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Veterinary Surveillance at the Human–Animal–Environment Interface: An Integrative Review of Zoonotic Early Warning, Data Integration, Biosurveillance, Interoperability, Cross-Sector Governance, and Coordinated Response, 2017–2025

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ABSTRACT

Zoonotic threats emerge across linked human, domestic-animal, wildlife, and environmental systems, yet surveillance remains frequently partitioned by sector, data structure, laboratory pathway, and authority. This integrative review examines how veterinary surveillance can contribute to earlier and more interpretable warning when signals must move across those boundaries. Evidence was selected from peer-reviewed literature published during 2017–2025 using an explicit integrative strategy that separated empirical surveillance evaluations, system descriptions, methodological frameworks, governance evidence, and review-level synthesis. The search identified 79 records; after removal of 12 duplicates, 67 were screened, 52 underwent full-record assessment, and 37 evidence units were included. Across the literature, the principal recurring problem was not absence of surveillance data alone but failure to connect signal generation with interoperable data structures, verification, contextual interpretation, and coordinated decisions. Animal-health, wildlife, environmental, laboratory/genomic, and digital streams each capture different facets of risk and differ in ascertainment, timeliness, representativeness, and transferability. Their combination therefore cannot be assumed to improve warning merely by increasing data volume. The review develops a proposed distinction between signal availability, signal interpretability, verified warning, and actionable cross-sector response. It also identifies governance, shared data semantics, laboratory linkage, feedback, and reassessment as necessary system properties for testing this distinction. The synthesis is bounded by heterogeneous study designs, uneven geographical representation, variable surveillance maturity, and limited prospective evaluation of integrated architectures. Consequently, the proposed model should be treated as an organizing framework for comparative validation rather than an implementation-ready standard.

Keywords: One Health surveillance, Zoonotic early warning, Veterinary biosurveillance, Environmental surveillance, Interoperability, Genomic epidemiology

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Introduction

Veterinary surveillance increasingly operates at interfaces where animal disease, human exposure, wildlife ecology, environmental contamination, and pathogen evolution intersect. A central limitation is that these domains are often observed through separate institutions, reporting rules, laboratories, and data systems. Contemporary One Health scholarship therefore frames surveillance as a cross-sector activity requiring collaboration and integration rather than as parallel sectoral programs [1–3]. That framing is important, but integration itself is not an outcome: surveillance systems differ in objectives, participating sectors, data availability, and the decisions they are designed to support.

Local interface structure further constrains generalization. Network-based analysis of zoonotic interactions in Austria showed that locally contextualized relationships can reveal patterns obscured by broader aggregation [4]. Thus, a signal that is informative in one species assemblage, production system, jurisdiction, or environmental setting may not carry the same meaning elsewhere.

This review examines veterinary surveillance as an evidential and decision architecture. It distinguishes signal generation from verification, data integration from interoperability, detection from actionable early warning, and formal coordination from functioning cross-sector response. The central contribution is a proposed integrated model in which animal, human, wildlife, environmental, laboratory/genomic, and digital inputs remain analytically distinct until their evidential status and decision relevance are assessed.

Review purpose and integrative approach

The review asks how heterogeneous surveillance streams can be combined without erasing the differences that determine what each can legitimately imply. Its approach is integrative rather than meta-analytic: empirical performance studies, system descriptions, methodological frameworks, stakeholder research, and review-level evidence are synthesized according to argumentative role rather than pooled into a common effect estimate.

Three distinctions organize the analysis. Surveillance observation is separated from confirmation; technical connectivity is separated from organizational interoperability; and integration is separated from effectiveness. A syndromic, environmental, genomic, or reporting anomaly is not automatically a verified outbreak, while cross-sector architecture may be conceptually appropriate without demonstrating better public-health outcomes.

The literature is therefore treated as evidence about component functions, constraints, and boundary conditions. Where no general rule is established, the synthesis is explicitly proposed. Particular attention is given to species and setting heterogeneity, reporting sensitivity, temporal lag, resource intensity, governance, and the possibility that additional data may increase ambiguity as well as information.

