UNIVERSIDAD COMPLUTENSE MADRID
Instituto de Matemática Interdisciplinar
MOMAT
VACDIVA

TECHNICAL REPORT

An Operational Eco-Epidemiological Decision-Support Platform.

Application to the 2025-26 African Swine Fever Outbreak in Wild Boar in Catalonia

Version: March 18, 2026

Jaime Bosch[a], Benjamin Ivorra[a,b], Cecilia Aguilar-Vega[a], Jose Manuel Sánchez-Vizcaíno[a], Angel M. Ramos[a,b]

[a] *VACDIVA Project Members, Complutense University of Madrid, Spain*
[b] *Interdisciplinary Mathematics Institute, MOMAT & Department of Applied Mathematics and Mathematical Analysis, Complutense University of Madrid, Spain*

Funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No 862874
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
Cofinanciado por la Unión Europea
AGENCIA ESTATAL DE INVESTIGACIÓN

Email addresses: `jbosch@ucm.es` (Jaime Bosch), `ivorra@ucm.es` (Benjamin Ivorra)

Abstract

African swine fever (ASF) is one of the most consequential transboundary animal diseases affecting both domestic pig production and wild boar populations, particularly in human-modified landscapes, where ecological complexity, delayed detection, and heterogeneous host movements complicate outbreak interpretation and control. In late 2025, the emergence of ASF in wild boar in Catalonia, Spain, created a high-priority peri-urban epidemiological scenario in which surveillance, wildlife ecology, and outbreak management converged under a newly emerging operational challenge: the interpretation of complex transmission dynamics in anthropised environments. In this study, we applied the Wild Integrated Movement Boar Outbreak and Risk Dynamics (WIMBOARD) platform, an operational epidemiological modelling and decision-support system developed within the European VACDIVA project (DOI: 10.3030/862874), to interpret and anticipate the spatio-temporal evolution of the Catalonia outbreak. WIMBOARD integrates experimental epidemiological knowledge, wildlife ecology, landscape connectivity, and scenario-based modelling, including the simulation of applied control measures, to support risk assessment and outbreak management under field conditions. The model outputs revealed a structured and directional epidemic rather than a homogeneous radial spread. Temporal dynamics indicated delayed detectability between infection prevalence and mortality signals, while cumulative risk maps and time-to-infection surfaces identified clear directional asymmetries and differentiated dispersal phases. Although early field observations and model projections indicated an initial southward dispersal signal consistent with actual outbreak detections, north-northwest expansion emerged as the most epidemiologically consequential scenario, reflecting the influence of highly connected ecological sectors with increased potential for regional amplification and long-term persistence. Monthly risk surfaces further showed that infection spread behaved as a moving eco-epidemiological wavefront, allowing the identification of anticipatory surveillance windows before visible mortality became evident. In addition, epidemiological patterns compatible with reduced apparent virulence or prolonged host survival may, under conditions of landscape-mediated transmission, favour more diffuse spatial spread, lower early mortality visibility, and extended persistence of infection pressure over time. Taken together, these results support the interpretation of ASF spread in this peri-urban outbreak as a landscape-mediated epidemiological process shaped by functional connectivity, wildlife urban adaptation, and delayed detection. This study also introduces and operationalises the concept of landscape-mediated epidemiological modulation to explain how fragmented urban-agro-natural mosaics can alter transmission structure, mortality visibility, and surveillance performance. Beyond the Catalonia case, WIMBOARD is presented not simply as a theoretical model, but as an already operational European decision-support tool for risk assessment and ASF outbreak management, capable of comparative scenario exploration and adaptable to other geographic settings and wildlife-mediated disease systems. WIMBOARD translates eco-epidemiological complexity into operational spatial intelligence for anticipatory wildlife disease management.

