to single-point data. This approach also addressed uncertainties regarding the methods used to determine the placement of CAFO point locations, ensuring greater reliability in the analysis. In some cases, entire parcels were within the floodplain, while others were only partially affected. Any CAFO with a parcel intersecting the floodplain was considered at risk of flooding, allowing for a detailed analysis of potential disruptions to operations and infrastructure.

CAFO polygons within the 100-year and 500-year floodplains were identified using the intersection algorithm, by overlaying floodplain maps and CAFO polygon data. This process enabled the identification of CAFOs located in flood-prone areas through a 2D set intersection analysis, highlighting facilities potentially exposed to flooding where their spatial boundaries intersect with mapped floodplains.

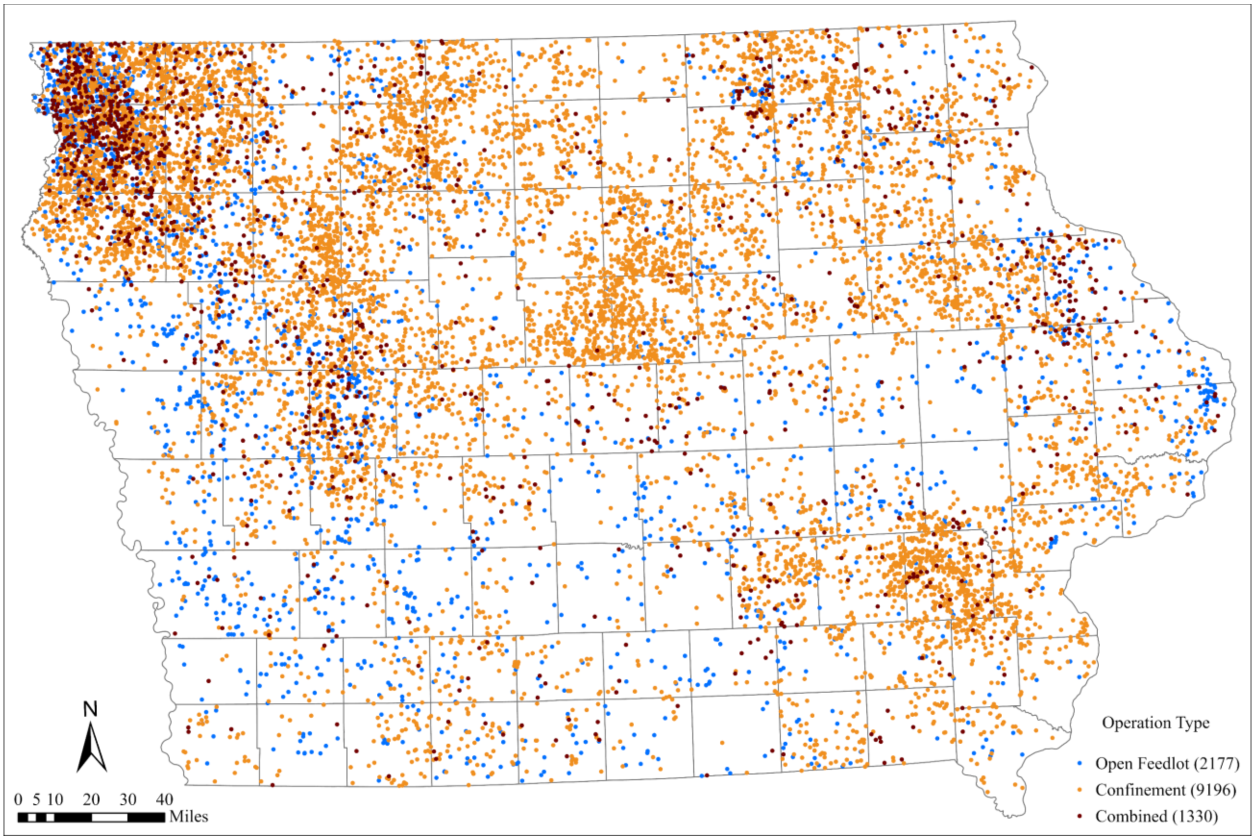

Figure 3. Spatial distribution of CAFOs by operation type in Iowa

2.4. Data Challenges and Improvements

During this study, several challenges were encountered related to the geospatial accuracy and completeness of the animal feeding operation data, which posed significant challenges for the reliability of flood risk assessments. Many CAFO points were found to be inaccurately placed, outdated, or misaligned with their actual locations. Specifically, 411 CAFO points did not correspond to their expected parcels. In some cases, no actual CAFO existed at the recorded location, while in others, the spatial extent of the CAFO was significantly larger than indicated by the point data.

Additionally, some CAFO points were clustered within a single parcel or misplaced in adjacent or unrelated locations, further complicating accurate floodplain representation. To address these issues, the attributes of each affected CAFO were meticulously verified. This process involved ensuring that the coordinates in the CAFO attribute table matched the points on the map and confirmed whether the CAFO owner and the landowner were the same individual. By rectifying these inaccuracies, the study significantly improved the spatial representation of CAFOs at risk of flooding in Iowa, ensuring a more robust and precise assessment of flood vulnerabilities.

Extensive data processing was required to align the tax parcel data and CAFO point data to the same spatial scale. Manual corrections were performed by thoroughly verifying CAFO attributes, such as addresses, coordinates, deed holders, and other key features. Consequently, the CAFO dataset was significantly improved. During this process, each CAFO's address, coordinates, deed holder, and other attributes were carefully reviewed and corrected as needed. Seven out of 12,703 CAFO points were discarded due to a lack of accurate validation based on the available data. While the exclusion of these CAFOs is not expected to significantly affect the overall analysis, their omission underscores the importance of precise data validation in future studies.

By resolving these data challenges and implementing the necessary improvements, the dataset used in this study was significantly enhanced, providing a robust foundation for assessing the impact of flooding on CAFOs. These data improvements were essential for ensuring that flood risk assessments were based on reliable, spatially accurate information, thereby enhancing the overall validity of the study.