Evidence scope and source selection

Evidence selection required direct relevance to a defined surveillance function, a verifiable DOI, publication during 2017–2025, and sufficient methodological or contextual detail to bound the planned claim. Multisectoral collaboration was treated as an analyzable organizational and functional property rather than a binary label [5]. Practical adoption was evaluated in relation to collaboration, knowledge exchange, interoperability, and dissemination rather than technology alone [6]. Recent One Health capacity assessments also identified gaps in leadership, harmonized indicators, FAIR data practices, and evaluation of outcomes and costs [7].

The search identified 79 records. Twelve duplicates were removed, leaving 67 records for screening; 15 were excluded. Fifty-two advanced to full-record assessment, none were lost to retrieval, and 15 were excluded, yielding 37 included evidence units. Exclusions reflected unverifiable Q1 eligibility, inadequate domain fit, redundancy after stronger evidence was selected, or insufficient evidence for the intended claim.

Extraction preserved study design, unit of analysis, surveillance modality, data source, validation strategy, implementation context, uncertainty, and transferability limits. No pooled effects or common performance thresholds were imposed across unlike systems.

Evolution of One Health surveillance

The evolution of One Health surveillance is better understood as a widening of relationships than as a linear replacement of conventional veterinary surveillance. Sector-specific systems remain necessary for routine animal-health intelligence, but increasingly sit within broader architectures in which information may be shared across public-health, wildlife, environmental, and laboratory domains. Contemporary formulations emphasize cross-sector collaboration because siloed observation can miss relationships visible only through joint interpretation [1].

Veterinary epidemiology provided an early bridge by emphasizing transdisciplinary collaboration, integrated information, joint priorities, and institutionalization [3]. Later initiatives developed practical infrastructures for knowledge exchange, harmonization, and interoperability across organizations [6]. These developments suggest a shift from surveillance as collection within a sector toward coordinated interpretation across sectors.

The transition is neither uniform nor necessarily progressive. Jurisdictions differ in authority, laboratories, workforce, data standards, and sharing incentives. Older and newer arrangements coexist, and highly integrated structures may still perform poorly when data quality, participation, or response authority is weak. Evolution should therefore be judged by function—what can be detected, interpreted, verified, and acted upon—rather than by a One Health label.

Animal-health surveillance systems

Animal-health surveillance remains the principal veterinary source of structured information on morbidity, mortality, production change, diagnoses, and notifiable disease. Electronic systems can convert clinical observations into a local biosurveillance stream, although usefulness depends on participation, workflow, and the population represented [8]. Digitization may accelerate transmission without correcting who is observed, what is recorded, or whether abnormality is recognized.

At national scale, Kenya's surveillance experience indicates that animal-health systems may support zoonotic detection while remaining constrained by fragmentation, resources, and cross-sector linkage [9]. At international scale, immediate animal-health notifications can characterize reporting and early-warning capacity, but remain conditional on national detection and notification practices [10]. Notification volume should therefore not be interpreted as disease incidence.

Local clinical reporting, national surveillance organization, and international notification serve different evidential purposes. Local data may provide granularity, national systems determine coverage and coordination, and international platforms provide cross-jurisdiction visibility. Their outputs become comparable only after differences in ascertainment, reporting rules, timeliness, and verification are considered.

Human-health surveillance interfaces

A One Health interface is not created merely because animal and human data exist concurrently. The evidential connection depends on whether signals can be linked through place, time, exposure pathway, pathogen identity, or another defensible relation. Cross-sector surveillance is intended to address interdependent threats [1], while locally resolved zoonotic-network analysis illustrates why contextual structure matters when interpreting such connections [4].

For veterinary surveillance, human-health information may corroborate an animal or environmental signal, or alter its consequence when plausible human exposure exists. Neither function means that temporal coincidence establishes transmission. Alternative sources, differential healthcare seeking, diagnostic availability, and surveillance intensity can produce apparently concordant or discordant patterns.

The proposed distinction is between parallel observation and linked interpretation. Parallel observation places sectoral data beside each other; linked interpretation evaluates whether they plausibly describe a shared event or risk pathway. That evaluation requires compatible definitions, temporal resolution, geospatial information, and explicit uncertainty. When these are absent, human and animal signals should remain separate rather than be forced into a single narrative of zoonotic emergence.