Keywords: African swine fever, wild boar, spatial epidemiology, decision-support modelling, landscape connectivity, peri-urban ecology

Contents

Executive summary

African swine fever (ASF) in wild boar populations poses a major challenge for surveillance and control, particularly in peri-urban and highly anthropised environments where wildlife ecology, landscape fragmentation, delayed detection, and human activity interact in complex ways. The ASF outbreak detected in Catalonia in late 2025 represents a paradigmatic case of this new epidemiological reality, in which disease spread cannot be adequately interpreted through simplified assumptions of homogeneous diffusion or exclusively reactive response frameworks.

This technical preprint presents the application of the Wild Integrated Movement Boar Outbreak and Risk Dynamics (WIMBOARD) platform, an operational eco-epidemiological modelling and decision-support system developed within the European VACDIVA project, to interpret and anticipate the spatio-temporal evolution of the 2025-26 Catalonia outbreak. WIMBOARD integrates experimental epidemiological evidence, wildlife ecology, host movement, landscape connectivity, and scenario-based simulation of control interventions in order to support risk assessment, surveillance prioritisation, and outbreak management under field conditions.

The results indicate that ASF spread in the Catalonia scenario is structured, directional, and strongly modulated by landscape configuration rather than behaving as a simple isotropic radial process. The simulations identify differentiated dispersal phases, including an early southward phase consistent with field observations and a north–northwest expansion scenario with increased epidemiological relevance due to its potential for regional amplification and longer-term persistence. Monthly infection-risk maps further show that spread behaves as a moving eco-epidemiological wavefront, generating shifting surveillance windows in space and time.

A central conclusion of this work is that visible mortality may substantially lag behind the true front of infection. Under such conditions, passive carcass-based surveillance may underestimate the actual spatial extent of viral circulation. This is particularly relevant in fragmented peri-urban systems, where wild boar movement is shaped by habitat discontinuities, anthropogenic food resources, riparian corridors, infrastructure barriers, and urban–natural ecological gradients. In this context, the 2025-26 Catalonia outbreak supports the interpretation of ASF spread as a landscape-mediated epidemiological process.

The study also highlights the translational value of WIMBOARD as an already operational decision-support framework. Beyond producing spatial simulations, the platform enables the integrated interpretation of epidemiological dynamics, functional landscape connectivity, ecological modulation of transmission, and scenario-based control planning. This makes it a useful tool for anticipatory surveillance, adaptive containment, and proactive wildlife disease governance.

From an operational perspective, the findings support several management priorities: intensifying surveillance not only within the initial outbreak cluster but also along ecologically plausible spread corridors; prioritising carcass search in functionally connected areas, riparian belts, and residual permeability points; strengthening peri-urban risk management through waste control and public communication; and using predictive spatial intelligence to define early containment buffers before visible mortality signals become widespread.

Overall, WIMBOARD is presented not only as a modelling framework, but as a practical and spatially transferable platform for ASF preparedness, outbreak interpretation, and risk management. The Catalonia case illustrates how eco-epidemiological complexity can be translated into operational spatial intelligence to support evidence-based decision-making in wildlife disease systems under real-world conditions.

Highlights

- WIMBOARD revealed a structured and directional ASF epidemic driven by functional landscape connectivity rather than homogeneous radial diffusion.
- Delayed detectability between infection prevalence and mortality signals may substantially underestimate the true spatial extent of viral circulation in wild boar populations.
- The north–northwest sector emerged as a potential epidemiological amplification landscape with increased risk of regional persistence and multidirectional spread.
- Monthly spatial risk dynamics identified anticipatory surveillance windows, enabling earlier targeting of control actions before visible mortality became apparent.
- The 2025-26 Catalonia outbreak supports the concept of landscape-mediated epidemiological modulation, whereby fragmented peri-urban mosaics and wildlife urban adaptation reshape transmission structure.
- WIMBOARD operates as an already deployable European decision-support platform integrating scenario exploration and applied control-measure modules for ASF outbreak risk assessment and management.