3. Results and Discussion

In this section, we present the results for the comprehensive analysis of the flood risks associated with CAFOs in Iowa, focusing on how these risks impact the state's animal units, cattle, swine, and poultry industries based on county. The analysis explores flood risk variations by operation types, size, and construction year particularly in areas prone to flooding. Additionally, we assess the vulnerability of CAFOs using the concept of animal units—a standardized measure representing the total capacity of a CAFO by accounting for different kinds of animals. This approach provides a thorough understanding of the flood risk affecting the overall capacity of these operations.

The findings are derived from a detailed examination of spatial distribution maps, floodplain data, and operational characteristics of CAFOs, revealing critical insights into the vulnerability of these agricultural operations to both 100-year and 500-year flood events. By analyzing the relationships between CAFO attributes and flood exposure, this discussion highlights the complex interaction of factors that contribute to flood risk. The implications of these results are significant, offering valuable perspectives on the resilience of CAFOs in the face of increasingly frequent and severe flooding events, and providing a foundation for informed policy and management decisions aimed at safeguarding Iowa's agricultural infrastructure.

The assessment of flood risk on CAFOs in Iowa, as illustrated in Figures 4(A) and 4(B), reveals significant potential impacts within both the 100-year and 500-year floodplains. Figure 4(C) provides a comparative analysis of flood exposure between the two floodplains. The geographic distribution of CAFOs affected by these floodplains shows a non-uniform vulnerability across the state, with certain counties exhibiting particularly high levels of exposure.

Figure 4(A) illustrates the distribution of animal units affected by the 100-year floodplain across Iowa, with the highest concentrations located in the northern and northwestern regions. Notably, Sioux County emerges as the most vulnerable, housing a total of 1,133,173 animal units, 183,791 of which (16.2%) are located within the 100-year floodplain. Statewide, the total number of animal units exposed to the 100-year floodplain is 1,906,001, representing approximately 13.35% of Iowa's total animal unit population of 14,283,073 as of December 2024

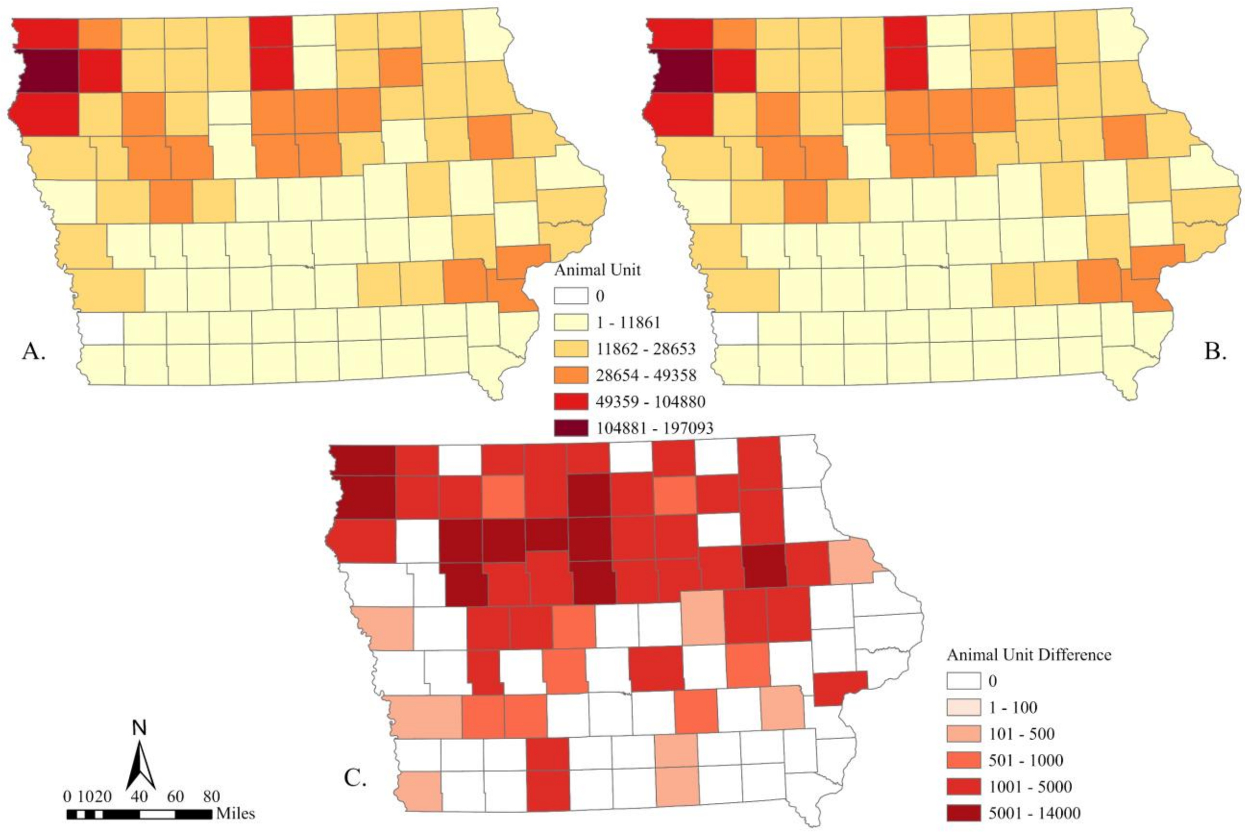

Figure 4. Animal unit distribution in Iowa CAFOs across 100-year (A), 500-year (B) floodplains, and differences between floodplains (C).

The northwestern part of Iowa, particularly counties like Hancock and O'Brien, shows significant vulnerabilities due to their proximity to rivers and other water bodies, increasing the likelihood of flooding. For instance, Hancock has 89,571 animal units, 18.4% of which are within the 100-year floodplain, demonstrating substantial exposure to flood risks. Figure 4(B) extends this analysis to the 500-year floodplain, which covers a broader geographic area and affects a larger number of animal units. In Sioux County, the number of animal units at risk increases to 197,093 (17.4%) when considering the 500-year floodplain.