Wildlife surveillance

Wildlife surveillance extends the surveillance field into populations with weaker denominator data, routine clinical contact, sampling access, and diagnostic coverage than most domestic-animal systems. Transdisciplinary programs at human–wildlife interfaces demonstrate that integrated field surveillance is operationally feasible [11]. Feasibility, however, does not establish consistently earlier detection or prevention of spillover.

Recent operational framing places wildlife health within explicit veterinary, environmental, and public-health structures rather than treating wildlife detections as an isolated specialist activity [12]. A wildlife signal may arise from mortality events, opportunistic sampling, rehabilitation centers, targeted pathogen studies, or ecological monitoring, each with different selection processes.

Global reporting evidence further shows that observed wildlife events are strongly conditioned by national surveillance sensitivity and recording capacity [13]. Absence of reports cannot therefore be equated with absence of infection or hazard. For integration, wildlife data should retain information on sampling opportunity, species ecology, geographic coverage, and reporting pathway. Wildlife surveillance is consequently treated as a distinct evidence lane whose outputs may corroborate, precede, or complicate domestic-animal and human signals without hiding uncertainty through aggregation.

Environmental surveillance

Environmental surveillance shifts observation from individual hosts toward matrices through which biological material, resistance determinants, or pathogen signals may accumulate, persist, or move. Detection in wastewater, surface water, farm environments, vectors, soil, or other matrices may indicate presence or circulation without identifying the infected source, direction of transmission, or magnitude of clinical risk.

This review proposes three questions before environmental evidence changes a One Health decision: how close is the sample to a plausible biological source; does the signal persist across space, time, or connected ecological compartments; and is there independent animal, wildlife, human, or laboratory information that changes competing explanations? These questions preserve the distinction between environmental detection and confirmed host infection.

Context remains decisive. Locally structured zoonotic interactions caution against assuming that identical environmental observations have identical meaning across settings [4]. Wildlife surveillance similarly shows that detectability depends on surveillance opportunity [13]. Environmental evidence is therefore treated as a contextualizing, potentially anticipatory stream whose evidential weight changes with source attribution and cross-sector corroboration.

Table 1 presents environmental detections arranged by source proximity, ecological connectivity, and corroboration needs.

Table 1. Environmental detections arranged by source proximity, ecological connectivity, and corroboration needs

Environmental question	Source-proximal signal	Connected downstream signal	Wildlife-interface signal	Diffuse unattributed signal
Pathway interpretation	Plausible local shedding/contamination	Possible dissemination	Possible cross-species interface activity	Presence without resolved source
Ecological controls	Species mix; production flow	Hydrology; persistence; wildlife access	Detectability; contact opportunity	Background ecology; multiple contributors
Pattern actually observed	Repeated signal near animal-use point	Signal across linked compartments	Environmental signal plus wildlife observations	Isolated or diffuse detection
Investigation footprint	Targeted veterinary verification	Expand spatial investigation	Coordinate wildlife/veterinary assessment	Continue surveillance; avoid escalation alone
What detection cannot establish	Source animal unresolved	Direction and clinical relevance uncertain	Observation effort may bias meaning	Source and actionability unresolved
Evidence that would reclassify the signal	Link repeat samples to animal/laboratory data	Test source attribution and persistence	Add species-specific sampling	Seek corroboration
Synthesis basis	Proposed	Proposed	Proposed	Proposed

Laboratory and genomic biosurveillance

Laboratory and genomic biosurveillance can increase specificity, characterize relatedness, and extend surveillance beyond conventional clinical case detection. Environmental and wastewater approaches illustrate this broader signal space: environmental sampling can complement established surveillance, abattoir wastewater and surface sampling can recover antimicrobial-resistance information, and treated-wastewater studies show measurable microbiome and resistome differences across connected aquatic compartments [14–16]. These findings support signal generation, not direct inference of individual infection or quantified clinical risk.

Genomic information adds value when sequences, metadata, sampling context, and epidemiological interpretation can be connected. A recent data-integration framework for real-time pathogen surveillance emphasizes partner identification, co-development, governance, informatics infrastructure, and joint analysis and interpretation [17]. Sequencing capacity alone is therefore not an integrated biosurveillance system.

The critical boundary is between laboratory detection and interpreted surveillance evidence. Sample provenance, assay characteristics, contamination control, genomic quality, background prevalence, and linkage to epidemiological metadata determine what a result can support. Cross-sector usefulness also depends on timely exchange of interpretable results. Biosurveillance should consequently be designed as a coupled laboratory–information function, with technical confidence and decision relevance assessed separately.

