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Fragility in the U.S. Egg Sector: Lessons from the HPAI Outbreaks

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Abstract

Recent outbreaks of Highly Pathogenic Avian Influenza (HPAI) revealed fragility in the U.S. egg sector. Outbreaks that began in 2014 and 2022 have impacts beyond the immediate biological shock, as unintended consequences expose how an industry built for maximum efficiency can amplify risk when crisis strikes. This paper argues that it is not the disease alone but the organization of production that can transform outbreaks into systemwide disruptions. A suite of policy measures, both preemptive and reactive, may offer a path forward to reducing fragility without compromising economic efficiency or market stability.

Keywords: economic efficiency, highly pathogenic avian influenza (HPAI), supply chain, systemic fragility

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Introduction

Animal disease outbreaks are a growing concern for food security and agricultural markets. They are no longer rare disturbances but recurring stress tests for how food systems respond under pressure. Animal pathogens impose costs well beyond immediate production losses, often triggering trade disruptions, shifts in consumer behavior, and policy actions that reshape entire supply chains (McElwain and Thumbi, 2017). Highly Pathogenic Avian Influenza (HPAI) is particularly disruptive, not only because of the biological severity, but also because of its frequency and capacity to disrupt markets (Myles, Hood, and Allen, 2009). Supply chain design, market structure, and the availability of coordinated policy tools ultimately affect whether an outbreak is swiftly contained or cascades into a nationwide emergency (Craighead, Ketchen Jr., and Darby, 2020; Choudhury et al., 2023).

In the United States, the 2014–2015 and 2022–2025 HPAI outbreaks have been among the most economically significant animal health events in recent history. The 2014–2015 epidemic resulted in the culling of approximately 50 million commercial birds, primarily in layer and turkey operations, and imposed an estimated $3.3 billion in direct and indirect economic losses across the production, trade, and consumer sectors (USDA-APHIS, 2016; Ramos, MacLachlan, and Melton, 2017; Zhao, Lee, and Saghaian, 2019).

Although surveillance systems and response protocols were strengthened following that episode, the outbreak that began in 2022 was even more disruptive, with cumulative detections surpassing 150 million birds by early 2025, affecting layers, broilers, and turkeys, and becoming the most geographically widespread HPAI outbreak on record (Schnirring, 2025; USDA-APHIS, 2025). Again, these production shocks were accompanied by significant market disruptions. The national average retail price of Grade A large eggs rose from $1.93 per dozen in January 2022, before the onset of the outbreak, to $4.82 per dozen in January 2023, reflecting the sharp contraction in supply caused by widespread flock losses and the biological production lags that delay recovery after depopulation (USDA-ERS, 2023; Mitchell, Thompson, and Malone, 2024). Although prices eased slightly in the months that followed, they remained elevated at around $4.15 per dozen by December 2024, suggesting that supply conditions had yet to fully normalize (USDA-ERS, 2024). Similar pressure was observed upstream: Midwest wholesale quotations for large, white, shell eggs delivered to warehouses in the major Midwest production region increased to $7.81 per dozen in the week of February 14, 2025, compared with $3.21 per dozen in the week of February 16, 2024, indicating continued tightness in monitored terminal markets (USDA-AMS, 2024, 2025).

Media reporting often focused on the escalating prices and offered a view of how price volatility manifested at the consumer level. For example, Reuters noted that average retail prices reached $4.95 per dozen in January 2025, with some urban markets, such as Chicago, seeing spikes as high as $8–$10 per dozen, while wholesale prices were simultaneously setting new records (Polansek and Douglas, 2025). CBS reported instances of retailers limiting customer purchases in response to tightening availability (CBS News, 2025).

We argue that the disruptions caused by HPAI are not simply the result of the biological nature of the virus but are amplified by structural and institutional features embedded within the supply chain itself. Decades of consolidation and efficiency-oriented investment have produced a system that is exceptionally good at supplying large volumes of affordable eggs. Yet that same efficiency has come at the cost of flexibility, allowing localized outbreaks to cascade into a broader market crisis when major disease outbreaks occur.

To understand why some systems bend while others break, we draw on systems theory, supply chain resilience literature, and lessons from both the 2014–2015 and 2022–2025 HPAI outbreaks. The goal is not to evaluate or critique the industry's efficiency, but to explore factors that unintentionally magnify risk and to suggest policy options that may increase system resilience while still preserving economic efficiencies.