Figure 4(C) provides a comparative analysis of animal units affected by the 100-year versus the 500-year floodplains. The comparison reveals that certain counties experience a significant increase in the number of animal units at risk when extending the flood risk to the 500-year floodplain. The incremental statewide increase of 148,840 animal units between the 100-year and 500-year floodplains suggests that even modest extensions in floodplain boundaries can substantially impact CAFOs, especially in regions with dense animal populations such as northern and northwestern Iowa.

These findings highlight the critical need for targeted flood mitigation strategies in Iowa's animal unit-dense regions, particularly in northern and northwestern counties where large animal unit populations intersect with significant flood risks. The geographic distribution of risk, as shown in Figures 4(A) and 4(B), indicates that such flood events could have severe economic and operational impacts on CAFOs in these areas.

Furthermore, the comparison between the 100-year and 500-year floodplains, as seen in Figure 4(C), underscores the necessity of long-term planning that considers the potential for rare but catastrophic flooding. As climate change continues to influence the frequency and severity of extreme weather events, Iowa's agricultural infrastructure must adapt to ensure the resilience and sustainability of its animal unit-dense CAFOs.

This considerable exposure to flood risk underscores the need for robust flood mitigation strategies to protect these operations from flood-related disruptions. In counties like Sioux, Lyon, and Hancock, where the flood risk is especially pronounced, targeted flood protection measures such as enhanced drainage systems, levees, and emergency preparedness plans could mitigate the impact of flooding on these vital agricultural operations.

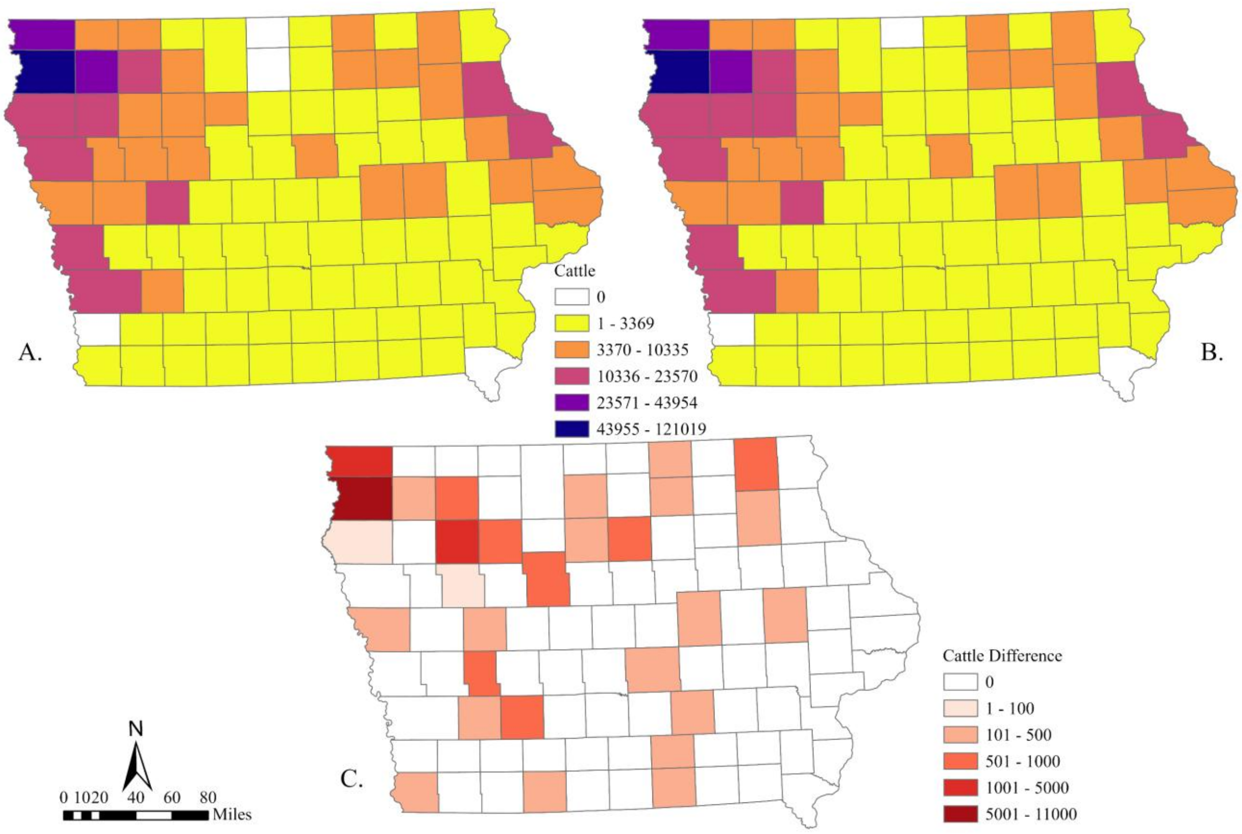

Figure 5. Cattle distribution in Iowa CAFOs across 100-year (A), 500-year (B) floodplains, and differences between floodplains (C).

Figure 5(A) illustrates the distribution of cattle affected by the 100-year floodplain across Iowa. Northwestern Iowa, particularly Sioux, Lyon, and O'Brien counties, emerges as a critical area, with a substantial number of cattle at risk. For example, Sioux County has a total of 481,982 cattle, 110,848 of which (23%) could be affected by the 100-year floodplain. In the 500-year floodplain, as seen in Figure 5(B), the risk extends further, with 121,019 cattle (25.1%) in Sioux County being vulnerable. The analysis demonstrates that the 500-year floodplain impacts a slightly higher number of cattle compared to the 100-year floodplain, highlighting how even a marginal increase in flood severity can significantly affect livestock in these regions.