Digital and syndromic surveillance

Digital and syndromic surveillance broaden the temporal window of veterinary intelligence by using observations that may precede definitive diagnosis. Electronic veterinary reporting shows that clinical information can become a biosurveillance stream, but participation and workflow condition what the system sees [8]. International notification data likewise illustrate that digital visibility reflects the capacity and behavior of reporting systems, not only underlying disease occurrence [10].

Here, “digital” denotes the information pathway, whereas “syndromic” denotes the inferential status of the signal. A digital system may transmit confirmed diagnoses, nonspecific signs, mortality, production changes, laboratory results, or environmental observations; a syndromic signal may arise through digital or structured manual reporting. Keeping these concepts separate prevents automation from being mistaken for validation.

Digital streams offer potential speed and scale, but introduce heterogeneous data quality, duplicated events, changing participation, coding drift, and interoperability problems. Integrated pathogen-surveillance work further indicates that useful real-time exchange requires governance, informatics, and joint interpretation rather than connectivity alone [17]. Digital surveillance should therefore be treated as an enabling layer whose warning value depends on verification, context, and downstream decision pathways.

Data integration

Data integration is more than assembling records in a common repository. For surveillance, integration must preserve what each observation represents while enabling linkage across species, locations, laboratories, environmental matrices, and reporting systems. The genomic-surveillance literature illustrates this socio-technical requirement: operational integration depends on partner identification, co-development, governance, informatics infrastructure, and joint interpretation [17]. Data can therefore be technically colocated yet remain analytically disconnected.

This distinction matters because surveillance streams differ in units, temporal resolution, denominators, certainty, and purpose. A laboratory result, wildlife mortality observation, production anomaly, environmental detection, and human syndrome cannot be interpreted as interchangeable events. Integration should retain provenance and evidence status while permitting comparison across them.

The synthesis proposed here treats integration as an ordered set of functions: semantic alignment, temporal and spatial linkage, preservation of provenance, cross-source comparison, and interpretive reconciliation. The objective is not to force agreement but to make concordance and discordance visible. Discordant signals may reflect genuine biological heterogeneity, reporting delay, sampling bias, incompatible definitions, or data failure and therefore require investigation rather than automatic averaging.

Interoperability and common data structures

Interoperability determines whether independently generated information can move between systems without losing its meaning. Community-developed wildlife-health data infrastructure shows how harmonized structures and vocabularies may improve compatibility, access, and reuse while retaining governance controls [18]. Such standardization addresses structural interoperability but does not establish that participating institutions will share or act on data.

Empirical comparison of participatory surveillance systems demonstrates substantial heterogeneity in the parameters collected across human, animal, and environmental domains [19]. Harmonization consequently requires more than common file formats; definitions, units, metadata, identifiers, and temporal conventions must also be interpretable across sectors.

The consequences of incomplete interoperability are visible in animal SARS-CoV-2 reporting, where official reporting alone omitted substantial information contained in other sources and multisource integration changed the observed surveillance picture [20]. That example is disease- and period-specific, but it demonstrates how source architecture shapes apparent evidence.

Interoperability is also organizational. Stakeholder research in Thai wildlife surveillance indicates that roles, communication, and institutional relationships influence whether wildlife information enters wider One Health pathways [21]. Technical standards and functioning information exchange should therefore be evaluated separately.

Signal verification

Integration produces candidate relationships; verification determines whether they warrant a change in interpretation. This distinction is necessary because missingness can differ dramatically across data sources, as illustrated by multisource animal-event reporting [20]. Likewise, international animal-health notifications depend on national detection and reporting capacity [10], while wildlife observations are conditioned by surveillance opportunity and recording sensitivity [13]. Agreement among incompletely independent sources cannot automatically be treated as confirmation.

A proposed verification gate should therefore ask whether a signal is reproducible, biologically plausible, temporally coherent, geographically compatible, and supported by a sufficiently independent source or confirmatory method. The required standard need not be identical for every purpose. A low-specificity production anomaly may require laboratory investigation, whereas a high-specificity laboratory detection may instead require epidemiological contextualization and assessment of exposure.