Structural Fragility

Vulnerability to disease outbreaks in the food sector is often framed narrowly as a technical or epidemiological issue. Yet, vulnerability lies not only in the biology of the disease, but also in the interconnections that bind the system together. Supply chain fragility arises when a system cannot absorb or adapt to disruption while maintaining its essential functions (Christopher and Peck, 2004), a view echoed by resilience theory (Walker et al., 2004; Tendall et al., 2015). The question, then, is not simply whether the system can prevent a shock but whether it can endure one without unraveling. Cascade risk is a central concept in evaluating fragility; it refers to the phenomenon in which a failure in one part of a tightly coupled system triggers a chain of failures elsewhere, amplifying the original disruption (Pescaroli, Suppasri, and Galbusera, 2024; Zhu et al., 2025). Tightly coupled systems are inherently prone to cascade risk, as sequential and interdependent tasks leave minimal room for local adaptation or autonomous decision making.

Yet, maximizing economic efficiency often leads to highly integrated supply chains and geographic clustering (Shambaugh et al., 2018). While full-capacity production, minimal surplus inventory, and reliance on a narrow set of suppliers reduce costs, they also leave little room to recover from an interruption. A disruption in one node, such as a disease outbreak or transportation halt, can spread rapidly across the network. Systems engineered for maximum efficiency tend to become brittle under crisis or unexpected conditions (Holling, 2001). In systems theory, high-density geographic clustering reduces the "modularity" of the network, or the ability to isolate and contain shocks before they spread. When all the pieces of a network are tightly bound together, a local outbreak ceases to be local.

Organizational structures and policies that once offered a comparative advantage can unintentionally introduce fragility (Rotz and Fraser, 2015; Li et al., 2025). For example, contracts that standardize pricing and delivery under stable conditions can limit adaptive capacity in crises when supply chains need to adjust operations quickly (Leibler, Otte, and Silbergeld, 2008). A single bottleneck, whether a temporary labor shortage, equipment malfunction, or localized disease outbreak, can ripple outward, affecting production schedules, transportation logistics, and ultimately retail availability. These structural characteristics make disruptions disproportionately

impactful, highlighting that operational efficiency alone cannot safeguard against systemic risk. Likewise, while improved digital tools enhance coordination within a supply chain, technology alone does not make a system resilient. Digitalization strengthens performance only when combined with adaptive capacity and recovery mechanisms (Zhao, Hong, and Lau, 2023). Tools such as dashboards and automated alerts are useful only if decision makers can respond and act flexibly.

Fallback options and diversified sourcing strategies are critical for supply chain and market recovery during a crisis (Mishra and Jha, 2024). Trade-offs between efficiency and fragility illustrate a fundamental tension in supply chain design (Lucker, Timonina-Farkas, and Seifert, 2025). Ultimately, resilience is not just about eliminating risk but also about organizing interconnections so that failure in one part of the system does not collapse the whole. Building redundancy and taking preemptive actions in a supply chain, once dismissed as inefficient, can function as insurance for resilience in an era of disruption.

This dynamic has been widely examined in supply chain and systems research. A growing body of literature shows that efficiency-oriented designs often trade long-term robustness for short-term cost savings (Hohenstein et al., 2015; van Staveren, 2023). Investments in resilience, such as inventory buffers or supplier diversification, frequently reduce measurable efficiency (Berendes et al., 2025), even as lean optimization strategies tend to limit adaptive capacity under stress (Markolf et al., 2022). Resilience-enhancing strategies, including fallback systems and modular logistics, can improve disruption response but often come at the cost of short-run performance in tightly synchronized systems (Ivanov and Dolgui, 2020).

Supply Chain Organization in the U.S. Egg Sector

The U.S. egg industry offers a clear illustration of the trade-off between efficiency and resilience: a sector engineered for speed, scale, and cost minimization that is increasingly exposed to systemic disease risk. Tight vertical integration and geographic concentration have long characterized the industry (Martinez, 2002). A small number of vertically integrated firms manage nearly every stage of production. In 2023, Cal-Maine Foods and Rose Acre Farms alone accounted for 13.8% and 7.9% of U.S. table-egg layers, with approximately 44.5 million and 25.5 million hens, respectively (USDA-NASS, 2023; Dawson, 2024). Their operations extend from pullet rearing and feed manufacturing to egg processing, packaging, and nationwide distribution. This structure delivers substantial efficiency gains through economies of scale, tight coordination, and standardized biosecurity, keeping unit costs low under normal operating conditions.

However, the same features that enhance efficiency also limit flexibility when disruptions occur. Highly integrated operations reduce modularity, making it difficult to isolate risks without affecting the entire network. HPAI outbreaks have exposed this fragility (Mitchell, Thompson, and Malone, 2024). Entire vertically integrated supply chains were idled not because all facilities were infected but because biosecurity protocols required shutting down interconnected components across the system. Even the largest integrators were unable to fully insulate their operations despite extensive in-house veterinary, compliance, and logistics capacity. In tightly coupled systems,

shocks propagate rapidly through shared infrastructure and contractual linkages, transforming localized disease events into systemwide disruptions.