Figure 5(C) provides a comparative analysis of cattle exposure between the two floodplains, showing an increase in cattle affected in the 500-year floodplain. Statewide, 540,729 cattle are affected by the 100-year floodplain, which represents 21.8% of Iowa's total cattle population of 2,476,519. The 500-year floodplain affects 568,113 cattle, or 22.9% of the total cattle population. These findings underscore the critical need for effective flood risk management, particularly in counties with large cattle populations. Sioux and O'Brien counties have substantial numbers of cattle at risk, with Sioux County alone having over 121,000 cattle vulnerable in the 500-year floodplain.

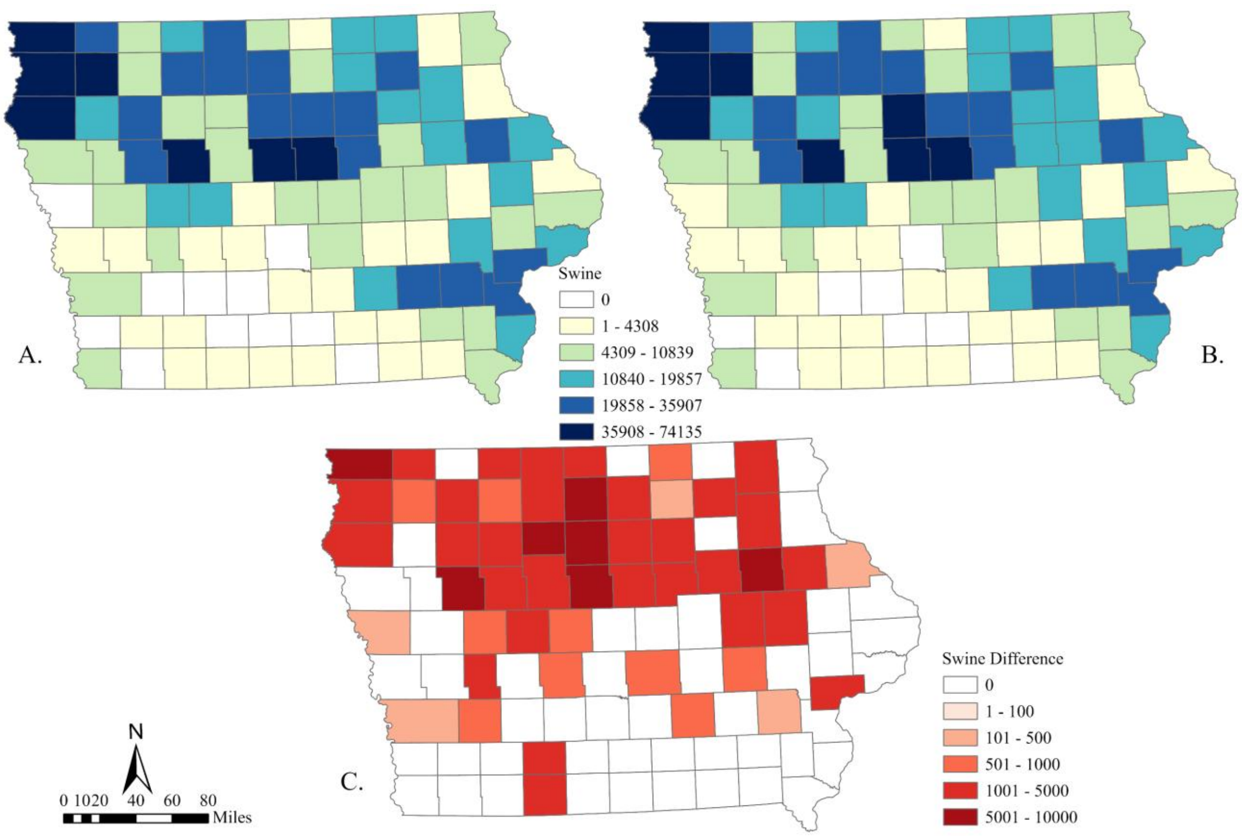

Figure 6. Swine distribution in Iowa CAFOs across 100-year (A), 500-year (B) floodplains, and differences between floodplains (C).

Given these risks, it is essential to implement adaptive measures in flood-prone areas to mitigate potential losses. Prioritizing strategies such as constructing elevated confinement structures, enhancing drainage systems, and developing robust early warning systems is vital. These measures should be particularly focused on the most vulnerable counties, like Sioux and O'Brien, where the potential impact on cattle is greatest due to the high numbers at risk.

Figure 6(A) presents the distribution of swine populations affected by the 100-year floodplain, with the most significant concentrations in the northwestern and central regions of Iowa, particularly in counties such as Sioux, Lyon, and Plymouth. Sioux County, with a total swine population of 570,834, has approximately 71,039 (12.4%) located within the 100-year floodplain. Similarly, Lyon County, with a total swine population of 371,263, has 54,304 (14.6%) at risk in the same floodplain. Central counties like Hamilton also show significant exposure, with 36,607 swine (10.8%) at risk.

The vulnerability of northwestern Iowa is attributed to its extensive drainage systems, proximity to rivers such as the Big Sioux River, and relatively flat, low-lying topography, all of which increase the likelihood of flooding. Statewide, the total number of swine potentially affected by the 100-year floodplain is 1,183,839, representing 10.98% of Iowa's total swine population of 10,777,971. This density of CAFOs exacerbates the potential operational and economic disruptions caused by flooding.

Figure 6(B) expands the analysis to the 500-year floodplain, which covers a broader area and increases the number of swine populations at risk. In Sioux County, for example, the number of swine at risk increases to 74,135 (13%) when considering the 500-year floodplain. Similarly, Lyon County sees its at-risk population rise to 59,324 (16%), and Hamilton increases to 44,544 (13.2%), reflecting the growing vulnerability under more extreme floodplains.