Verification should also preserve unresolved alternatives. A discordant observation may reflect sampling error, reporting lag, ecological heterogeneity, or genuinely different processes. The aim is consequently not to eliminate uncertainty before action, but to make the remaining uncertainty explicit before escalation.

Early-warning translation

Early warning occurs only when a detected signal is translated into an interpretable change in concern soon enough to affect surveillance or response. Ascertainment design directly conditions this process: comparison of facility-based and household-enhanced surveillance in rural Guatemala showed that surveillance intensity altered sensitivity and representativeness, while also implying a resource–coverage trade-off [22]. More observation is therefore not costless or automatically sustainable.

Participation introduces another boundary. Farmer-generated observations can augment passive animal-health surveillance, but reporting behavior and engagement condition system performance [23]. Routine production information offers a different pathway. Analysis of Irish dairy milk-recording data showed that such information can generate prediagnostic signals in some outbreak settings, although those signals require validation against confirmed events [24].

Similarly, voluntary cattle mortality notification should be evaluated in terms of participation, timeliness, and signal characteristics rather than presumed to provide reliable warning [25]. These examples support a proposed translation distinction between signal detected, signal interpretable, warning actionable, and warning reassessed. **Table 2** presents evidence transitions from anomaly detection to warning activation and return to surveillance.

Table 2. Evidence transitions from anomaly detection to warning activation and return to surveillance

Warning stage and basis	Evidence entering the stage	What confidence changes	Cross-sector work opened	Why the warning is not final	Exit or return condition
Stage: Detected anomaly **Basis: Proposed**	**Observed:** Syndromic, production, mortality, or reporting change **Coverage/context:** Coverage; reporting behavior; baseline stability	Departure from expected pattern	Intensify observation	Etiology unresolved	Test persistence and data quality
Stage: Corroborated signal **Basis: Proposed**	**Observed:** Repeat or cross-source concordance **Coverage/context:** Source independence; temporal alignment	Independent information supports concern	Initiate targeted verification	Shared bias may remain	Seek diagnostic/contextual confirmation
Stage: Actionable warning **Basis: Proposed**	**Observed:** Verified signal plus relevant context **Coverage/context:** Consequence severity; response capacity	Evidence justifies predefined escalation	Activate cross-sector decision pathway	Outcome benefit not assured	Track response and new evidence
Stage: Reassessed warning **Basis: Proposed**	**Observed:** Confirmation, attenuation, or contradiction **Coverage/context:** Diagnostic results; expanded sampling	New evidence alters confidence	Continue, adapt, or de-escalate	Residual uncertainty explicit	Return evidence to surveillance baseline

Cross-sector decision pathways

Even a verified warning has limited operational value if no pathway specifies who receives it, who interprets it, and what level of evidence warrants escalation. Integrated genomic surveillance frameworks emphasize joint interpretation and governance alongside data infrastructure [17]. Stakeholder evidence further indicates that organizational relationships can determine whether wildlife information enters broader decision processes [21].

The decision pathway proposed here begins after—not before—signal characterization. A sector generating the initial observation retains responsibility for provenance and technical interpretation, while cross-sector review evaluates whether human, animal, wildlife, environmental, or laboratory evidence changes its consequence. Escalation should be linked to predefined responsibilities rather than simply to the number of participating organizations.

Decision pathways also require explicit de-escalation. Voluntary and passive surveillance components may produce signals whose meaning changes as participation, confirmation, or background rates are clarified [25]. Feedback should therefore return verification outcomes, alternative explanations, and response information to the contributing systems. In this architecture, coordinated action is a reversible evidence-informed state, not the automatic endpoint of every cross-sector data connection.

Governance and information sharing

Cross-sector governance requires operational collaboration, explicit role definition, and decision-oriented systems mapping rather than formal structure alone [26–28]. Qualitative evidence from Ghana indicates that collaboration may intensify around events while routine surveillance functions remain siloed [26]. Formal national frameworks can define multisector responsibilities and coordination arrangements, but their practical effectiveness depends on operationalization and evaluation [27]. Prioritization linked with systems mapping can additionally identify where selected hazards intersect with existing institutional structures and coordination gaps [28].

These findings distinguish governance design from governance performance. Written mandates, committees, memoranda, or platforms create authority and opportunity for information sharing but do not establish timely exchange, joint interpretation, or response.