Contractual arrangements within the U.S. egg supply chain designed to maximize economic efficiency can exacerbate fragility. Fixed-volume, fixed-price contracts between the wholesale and retail stages provide stability under predictable conditions but restrict adaptive responses during crises. When flock losses occur, producers may be unable to meet contractual volumes, triggering financial penalties, strained buyer relationships, and logistical breakdowns. Independent producers, even when geographically distant from outbreaks, often lack the scale, certifications, or contractual access needed to replace lost supply. Similarly, just-in-time logistics systems minimize inventory holding costs and improve efficiency in stable periods, but they leave little room for rerouting or scaling when disruptions arise. Thin buffers, limited transportation alternatives, and tightly synchronized schedules erode shock-absorbing capacity, increasing the likelihood of cascading failures (Gereffi, 2020; Mu, van Asselt, and van der Fels-Klerx, 2021).

Automation and digital systems are used within vertically integrated supply chains but leave little room for industry-wide coordination and are not designed for adaptive response. Large integrators have invested heavily in proprietary automation, inventory tracking, and centralized control systems to enhance efficiency and coordination (Martinez, 2002). Yet these technologies introduce new dependencies on specialized labor, software, and technical infrastructure. Equipment malfunctions or personnel shortages can halt entire production lines, particularly in facilities without redundancy or manual fallback systems. Automation is less prevalent among midsized producers, where cost and technical complexity limit access to integrated platforms (Caputo et al., 2023). While some smaller firms may adjust operations more nimbly at the farm level, their adaptive capacity rarely extends across the broader supply chain.

Spatial organization further amplifies systemic risk. U.S. poultry production is heavily concentrated in the Midwest. In 2024, three states—Iowa, Ohio, and Indiana—accounted for roughly 32% of the national flock (USDA-NASS, 2025). This clustering emerged for sound economic reasons, including proximity to corn and soybean feed supplies, established transportation corridors, and dense producer networks (MacDonald, Dong, and Fuglie, 2023). Yet this spatial efficiency has proven fragile under disease pressure. During the 2014–2015 HPAI outbreak, Iowa alone lost more than 30 million birds, nearly 70% of national losses (USDA-APHIS, 2016). What began as a regional shock quickly rippled through national markets, ultimately affecting over 48 million birds (Greene, 2015). Subsequent analyses confirmed that geographic concentration magnified these impacts, as localized depopulation cascaded into national supply shortages and price spikes (Ramos, MacLachlan, and Melton, 2017). Similar patterns re-emerged during the 2022–2025 outbreak, with the densest production regions again experiencing the earliest and most severe losses (Biondo, 2025).

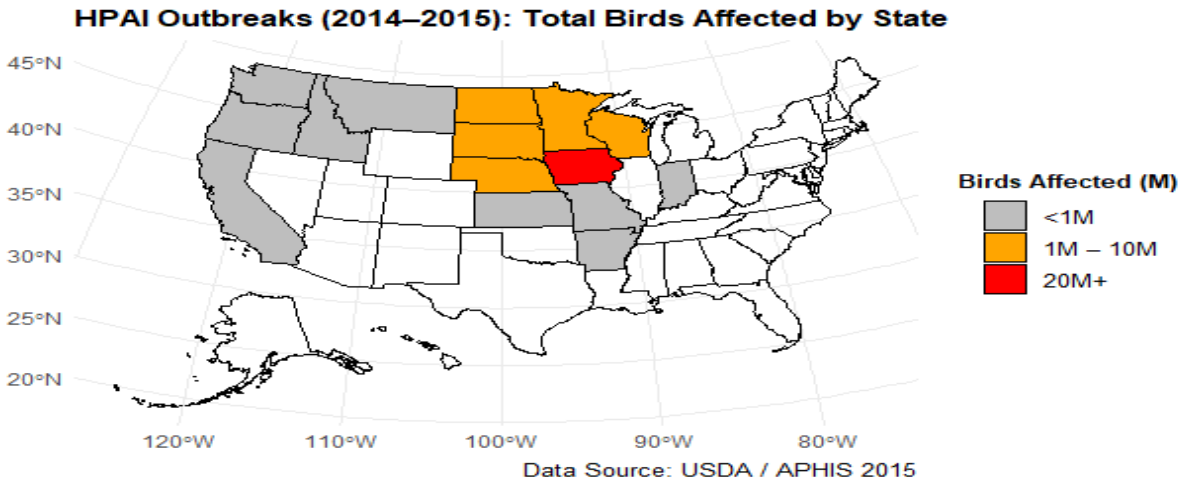


Figure 1. Geographic Distribution of Bird Losses during the 2014–2015 HPAI Outbreak in the United States

Clustering across poultry species heightens cascade risk. In states such as Iowa and Minnesota, layer farms are often located near turkey and broiler operations, increasing opportunities for cross-species transmission. Mixed-species proximity can sustain viral circulation and prolong outbreaks (Torremorell et al., 2016). Shared service providers, including feed mills, manure haulers, equipment suppliers, and contract labor crews, create additional organizational linkages that function as hidden transmission pathways. Reviews of the 2014–2015 outbreak found that shared equipment, vehicle movement, and personnel contacts materially contributed to farm-to-farm spread (USDA-APHIS, 2016). Although wild birds were identified as primary carriers during the 2022–2025 outbreak, lapses in biosecurity and equipment handling played a role in amplification (Patyk et al., 2023).