1. Introduction

African swine fever (ASF) has become one of the most disruptive transboundary animal diseases affecting both livestock production systems and wildlife populations across Europe and beyond. In recent years, the epidemiology of ASF has increasingly been shaped by the spatial ecology, demographic dynamics, and behavioural plasticity of wild boar populations, particularly in landscapes profoundly modified by human activity. The confirmation of ASF cases in wild boar in Catalonia (Spain) in late 2025 represents a critical example of this evolving epidemiological reality, highlighting the challenges of detecting, interpreting, and managing disease spread in heterogeneous and highly anthropised environments.

In such contexts, traditional control strategies have often relied on reactive responses following outbreak confirmation, including passive surveillance, carcass removal, movement restrictions, and population management interventions. While these measures remain essential components of ASF control frameworks, their effectiveness may be constrained by delays in detection, uncertainty regarding infection dynamics, and the complex interaction between ecological and human-driven processes influencing wild boar movements (Bosch et al., 2012). This raises a fundamental operational question: are current surveillance and control approaches sufficiently anticipatory to address the spatio-temporal complexity of ASF spread in free-ranging wildlife populations?

Experimental epidemiological research has progressively expanded our understanding of ASF transmission patterns in wild boar, including the potential role of viral strain variability in shaping outbreak trajectories. Evidence derived from controlled infection studies suggests that differences between highly virulent and attenuated strains may influence persistence mechanisms, spatial diffusion rates, and long-term epidemiological scenarios. These findings underline the need for integrative approaches capable of translating biological knowledge into operational preparedness and decision-support tools.

Beyond a purely reactive response, integrated epidemiological modelling frameworks are increasingly recognised as essential components of modern disease surveillance systems. Such tools can support risk assessment, facilitate comparative scenario analysis, and enable proactive planning of control strategies under conditions of uncertainty. The development of operational modelling platforms that combine ecological realism with applied decision-support capabilities therefore represents a critical step towards strengthening ASF preparedness at both regional and international scales. In this context, we present the application of the Wild Integrated Movement Boar Outbreak and Risk Dynamics (WIMBOARD) platform, an operational decision-support modelling system developed within the European VACDIVA project. The platform integrates experimental epidemiological knowledge, spatial ecology, and scenario-based simulation to assess potential outbreak trajectories and inform surveillance and control planning. Building upon previous applications in European outbreak contexts, where retrospective evaluations indicated spatio-temporal consistency between model projections and field observations, this study illustrates the use of WIMBOARD to interpret and anticipate the evolution of the ASF outbreak detected in Catalonia. By bridging experimental evidence and operational modelling, this work aims to contribute to a more proactive, evidence-based framework for managing ASF risks in complex wildlife-dominated landscapes.

2. Epidemiological context of ASF emergence in Catalonia

The re-emergence of ASF in Spain in late November 2025 marked a critical epidemiological turning point for the Iberian Peninsula after more than three decades without confirmed circulation. The first detected cases were reported between 25 and 26 November 2025, when two wild boar carcasses were found in the municipality of Cerdanyola del Vallès, in the metropolitan area of Barcelona, northeastern Spain. This initial outbreak focus was located in a highly anthropised peri-urban landscape, characterised by a mosaic of residential areas, transport infrastructures, and fragmented forest and agroforestry patches belonging to the Collserola Natural Park. Wild boar abundance in this area has been estimated as medium to high, reflecting the species' increasing adaptation to human-dominated environments.

From the outset, the epidemiological pattern displayed several distinctive features. Detection was initially limited to carcasses, with no infected live animals or affected domestic pig farms identified. Necropsy findings and laboratory confirmation by the national reference laboratory established the presence of ASF virus genotype II, confirming the disease in Spain for the first time since its official eradication in 1994, after a 31-year disease-free period. The subsequent detection of skeletal remains suggested that viral circulation may have preceded official notification by several weeks or months, which is consistent with the delayed detection commonly observed in wildlife disease outbreaks. The Catalonia outbreak therefore represents not only a sanitary emergency but also a real-time operational epidemiological framework in which preparedness plans, wildlife management strategies, and surveillance systems are being simultaneously tested under field conditions.