This distinction is reinforced by assessment of a One Health platform in Guinea, where operational performance varied across regions and functions [29]. The implication is not that one governance structure is preferable everywhere. Rather, governance should be evaluated through observable functions: authority to share information, responsibility for verification, decision ownership, escalation procedures, feedback, and continuity outside emergencies. Legal, administrative, and resource conditions remain jurisdiction-specific.

Implementation barriers

Implementation barriers occur at several linked levels and should not be compressed into a single deficit of “collaboration.” Evaluations of European One Health surveillance capacity have identified limitations involving shared leadership, harmonized indicators, FAIR data practices, and assessment of outcomes and costs [7]. Integrated pathogen-surveillance work similarly emphasizes that informatics infrastructure must be accompanied by governance, partner engagement, and shared interpretation [17].

Operational barriers also arise from routine institutional behavior. Evidence from Ghana suggests that collaboration can remain reactive even where cross-sector activity exists [26], while platform evaluation in Guinea indicates that formal organization may coexist with uneven operational performance [29]. These observations do not establish a universal hierarchy of barriers.

The synthesis therefore proposes four implementation interfaces: capacity—staff, laboratories, infrastructure, and financing; compatibility—data structures, terminology, and workflows; authority—mandates, sharing permissions, and decision ownership; and continuity—maintenance, feedback, training, and evaluation between crises. Failure at any interface can interrupt an otherwise technically plausible surveillance pathway. The relative constraint is expected to differ by jurisdiction, hazard, species system, and surveillance maturity.

A proposed integrated surveillance model

The proposed model treats One Health surveillance as a cross-sector network in which source systems remain distinct until evidence passes through interoperability, verification, and decision boundaries. Field experience in western Kenya demonstrates that integrated zoonotic surveillance is operationally feasible while demanding sustained coordination, sampling logistics, and information management [30]. That evidence supports feasibility of integration, not universal superiority of any single architecture.

The model therefore avoids assuming that completeness means combining every available stream. Review evidence indicates that published One Health applications have unevenly represented governance, financing, information, coordination, and particularly environmental dimensions [31]. These omissions justify making system dimensions explicit, but their inclusion does not guarantee improved outcomes.

Priority setting is positioned upstream of surveillance configuration. A multisector exercise in Guyana illustrates that prioritization can focus finite resources, while resulting rankings remain context-dependent rather than predictive risk estimates [32]. Capacity forms an external constraint: regional synthesis from sub-Saharan Africa highlights infrastructure, data sharing, workforce, laboratory capability, environmental surveillance, and governance as interdependent requirements [33].

The resulting architecture is explicitly **proposed**. Its central scientific claim is that evidential status should change visibly as signals cross integration, verification, escalation, and response boundaries.

The model's value lies in making those changes of evidential status and the feedback between sectors visually recoverable rather than burying them within a linear surveillance pipeline.