High-density production can constrain response logistics once outbreaks occur. In heavily affected regions, depopulation crews, composting capacity, and carcass disposal sites are often limited. During the 2014–2015 outbreak, these constraints delayed culling and disposal in several counties, prolonging viral circulation and compounding economic losses (USDA-APHIS, 2016). The result is a recurring feedback loop: the same density that improves efficiency during normal operations generates congestion and bottlenecks during crisis response.

Finally, demand-side conditions magnify the consequences of supply-side fragility. Eggs are a household staple with relatively stable demand, meaning supply disruptions translate quickly into price volatility. Panic buying and retailer adjustments can amplify price volatility further (Bakhtavoryan et al., 2021; Zamani, Bittmann, and Ortega, 2024). USDA and BLS data show sharp increases in national average egg prices during both the 2014–2015 and 2022–2025 HPAI outbreaks, closely tracking periods of large-scale depopulation and production loss (see Figure 2).

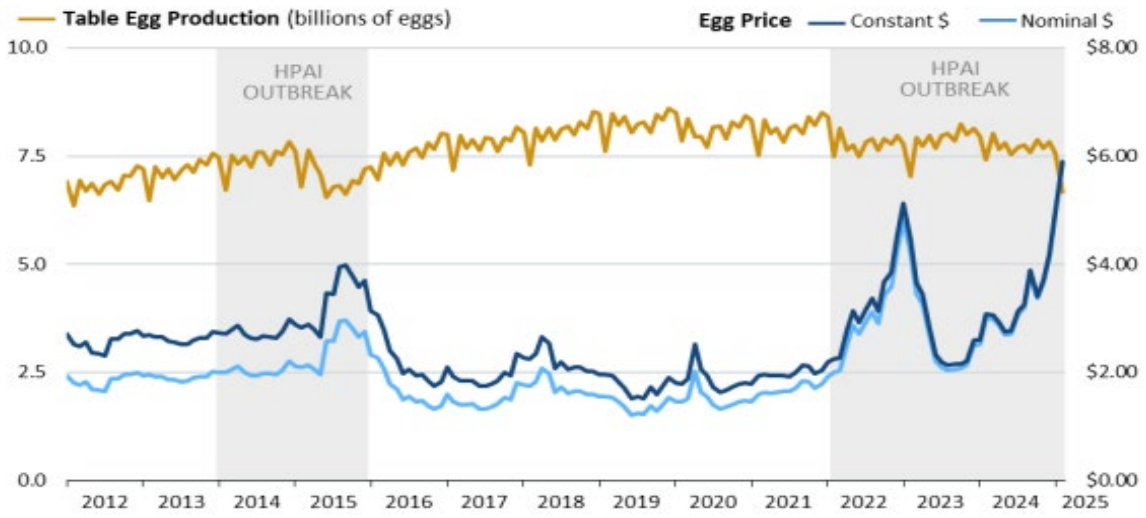


Figure 2. U.S. Table Egg Production and Retail Prices, 2012–2025
Source: Biondo (2025)

Poultry Health Governance in the United States

Poultry health governance in the United States is organized around a policy framework that combines preventive measures, such as biosecurity standards, disease surveillance, and certification programs, with reactive outbreak response tools, including depopulation, movement controls, and indemnity payments (USDA-APHIS, 2015). Federal oversight is led by USDA-APHIS in coordination with state animal health authorities and industry actors. This framework has evolved through repeated disease shocks and reflects both the biological realities of poultry production and the institutional structure of U.S. animal health governance. While the system has been effective at limiting catastrophic collapse during major HPAI events, it remains heavily oriented toward managing outbreaks after detection rather than preventing localized shocks from escalating into systemwide disruptions.

The National Poultry Improvement Plan (NPIP) is central to existing **preemptive measures**, providing standardized testing, monitoring, and biosecurity certification that underpins interstate and international poultry trade (USDA-APHIS, n.d.; USDA-APHIS, 2016). These efforts are complemented by federal and state surveillance programs that monitor commercial flocks, backyard poultry, and wildlife reservoirs, reflecting long-standing recognition of migratory pathways as persistent sources of HPAI risk.