Following confirmation, a coordinated emergency response framework was activated. Measures implemented included the establishment of a high-risk infection core zone with a radius of 6 km and a surrounding surveillance buffer zone extending up to 20 km. Intensive carcass search and recovery operations were deployed using trained personnel, detection dogs, aerial surveillance, and drone technology. Traditional hunting activities were temporarily suspended to minimise disturbance-driven dispersal of wild boar, while targeted population management strategies using trapping systems and controlled removal were implemented to reduce host abundance. Reinforcement of farm biosecurity and restrictions on human activities in the natural environment were prioritised to prevent indirect virus spread. These interventions followed established European standards for ASF control in wildlife and reflected the high level of preparedness historically developed in Spain through national surveillance programmes and contingency planning.

Despite rapid operational deployment, several epidemiological uncertainties emerged. As of early 2026, all confirmed cases remained confined to wild boar populations, and spatial containment initially appeared to be effective. However, the outbreak occurred in an ecological context markedly different from many previous European ASF events, which were often detected in more remote and less anthropised landscapes. In peri-urban ecosystems such as Collserola, indirect human-mediated transmission pathways, including contaminated fomites, waste accessibility, and intense recreational use of natural areas, may become as relevant as natural host movement in shaping spatial transmission dynamics. This highlights the broader risk of disease spread in wildlife populations under conditions of ecological connectivity and human-mediated landscape disturbance (De la Torre et al., 2015; Bosch et al., 2026, 2017a).

2.1. Genomic uncertainty and epidemiological interpretation

From a molecular epidemiology perspective, the available public information indicates that the detected virus belongs to genotype II, associated with the Eurasian epidemic lineage since 2007, but exhibits distinctive genomic characteristics that differentiate it from currently circulating European isolates. The strain has been provisionally classified as a new genetic group, highlighting an unexpectedly high level of genetic divergence for a large double-stranded DNA virus with a relatively low evolutionary rate. On the basis of publicly accessible data, the precise origin of the outbreak cannot be confirmed or excluded. Hypotheses under consideration include sporadic long-distance introduction linked to human activities, undetected circulation in wildlife, and other epidemiological scenarios requiring further genomic evidence. However, in line with experience from previous European outbreaks, determining the origin remains secondary to the immediate priority of interrupting transmission and containing spatial spread.

Additional working hypotheses include sporadic introduction associated with human-mediated activities, such as the disposal of contaminated pork products or waste accessible to wild boar, as well as accidental release from facilities handling ASF virus or experimental vaccines. Intentional introduction as a deliberate act targeting livestock production cannot be formally excluded at this stage. Conversely, progressive natural spread through wild boar movements from the nearest known infected areas in Europe appears epidemiologically less likely, given the species' limited long-distance dispersal capacity and the absence of spatial epidemiological continuity across intervening regions. Nevertheless, in the absence of direct evidence, all potential introduction pathways remain under investigation.

Another critical dimension relates to the apparent epidemiological behaviour of the circulating strain. Field observations suggesting moderate mortality patterns have led to consideration of a potential lower-virulence scenario. In wildlife populations, moderately virulent or attenuated ASF strains may generate more complex transmission dynamics than highly virulent variants. Increased survival time of infected individuals can allow longer dispersal distances, more diffuse spatial clustering, and reduced detectability through passive surveillance based on carcass recovery. These mechanisms may complicate the delimitation of infected areas and prolong environmental virus persistence. Experimental evidence derived from controlled infection studies in wild boar has shown that coexistence scenarios involving strains of different virulence may produce heterogeneous transmission patterns and intermittent persistence dynamics Martínez (Martínez & Bosch et al., 2023). Although the epidemiological characteristics of the Catalonia outbreak strain remain under investigation, this uncertainty reinforces the need for adaptive surveillance strategies capable of integrating multiple plausible transmission scenarios.