Figure 6(C) provides a comparative analysis of swine populations affected by the 100-year and 500-year floodplains across Iowa's counties. Counties such as Wright, Calhoun, and Butler show substantial increases in swine populations at risk in the 500-year floodplain. For instance, Wright County's swine at risk rise from 31,484 (17.4%) in the 100-year floodplain to 40,541 (22.4%) in the 500-year floodplain, indicating a significant escalation in vulnerability during more extreme flood events.

The pronounced increase in flood exposure, particularly in regions with high swine densities, underscores the need for comprehensive flood mitigation strategies. The geographic distribution of risk, as illustrated in Figures 6(A) and 6(B), suggests that even moderate flood events could severely disrupt swine CAFOs, leading to significant economic and operational consequences.

Counties with large swine populations, such as Sioux, Lyon, and Hamilton, are especially vulnerable. Additionally, counties like Wright, Calhoun, and Butler, while less affected by the 100-year floodplain, face substantial risks under the 500-year floodplain. The increase in flood exposure between these two floodplains is particularly notable, with Wright County's at-risk population rising from 17.4% under the 100-year floodplain to 22.4% under the 500-year floodplain.

Counties experiencing significant increases in risk for swine, such as Wright and Calhoun, demand immediate attention. The dramatic escalation in vulnerability between the 100-year and 500-year floodplains emphasizes the need for robust flood defenses and comprehensive emergency planning in these areas. Wright County's increasing vulnerability highlights the potentially devastating impact of a 500-year flood, necessitating proactive planning and targeted flood protection measures.

The comparison between the 100-year and 500-year floodplains, as shown in Figure 6(C), reinforces the importance of long-term strategies that account for rare but catastrophic flood events. As climate change continues to exacerbate the frequency and intensity of extreme weather, Iowa's agricultural infrastructure, particularly its swine CAFOs, must adapt to ensure resilience and sustainability in the face of evolving flood risks.

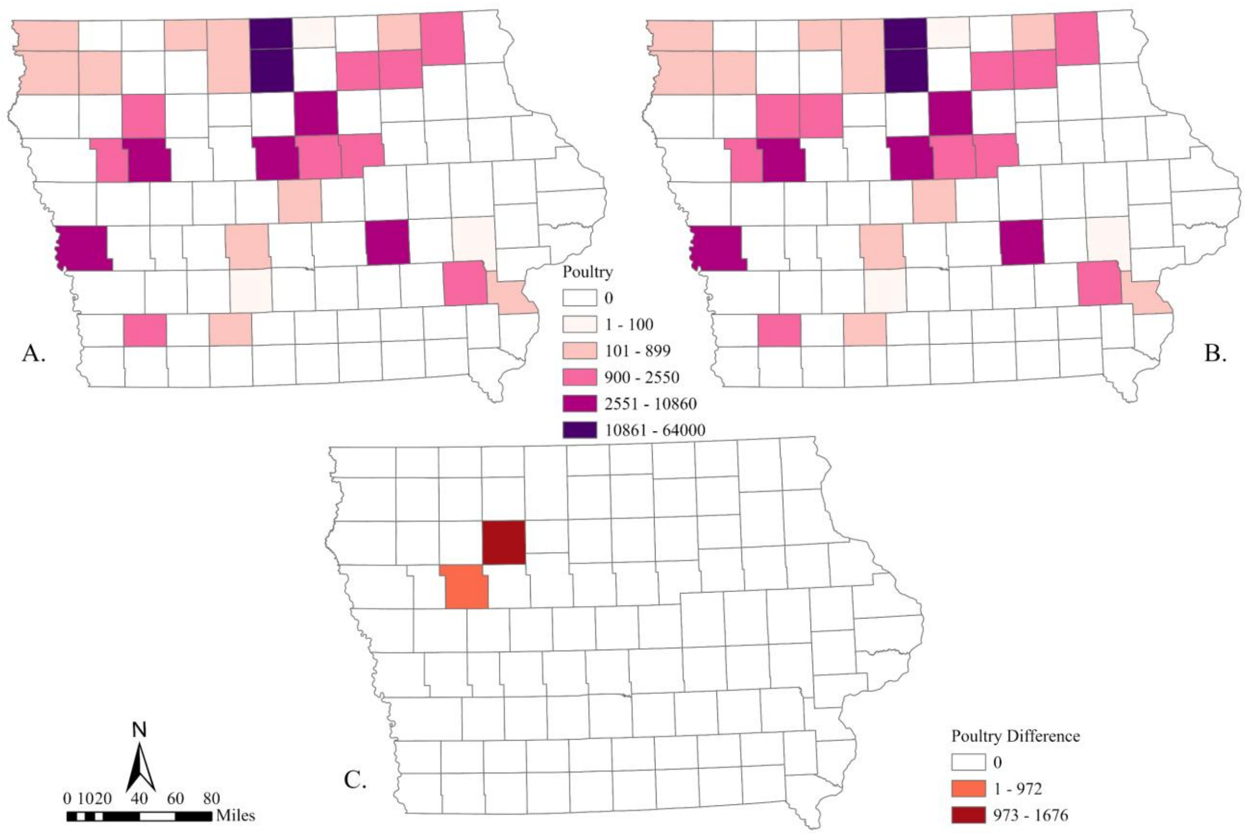

Figure 7. Poultry distribution in Iowa CAFOs across 100-year (A), 500-year (B) floodplains, and differences between floodplains (C).

The analysis of flood impacts on Iowa's poultry operations reveals significant vulnerabilities in key regions. While Iowa's poultry industry is smaller compared to its cattle and swine sectors, it remains critically important to the state's agricultural economy. Given the relatively modest scale of Iowa's poultry sector, any disruption due to flooding could have severe consequences for producers and communities reliant on them.