Despite this foundation, preventive capacity is unevenly distributed across the production landscape. Participation in NPIP and compliance with enhanced biosecurity and reporting requirements are closely tied to firm size, vertical integration, and access to veterinary and administrative resources. Large, vertically integrated operations typically possess the infrastructure needed to comply continuously with surveillance and documentation standards,

whereas small and mid-scale producers, including independent growers and regional suppliers, often face financial, informational, and administrative barriers (Leibler, Otte, and Silbergeld, 2008; GAO, 2017). These disparities create gaps in surveillance coverage and preparedness, limiting the ability of preventive instruments to operate uniformly across a highly concentrated and tightly coordinated industry.

Once disease is detected, governance shifts decisively toward a **reactive response**. USDA-APHIS and state partners implement movement restrictions, depopulation orders, disposal protocols, and emergency biosecurity measures to contain spread and stabilize markets (USDA-APHIS, 2016). Indemnity and compensation mechanisms are intended to support compliance with these measures, but access is conditioned on extensive documentation, verified flock inventories, and proof of biosecurity compliance under VS Guidance 8603.2 (USDA-APHIS, 2023). In December 2024, APHIS further strengthened these requirements by conditioning indemnity payments and restocking approvals on verified biosecurity audits under the Secure Poultry Supply Plan (USDA-APHIS, 2024). While large operations routinely manage these requirements with dedicated compliance staff, smaller producers often experience delays that complicate recovery and, in some cases, force permanent exit from production.

Reviews of past outbreaks have also documented coordination challenges between federal and state agencies and weaknesses in emergency logistics, including deficiencies in the National Veterinary Stockpile (GAO, 2017; USDA-OIG, 2020). These governance frictions are not merely administrative; they directly affect the speed, consistency, and effectiveness of outbreak response in highly integrated supply chains, where delays or uncertainty can amplify both economic and epidemiological impacts (Kalaitzandonakes and Ridley, 2025).

Preemptive Policy Options

As recent outbreaks demonstrate, existing baseline prevention and response measures have not prevented localized shocks from cascading through tightly coupled supply chains. Resilience increasingly depends on policies that act before exposure or at the point of exposure (i.e., preemptive), rather than after outbreak detection (i.e., reactive). Preemptive policy approaches differ from baseline prevention in that they are designed to anticipate failure and reduce the likelihood that localized disease events escalate into systemwide disruption. These measures seek to preserve production continuity while maintaining disease control. Such approaches have been implemented in varying forms in other poultry-producing countries and are now under active consideration in the United States (Swayne, 2024). The following sections examine four preemptive policy options and assess their relevance within the structural constraints of the U.S. poultry sector.

Vaccination As a Risk Mitigation Strategy

Vaccination is a core disease-control tool in animal health, designed to reduce susceptibility, viral shedding, and onward transmission within and between hosts. In the context of HPAI, vaccination does not eliminate the risk of viral introduction from wildlife reservoirs, but it can lower outbreak

intensity, shorten transmission chains, and reduce the scale of depopulation required once exposure occurs. Despite its widespread use in many livestock systems globally, vaccination against HPAI has historically been approached with caution in the United States (Cohen, 2023), largely based on operational and governance concerns.

Large-scale vaccination programs require coordinated deployment, repeated administration, and continuous monitoring, all of which increase labor demand and program complexity. In addition, vaccine performance can vary across poultry species and production systems, and effectiveness depends on the match between vaccine strains and circulating viruses. Recent advances in vaccine technology have substantially improved performance against contemporary HPAI strains. However, protection duration and immune response vary by species, production stage, and vaccine platform, making adaptive program design essential. These challenges underscore the need for vaccination strategies that are tightly integrated with surveillance and biosecurity rather than implemented as standalone interventions. Rising economic losses from repeated outbreaks, improvements in vaccine design, and growing awareness of zoonotic spillovers have renewed policy interest in vaccination as part of a broader risk-management portfolio (Ison and Marrazzo, 2024).

These biological realities reinforce a key lesson from prior experience: vaccines are only as effective as the institutional systems that deploy, monitor, and calibrate them. Early national vaccination efforts in Egypt reduced clinical disease but struggled with antigenic mismatch and limited monitoring capacity, allowing the virus to persist in backyard and rural production systems (Peyre et al., 2009). By contrast, Vietnam achieved more durable control by pairing vaccination with routine surveillance and systematic program adjustment in response to outbreak feedback (Tran et al., 2016). Vaccination outcomes can depend less on the act of immunization itself than on how it is embedded within governance, surveillance, and response frameworks.