Beyond virological and operational aspects, the outbreak highlights a broader ecological reality. Wild boar populations across Europe have undergone profound demographic and behavioural transformations driven by anthropogenic landscape changes (Barrios-García and Ballari, 2012; Bosch et al., 2012). As opportunistic omnivores, they exhibit high ecological plasticity, enabling them to exploit a wide spectrum of natural and anthropogenic food resources in heterogeneous landscapes. Expansion of urban–forest interfaces, continuous food availability linked to agricultural intensification, the absence of large predators, and historically uncoordinated hunting practices have contributed to increased abundance and altered movement ecology (Amici et al., 2012; Aguilar-Vega et al., 2024). As opportunistic scavengers capable of consuming carcasses and anthropogenic waste, wild boars are particularly exposed to environmentally persistent pathogens such as ASF virus. In this context, the species should not be regarded solely as a disease reservoir, but also as a biological indicator of deeper ecosystem imbalance. More broadly, wild boar populations can act as ecological amplifiers of pathogen persistence within human-modified landscapes, linking environmental disturbance, host demography, and pathogen transmission into a single epidemiological system.

Taken together, the Catalonia outbreak illustrates the convergence of molecular uncertainty, ecological complexity, and operational challenges typical of transboundary wildlife diseases. It also underscores the limitations of purely reactive response frameworks. Anticipatory epidemiological tools capable of integrating landscape connectivity, host movement, control interventions, and alternative virulence scenarios may therefore play a critical role in strengthening surveillance prioritisation and preparedness planning in such highly dynamic epidemiological contexts. Such tools are particularly relevant in peri-urban outbreak scenarios, where uncertainty regarding virulence patterns, delayed detection, and heterogeneous host movement may rapidly alter spatial risk dynamics.

To interpret this emerging epidemiological configuration more robustly, it is essential to integrate insights derived from experimental infection research with theoretical transmission modelling frameworks and predictive epidemiological modelling approaches.

3. Translational epidemiological framework, 2025-26 Catalonia scenario

This section presents the translational epidemiological framework used to interpret the Catalonia outbreak scenario by linking experimental evidence, biological assumptions on African swine fever (ASF) transmission, and operational predictive modelling. First, we summarise how insights from experimental infection studies, including differences in virulence expression, host survival, and infectious-period duration, can inform the interpretation of field dynamics in wild boar populations. We then examine how these biological and epidemiological elements help contextualise the Catalonia outbreak and how they are incorporated into the WIMBOARD platform to generate predictive transmission scenarios under complex peri-urban landscape conditions. In this way, the section provides the conceptual bridge between experimental epidemiology, field interpretation, and the spatially explicit operational analyses presented in the following sections.

3.1. From experimental epidemiology to predictive transmission scenarios

Understanding the epidemiological behaviour of ASF in wild boar populations requires integrating insights derived from both theoretical transmission modelling and experimental infection studies. Classical deterministic modelling frameworks have long emphasised the role of virulence gradients in shaping epidemic dynamics, particularly through their influence on the duration of the infectious period, mortality detectability, and the potential for long-term persistence within host populations.

Under high-virulence scenarios, transmission processes are often characterised by rapid disease progression, acute mortality, and relatively short infectious windows, resulting in spatially clustered outbreaks that may be more readily detected through passive surveillance based on carcass recovery. Conversely, modelling approaches exploring lower-virulence or moderately pathogenic variants suggest the possibility of extended infectious periods, reduced apparent mortality, and more diffuse spatial transmission patterns. These dynamics may increase the risk of endemic persistence by allowing infected individuals to survive longer, disperse over greater distances, and contribute to sustained environmental contamination. In such contexts, intervention strategies may progressively shift towards intensified host population management measures aimed at artificially increasing mortality rates in order to compensate for reduced pathogen lethality.