Figure 7(A) shows that 170,383 poultry units, or approximately 17.26% of Iowa's total poultry population, are situated within the 100-year floodplain. These at-risk poultry operations are primarily concentrated in the northern and north-central parts of the state. For instance, Hancock County, with a total poultry population of 76,942, has 64,000 units (83.2%) located in the 100-

year floodplain, while Winnebago County has all 58,500 poultry units (100%) within the same high-risk zone. The density of poultry CAFOs in these counties highlights their susceptibility to moderate flood events.

Figure 7(B) extends the analysis to the 500-year floodplain, where the number of affected poultry units rises slightly to 173,031 (17.54%). Notably, some counties, such as Hancock and Winnebago, show no change in the number of at-risk poultry units, indicating a persistent vulnerability across both floodplains. This underscores the precarious position of poultry operations in these regions, where flood risks are consistently high.

The comparative analysis in Figure 7(C) reveals that counties such as Pocahontas and Sac experience a notable increase in risk when considering the 500-year floodplain. Pocahontas, for instance, had no poultry at risk in the 100-year floodplain but sees 1,676 units at risk under the 500-year floodplain. Sac similarly shows an increase from 3,586 units (15%) to 4,558 units (19%). This escalation of risk during more severe flood events emphasizes the need for mitigation strategies that account for both moderate and extreme flooding

The data presented highlights the urgent need for targeted flood mitigation efforts, particularly in counties like Hancock and Winnebago, where significant portions of the poultry population are at risk in both floodplains. While poultry CAFOs are fewer in number compared to cattle and swine operations, they play a vital role in Iowa's agricultural economy. Any disruption in these concentrated poultry operations could have far-reaching effects on the state's food supply and economic stability.

The increased risk in counties like Pocahontas and Sac between the 100-year and 500-year floodplains further underscores the importance of long-term planning. Given the impact of climate change on the frequency and intensity of extreme weather events, robust flood management strategies are essential to safeguard Iowa's poultry industry. These measures could include the development of flood-resistant infrastructure, improved drainage systems, and enhanced emergency preparedness plans.

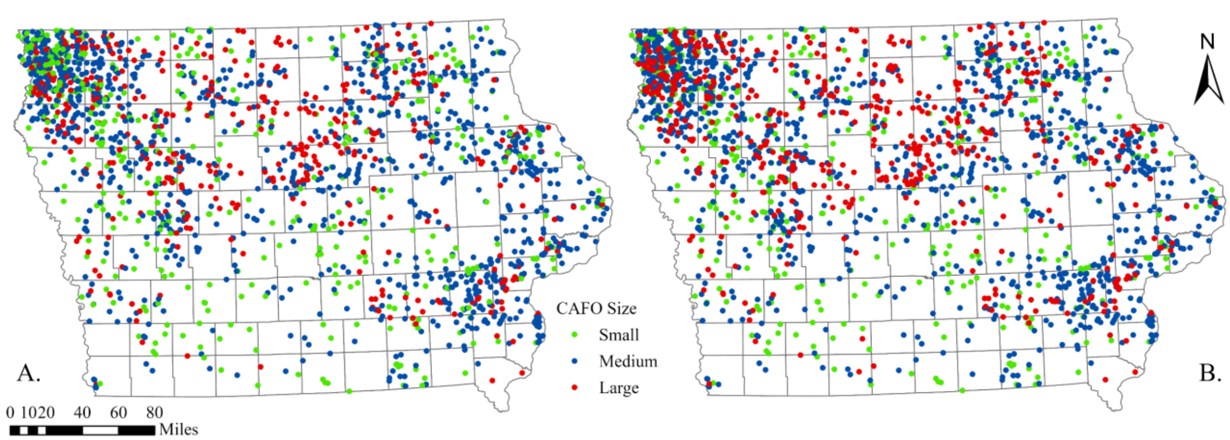

Figure 8. Comparison of CAFO size distribution in Iowa across 100-year (A) and 500-year (B) floodplains.

As a final point, while fewer in number, Iowa's poultry CAFOs are critical to the state's food security and economic health. The vulnerability of these operations to flooding, as shown in Figures 7, highlights the need for tailored mitigation strategies that address the risks posed by both the 100-year and 500-year floodplains. Protecting this sector from future climate-driven flood events is essential to ensuring its sustainability and resilience.

Figure 8(A) reveals that large CAFOs are clustered in northwestern Iowa, particularly in counties like Sioux, Plymouth, and Lyon. For example, Sioux has 137 large CAFOs in the 100-year floodplain, representing 18% of all large CAFOs at risk statewide. The high concentration of large CAFOs in this region suggests greater potential for economic disruption, given the scale of livestock housed in these operations. In central Iowa, medium and small CAFOs are more uniformly distributed. Counties like Hamilton show a balanced mix, with 68 medium CAFOs at risk in the 100-year floodplain. While the overall impact on smaller CAFOs may be less severe, these facilities still face the threat of prolonged operational disruptions due to flooding.

Figure 8(B) with 500-year floodplain highlights a broader geographic spread of flood risk, increasing the number of at-risk CAFOs by 14% compared to the 100-year floodplain. Central counties like Polk see a notable rise in medium CAFOs at risk, with the number increasing from 45 to 78—an increase of 73%. This expansion underscores the heightened vulnerability during extreme flood events, especially for medium-sized CAFOs in central and southern Iowa.

The comparison between Figures 8 shows that large CAFOs in the northwest remain highly vulnerable, while the 500-year floodplain brings significant new risk to medium and small CAFOs in central Iowa. This suggests that both regions require tailored flood mitigation strategies: robust defenses for large CAFOs in the northwest, and a mix of physical and emergency response measures for medium and small CAFOs in central Iowa.