More recent evidence comes from the 2023–2024 HPAI vaccination campaign targeting domestic ducks in France. A nationwide program was implemented to combine mass vaccination with enhanced epidemiological surveillance. As shown in Figure 3, poultry outbreaks declined sharply immediately after the campaign's launch in October 2023 (Panel A), even as detections of HPAI in wild birds remained high throughout the same period (Panel B). Observed poultry outbreaks fell far below levels predicted by models calibrated on historical wild-bird and poultry data (Panel C), suggesting that vaccination effectively disrupted transmission within domestic flocks. France experienced substantially fewer outbreaks than neighboring non-vaccinating countries facing similar ecological conditions during the same season (Panel D) (Guinat et al., 2025). These patterns indicate that vaccination can decouple exposure from outbreak escalation when deployed at scale and supported by surveillance.

The French experience does not imply that vaccination eliminates HPAI risk, but it demonstrates how immunological barriers can limit repeated introductions from cascading into widespread production losses. For U.S. policy makers, the relevance lies not in replicating any single national model, but in recognizing vaccination as a preemptive tool that can limit the magnitude and

persistence of outbreaks. Vaccination complements existing biosecurity and response measures by reducing systemic vulnerability rather than replacing established controls.

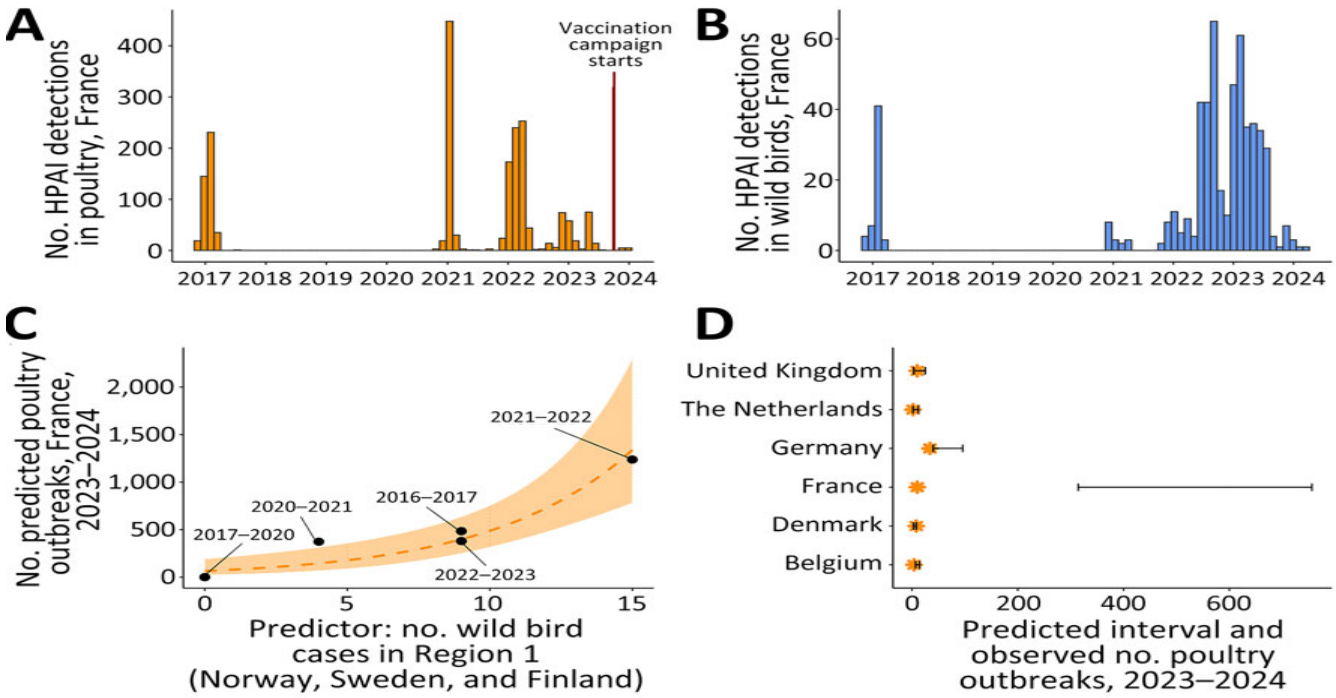


Figure 3. Outcomes of France's 2023–2024 HPAI Vaccination Campaign
Source: Guinat et al. (2025)

(A) Sharp decline in poultry outbreaks after vaccination.
(B) Wild bird cases remained high, indicating ongoing exposure.
(C) France's outbreak count fell well below model predictions based on regional wild bird data.
(D) France outperformed five non-vaccinating countries in outbreak reduction.