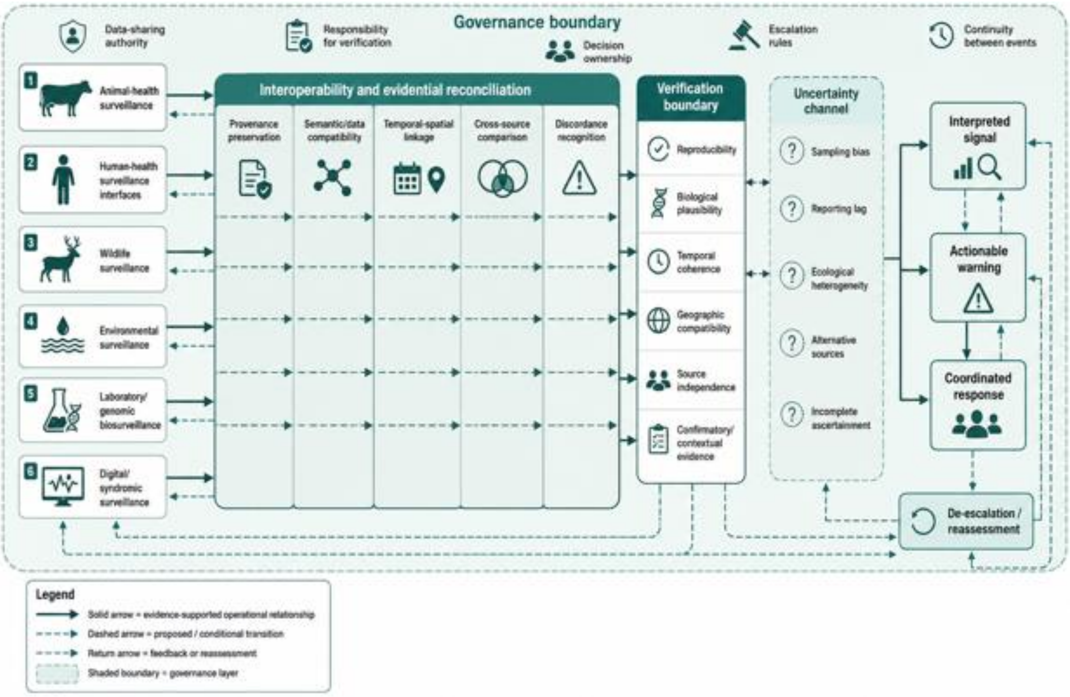

Figure 1. Where Zoonotic Signals Change Evidential Status: Cross-Sector Verification, Escalation, and Feedback Architecture

Validation and evaluation priorities

Evaluation should test the proposed architecture by function rather than assign a single global performance score. Multisectoral collaboration can itself be decomposed into organizational and functional attributes [5], while implementation assessments demonstrate that capacity and outcome evaluation may remain incomplete even within established One Health initiatives [7]. These observations support evaluation at multiple levels rather than assuming that structural integration denotes system effectiveness.

Signal-level assessment should consider timeliness, ascertainment, representativeness, reproducibility, specificity where measurable, and stability under changing participation. The Guatemala comparison shows why ascertainment and representativeness require explicit assessment [22]. Passive mortality surveillance similarly illustrates why notification components should be evaluated empirically rather than assumed reliable [25].

A second level should test whether records retain provenance and meaning across interoperable systems. A third should evaluate whether verified signals actually enter decision pathways with appropriate escalation and feedback. Prospective evaluation should also document false alarms, missed events, resource demands, and differences across species, sectors, and settings. No universal threshold or composite certainty grade is justified by the present evidence.

Research priorities

Digital surveillance requires stronger validation before automation can be equated with operational warning. Machine-learning classification of veterinary necropsy reports demonstrates that large clinical-text corpora can yield syndromic information, but external and prospective validation remains necessary [34]. Future studies should compare models across institutions, species mixes, coding practices, and changing disease prevalence rather than report development-set performance alone.

Alternative routine data sources also require system-specific testing. Production data from Norwegian salmon farms illustrate the potential for syndromic outbreak detection while emphasizing the need for validation and control of false signals within the relevant production system [35]. Cross-species transfer should therefore be tested rather than presumed.

Veterinary clinical language itself constitutes a measurement problem. Large-scale analysis shows domain-specific linguistic variation that constrains simple text-search surveillance [36]. Subsequent methodological work emphasizes transparent annotation, feature identification, validation, uncertainty handling, and domain-shift assessment before operational natural-language-processing systems are relied upon [37].

Research should consequently prioritize prospective multisector comparisons, external validation, domain-shift testing, source-combination experiments, implementation evaluation, and reproducible methods for updating surveillance models as epidemiology and data-generating systems change.

Conclusion

Veterinary surveillance at the human–animal–environment interface is not made integrative simply by accumulating more data or connecting more institutions. Its central challenge is preserving the meaning and uncertainty of heterogeneous signals while moving them through interoperability, verification, contextual interpretation, and coordinated decisions. Animal, wildlife, environmental, laboratory/genomic, human, and digital streams provide complementary but non-equivalent evidence.

The synthesis developed here proposes that detection, interpretable signal, actionable warning, response, and reassessment should remain visibly distinct surveillance states. Governance and data standards enable those transitions but do not guarantee them. The resulting architecture is therefore a framework for testing how surveillance systems function, not a validated universal design. Its utility will depend on prospective evaluation across hazards, species, jurisdictions, resource settings, and institutional arrangements, including whether integration improves decisions without obscuring uncertainty or generating disproportionate verification burden.

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