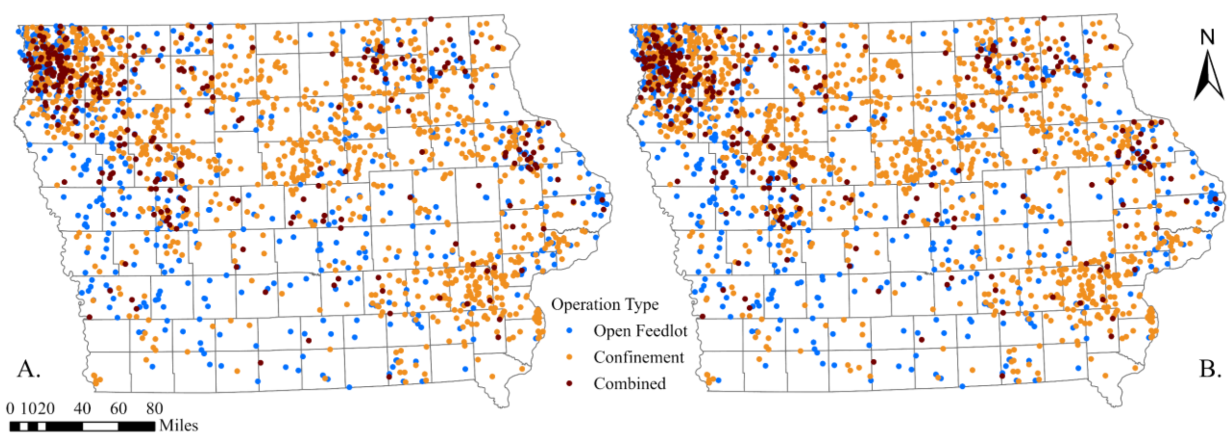

Figure 9. Spatial distribution of CAFOs by operation types in Iowa within the 100-year (A) and 500-year (B) floodplains.

Figure 9(A) shows that a significant number of CAFOs built before 2004 (black and orange dots) are clustered in northern and western Iowa, regions that experience higher flood exposure. These older facilities may face greater vulnerability due to potentially outdated flood mitigation infrastructure. Figure 9(B) illustrates the broader distribution of newer CAFOs (constructed between 2005 and 2024, represented by purple and green dots), especially in central and eastern areas. Despite their more recent construction, a considerable number of these facilities are still located within flood-prone areas. This indicates that flood risk remains a persistent challenge, even for newly built operations. Furthermore, it is important to note that floodways can change over time due to shifts in land use, hydrological patterns, or climate impacts, meaning the 100-year flood extent from more than 20 years ago may differ significantly from current conditions.

Overall, the analysis underscores the need for targeted interventions for older CAFOs, which are more likely to lack modern flood-resilience designs. Additionally, although recent constructions benefit from improved engineering standards, the ongoing flood risks necessitate further flood prevention measures for both older and newer CAFOs to ensure long-term operational stability.

Figure 9(B) expands the analysis to the 500-year floodplain, where 27.5% of open feedlots fall within the affected areas. The broader geographic reach of the 500-year floodplain shows that more facilities, especially in central Iowa, are at risk from extreme but less frequent flood events. While the percentage increase in at-risk facilities is relatively small, the inclusion of additional regions suggests that rare, large-scale floods could have far-reaching consequences for Iowa's livestock industry. The continued high density of combined operations in the northwest presents ongoing challenges, as these facilities often integrate open and confined spaces, increasing the complexity of flood management and recovery efforts.

The comparison between the 100-year and 500-year floodplains reveals that while the overall flood risk is slightly higher in the latter, the concentration of open feedlots and combined operations in both floodplains underscores the need for proactive flood mitigation strategies. Open feedlots, due to their outdoor nature, face unique challenges in mitigating flood damage, particularly in regions prone to both frequent and rare flood events. Combined operations, which house a variety of livestock types, must account for multiple vulnerabilities, including waste management and livestock safety.

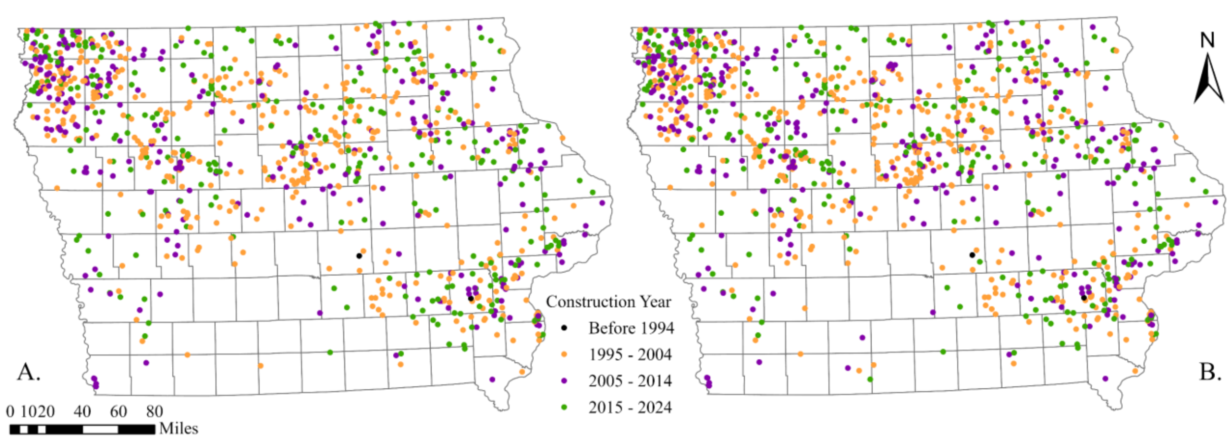

Figure 10. Analysis of CAFOs by construction year and floodplain risk: 100-year (a) and 500-year (b) floodplains

Figure 10(A) shows that many CAFOs built before 2004 (black and orange dots) are clustered in northern and western Iowa, areas with higher flood risk. These older facilities are more vulnerable to operational disruptions due to outdated flood mitigation measures. Figure 10(B) illustrates the distribution of newer CAFOs (2005-2024, purple and green dots), mainly in central and eastern Iowa. Despite modern construction, many of these newer facilities remain in flood-prone areas, showing that flood risk is a concern for both older and newer operations. The analysis extends to the 500-year floodplain, where 27.5% of open feedlots are at risk, particularly in central Iowa. Open feedlots, with their outdoor setup, face unique challenges, while combined operations must address waste management and livestock safety concerns. This comparison highlights the need for targeted interventions for older CAFOs and ongoing flood management for newer facilities to ensure long-term stability as flood risks increase.