Compartmentalization and Supply Chain Continuity

Compartmentalization refers to animal health governance that defines disease-free status not by geography, but by how production systems are organized and managed. Recognized by the World Organization for Animal Health, a compartment is an epidemiologically distinct production unit that operates under a common set of biosecurity, surveillance, and traceability standards, allowing it to maintain continuity even when outbreaks occur elsewhere (WOAH, 2024). If disease risk is generated through management practices and network connections, then control measures should reflect those realities rather than rely solely on spatial boundaries (WOAH, 2000).

In theory, compartmentalization offers a way out of the all-or-nothing response that characterized early HPAI control efforts. Instead of shutting down entire regions or supply chains when infection is detected, certified compartments can continue operating under heightened monitoring, limiting

unnecessary disruption. This practice is particularly appealing in highly integrated food systems, where blanket movement restrictions can trigger cascading failures far beyond the original outbreak site.

European experience highlights both the promise and the limits of this approach. During recent HPAI outbreaks, France paired vaccination with compartment-based trade arrangements within the EU, allowing certified units to maintain market access despite widespread infection pressure (Guinat et al., 2025). These outcomes were not the product of compartmentalization alone, but of sustained investment in surveillance, regulatory coordination, and trust between public authorities and industry. Replicating such arrangements in the United States would require confronting long-standing fragmentation across federal and state jurisdictions, as well as uneven capacity among producers.

In early 2024, United Egg Producers endorsed the creation of pilot vaccination zones in high-risk states, implicitly raising questions about whether compartment-like structures could reduce reliance on mass depopulation in a consolidated but geographically dispersed system (United Egg Producers, 2024). These proposals do not yet amount to a coherent compartmentalization framework, but they reflect growing interest in alternatives to geographically indiscriminate shutdowns as outbreaks become more frequent.

Rather than a standalone policy, compartmentalization should be understood as a selective tool for managing spillovers in tightly coupled systems. Its value lies not in preventing exposure outright, but in limiting how far disruption spreads once exposure occurs. Whether it ultimately strengthens resilience in the U.S. poultry sector will depend less on formal recognition than on how deliberately it is designed to work within and across existing supply chains.

Surveillance Systems

Early detection and sustained monitoring are central to preemptive disease governance because they determine whether outbreaks remain localized or cascade through tightly coupled production systems. Surveillance platforms enhance resilience not by eliminating risk, but by enabling timely coordination, targeted containment, and informed fallback decisions. When embedded within governance frameworks that link diagnostics to compartmentalization, compensation, and movement controls, surveillance becomes a preemptive instrument rather than a purely reactive one. Surveillance systems can also underpin reactive policies once outbreaks occur, enabling movement controls and depopulation measures to function as coordinated interventions rather than isolated responses. In vaccinated populations, surveillance capacity becomes especially critical, as diagnostic systems must distinguish vaccine-induced immunity from active infection to preserve epidemiological visibility (DVFA, 2022).

A recent global expert review emphasized that vaccination against HPAI is only effective when paired with robust, science-based surveillance systems capable of detecting virus circulation in vaccinated flocks (Sajjadi et al., 2025). Surveillance system performance depends on coordinated reporting across producers, laboratories, and regulatory authorities (Hoinville et al., 2013). In

practice, surveillance data are often distributed across multiple organizational and regulatory actors, and their usefulness depends on whether reporting systems allow diagnostic findings to be rapidly translated into operational awareness and intervention (Meidenbauer, 2017).

In the United States, surveillance capacity remains unevenly distributed across firms and jurisdictions. Access to diagnostic tools, reporting platforms, and real-time data sharing varies widely, and proprietary systems often operate in silos, delaying detection and complicating a coordinated response (Meidenbauer, 2017). These gaps limit the ability of surveillance to function as a systemwide early warning mechanism, particularly in a highly consolidated industry where delays in one segment can rapidly propagate through national supply chains.

Comparative experience demonstrates that surveillance effectiveness depends less on the volume of data collected than on institutional integration. European animal health governance emphasizes interoperable databases, standardized alert thresholds, and clear reporting hierarchies, reducing coordination delays during transboundary livestock emergencies (EC, 2021; EC, 2025). In the Netherlands, surveillance operates under One Health principles that integrate veterinary, environmental, and public health actors within a unified national framework (Royal GD, n.d.; WOAH, 2000). As a result, an estimated 98% of poultry outbreaks are detected through active surveillance rather than passive reporting, substantially improving response speed and containment effectiveness (Vredenberg et al., 2025).

Surveillance platforms also enable differentiated and less disruptive response strategies. Tools such as digital animal identification, movement tracking, and geofencing support risk-based interventions that prioritize high-transmission nodes rather than relying on blanket depopulation (te Beest et al., 2011). In this way, surveillance creates functional redundancy by preserving operational flexibility and allowing production continuity in lower-risk segments, even during periods of elevated disease pressure.