Overall, proactive strategies, such as improved drainage systems and strengthened infrastructure, are essential for mitigating the risks posed by frequent and extreme flood events for both older and newer CAFOs. Improved drainage systems can incorporate natural infrastructure features, such as riparian buffers, ditches, and flood retention ponds, to manage runoff and reduce floodwater accumulation. These approaches not only help direct water flow away from vulnerable areas but also offer additional benefits, including improved water quality, erosion control, and habitat restoration.

4. Conclusion

This study provides a comprehensive assessment of flood risks facing Concentrated Animal Feeding Operations (CAFOs) across Iowa, revealing significant vulnerabilities in geographic distribution, animal unit exposure, and operational sectors. County-level analysis highlights how specific regions, particularly Sioux, Lyon, and Hancock counties, are disproportionately exposed to flood risks. These counties, housing large livestock populations, are at risk under both 100-year and 500-year floodplain, with the incremental increase between these floodplains underscoring how even small extensions in flood boundaries can have substantial impacts on the livestock industry and the local economy.

The results show that over 14% of Iowa’s total animal unit population is exposed to the 500-year floodplain, which has serious economic and operational consequences. This level of exposure threatens livestock productivity, disrupts supply chains, and jeopardizes local employment in agriculture-dependent communities. In regions like northern and northwestern Iowa, where cattle and swine operations are concentrated, even moderate flood events could lead to significant losses in livestock, operational downtime, and costly recovery efforts. Poultry operations, though smaller in number, are also heavily concentrated in flood-prone areas such as Hancock and Winnebago counties. Given the sector’s reliance on fewer facilities, any flood-induced disruptions could disproportionately impact Iowa’s poultry production, causing ripple effects in the state’s food supply chain and market stability.

Operation types and size further influence the level of vulnerability. Open feedlots and combined operations are particularly exposed, especially in flood-prone areas. Open feedlots, due to their large spatial extent, are at greater risk of direct flood damage, while combined operations face compounded risks related to waste management and infrastructure. Larger CAFOs, predominantly located in the northwestern part of the state, are more vulnerable due to the scale of their operations, which increases the potential for significant economic losses during flood events by simultaneously affecting more livestock and infrastructure.

Medium and smaller CAFOs in central Iowa are increasingly at risk as flood exposure expands to these regions. Low-lying terrains and poorly permeable soils, such as clay loams, can contribute to greater surface runoff and reduced infiltration during heavy rainfall (Cruse et al., 2006). Agricultural intensification, characterized by widespread row cropping and reduced vegetative cover, can exacerbate soil erosion and compaction, further diminishing water retention. Urban expansion has also disrupted natural drainage systems, amplified runoff volumes and increased localized flooding risks (Schilling & Helmers, 2008). Additionally, climate change has intensified precipitation events, expanding flood extents and threatening agricultural infrastructure (Mallakpour & Villarini, 2015). These combined factors can underscore the heightened vulnerability of CAFOs in central Iowa, necessitating targeted mitigation strategies to address these evolving challenges.

A key finding of this study is the heightened vulnerability of older CAFOs, particularly those constructed before 2004, which may be less equipped to manage modern flood risks. Newer CAFOs, built between 2005 and 2024, may incorporate improved engineering standards that enhance resilience; however, many of these facilities are still located in flood-prone areas. This suggests that while advancements in construction practices can improve structural robustness, the issue of facility location within high-risk zones remains a persistent challenge. Both older and newer CAFOs could face potential economic losses due to flood events, including infrastructure damage, livestock loss, increased recovery expenses, and elevated insurance costs. This highlights the ongoing need for strategies that consider both structural improvements and floodplain management to mitigate these risks effectively.

The vulnerability of different livestock sectors is a critical aspect of this study. The cattle and swine industries, concentrated in northern and northwestern Iowa, are particularly at risk. Any significant flood event could lead to widespread economic disruption, not only for the farms but also for the surrounding communities that rely on these industries for employment and economic stability. The poultry sector, though smaller, faces similar risks, and any disruption could have far-reaching consequences for Iowa's food production and pricing stability. These sector-specific risks underscore how deeply interconnected flood exposure is with economic outcomes, especially in regions where agriculture forms the backbone of the economy.

Additionally, the study identified challenges with CAFOs data accuracy, which complicates reliable flood risk assessments. To improve future evaluations, it is essential to enhance the precision of CAFO occupancy data in DNR databases. Leveraging advanced technologies for the identification and analysis of CAFO locations could significantly enhance the accuracy of flood risk assessments. These technological advancements have the potential to play a pivotal role in the development of more effective flood risk management strategies, ultimately contributing to the improved protection of Iowa's agricultural infrastructure.

In conclusion, this study emphasizes the growing flood risk faced by Iowa's CAFOs and the urgent need to recognize the broader economic implications of this exposure. Flood events pose significant risks not only to the operations themselves but also to the state's agricultural economy, affecting livestock production, employment, and food supply chains. With increasing frequency and intensity of extreme weather events, it is essential for future research to refine spatial data accuracy, improve site planning, and develop adaptive strategies that enhance CAFO resilience. Addressing flood risk through better-informed policies, rigorous zoning regulations, and sector-specific interventions will be critical for ensuring the long-term viability of Iowa's livestock industry and its vital contributions to the state's economy. Future efforts should focus on integrating advanced technologies such as Geographic Information Systems for precise flood risk mapping, promoting adaptive infrastructure designs, and fostering collaboration between policymakers, industry stakeholders, and environmental scientists to develop sustainable and scalable solutions.

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