Recent U.S. policy developments indicate growing recognition of these principles. Updated USDA-APHIS surveillance guidance for poultry shipments, effective August 2025, strengthens premovement testing requirements by introducing short isolation periods and tighter testing timelines prior to slaughter. These measures aim to reduce the risk of moving infected but asymptomatic birds, particularly from states outside designated control zones, and to align indemnity eligibility with verified surveillance compliance (Fairman, 2025). While these updates do not constitute a fully integrated national surveillance platform, they signal a shift toward more proactive, risk-based monitoring consistent with international best practices.

Small and Mid-Scale Producer Support

Strengthening poultry biosecurity requires active participation from producers of every size. In practice, policy options are inseparable from questions of who can realistically participate. While the U.S. egg sector is concentrated among larger operations, thousands of small and mid-scale farms remain essential to rural livelihoods and local food networks. Enhancing long-term system resilience will depend on the ability of all producers to meet the new standards. Smaller operations

often exist at the edges of official surveillance systems, creating epidemiological "blind spots" where HPAI can circulate undetected (Otte et al., 2007). Effective national preparedness must therefore ensure that no segment of the production chain is left out of early warning and response systems.

In the United States, flocks with more than 30,000 birds account for approximately 80% of all laying hens nationwide (USDA-NASS, 2025). While the majority of production is concentrated in these large operations, almost 20% remain in smaller flocks. Simplified indemnity claim forms, mobile-friendly reporting systems, and smallholder response funds could make participation easier for these producers. Cooperative models could further strengthen resilience by allowing farms to share diagnostic costs, coordinate vaccination efforts, and access veterinary extension services that would otherwise be unaffordable individually.

Several states have pioneered outreach initiatives aimed specifically at small and noncommercial poultry keepers. The University of Minnesota Extension, for example, provides bilingual biosecurity workshops and easy-to-use resources for small flock owners (University of Minnesota Extension, 2023). In California, the Department of Food and Agriculture (CDFA) and the California Animal Health and Food Safety Laboratory (CAHFS) jointly operate programs such as Backyard Biosecurity for Poultry and Necropsy Services for Backyard Poultry Owners. These programs provide free or low-cost diagnostic testing, educational materials, and practical tools to improve on-farm biosecurity (CDFA, n.d.; CAHFS, 2024). Such initiatives demonstrate that accessibility and trust, not merely enforcement, are key to achieving broad compliance.

International experience reinforces this lesson. Denmark maintains one of Europe's most comprehensive surveillance systems, requiring all holdings with more than 100 birds to participate in risk-based testing. This mandate is coupled with support for compliance, including mobile veterinary training units and public funding for essential biosecurity improvements (DVFA, 2022). France and the Netherlands also extend targeted support and training for smallholders, while the European Food Safety Authority continues to promote cooperative models that combine technical and financial assistance for backyard producers (EFSA, 2023). These programs recognize that risk mitigation succeeds only when the smallest producers are equipped to meet standards that are practical and proportional to their capacity.

Conclusions

The extent of HPAI impact on U.S. egg markets cannot be explained by biology alone. The way an industry is organized plays a defining role in how far and fast economic and physical disruptions spread. Recurrent HPAI outbreaks have exposed systemic fragility in the U.S. egg sector and have shown that the system is calibrated for maximal efficiency under normal conditions but becomes acutely fragile in the face of shock. Tight supply chains, geographically concentrated production, and limited inclusion of smaller flocks have created a system that is highly efficient but brittle in times of crisis. The consequences of failure extend far beyond the farm, affecting prices, supply chains, and public confidence.

Ultimately, resilience is not only about eliminating risk but also about how interconnections are organized. Systems designed for speed and tight coordination perform well under stable conditions, but when shocks occur, those same linkages allow disruptions to spread rapidly. As shown earlier, digital tools and automation can improve visibility and coordination, yet they do not, on their own, prevent cascading failure. In this sense, redundancy and optionality are not signs of inefficiency, but structural features that determine whether disruptions remain localized or escalate into systemwide crises.

The revealed weaknesses, however, are not inevitable and may be, at least partially, mitigated through a broader national policy approach that shifts from a predominantly reactive stance to one that expands preventive capacity. The scale and persistence of HPAI outbreaks indicate a need to expand preemptive policies along with reactive containment strategies to manage and respond to disease risk. Regulatory adjustments have signaled a shift toward stronger preventive accountability. Comparative lessons from global markets offer examples of how coordinated, inclusive, and evidence-based strategies might help mitigate epidemic risks. Maintaining economic efficiency that supports low pricing in the egg sector is critical for consumers. But unintended consequences of system fragility suggest a balance is needed. Building on world-class scientific expertise, technological capacity, and institutional reach, policy adjustments could blend preemptive and reactive policies to make disease control less destructive, while still preserving efficiencies and market access.

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