While these conceptual frameworks provide valuable theoretical insights into ASF transmission mechanisms, experimental epidemiology offers an essential complementary perspective by directly quantifying infection outcomes under controlled conditions. Experimental infection studies conducted in wild boar have shown that transmission dynamics may be substantially more heterogeneous than those predicted by simplified deterministic models. In particular, recent evidence indicates that coexistence scenarios involving strains of differing virulence can generate complex epidemiological patterns, including variable mortality curves, prolonged survival of seropositive individuals, and intermittent transmission windows extending beyond the acute outbreak phase (Martínez & Bosch et al., 2023) .

These findings suggest that the epidemiological signal observed in the field may not necessarily reflect a single dominant transmission regime, but rather a composite outcome resulting from interactions among pathogen virulence variability, host demographic structure, and environmental persistence processes. Consequently, predictive frameworks based solely on theoretical transmission assumptions may underestimate the temporal and spatial complexity of ASF dynamics in free-ranging wildlife populations. Integrating experimentally derived infection parameters into predictive modelling approaches therefore represents a critical step towards improving the realism and operational relevance of epidemiological scenario analysis. These experimental findings thus provide a biological basis for interpreting field epidemiological patterns that may otherwise appear inconsistent with simplified theoretical expectations.

3.2. Application of experimental insights to Catalonia outbreak dynamics

The epidemiological mechanisms derived from experimental infection studies provide a particularly relevant framework for interpreting the field dynamics currently observed in the Catalonia outbreak. Preliminary surveillance findings, including the detection of seropositive wild boar individuals and reports of heterogeneous mortality patterns, suggest that the epidemiological behaviour of the circulating virus may differ from the classical acute high-virulence scenario typically associated with genotype II epidemics.

A lower apparent lethality, or the presence of moderately virulent or attenuated infection dynamics, may lead to prolonged survival of infected hosts, thereby extending the potential infectious period at the population level. Such conditions can generate delayed and less conspicuous epidemiological signals, as carcass-based passive surveillance systems may underestimate the true spatial extent of viral circulation. In turn, surviving infected individuals may contribute to the gradual spatial diffusion of infection, increasing the likelihood of disease spread beyond the initially delimited core zones.

These processes may result in diffuse transmission patterns characterised by slow epidemic progression, intermittent detection events, and extended environmental contamination cycles (Ito et al., 2024; Kawaguchi et al., 2025). Under such epidemiological configurations, defining precise infection boundaries becomes operationally challenging, and apparent spatial containment may not fully reflect the underlying transmission dynamics. This scenario reinforces the need to interpret field observations cautiously, particularly in complex peri-urban ecosystems where host movement behaviour, landscape connectivity, and anthropogenic disturbance can further modulate disease spread.

In this context, the Catalonia outbreak can be considered a real-world epidemiological situation in which uncertainty regarding virulence expression, delayed mortality detection, and heterogeneous transmission processes interact to shape disease expansion. Such complexity highlights the importance of integrating experimental epidemiological evidence with predictive modelling approaches capable of exploring alternative transmission scenarios and supporting proactive surveillance prioritisation.

Beyond conceptual transmission assumptions, experimental epidemiology in wild boar provides quantitatively grounded parameters that substantially refine predictive ASF dynamics. Controlled infection studies have revealed a biologically more resolved spectrum of transmission outcomes than those typically represented in simplified deterministic frameworks. In (Martínez & Bosch et al., 2023) , empirical parameterisation of attenuated genotype II infection scenarios yielded an experimental intraherd reproduction value (R_x) of 4.5 and demonstrated that infection outcomes may include prolonged infectiousness, heterogeneous mortality, serological survival, and delayed re-exposure effects. Importantly, the study showed that, under mixed-virulence scenarios, between 4% and 17% of animals could remain in intermittent or permanent infectious states after the epidemic peak, while 5% to 11% of the population could remain recovered but susceptible to subsequent exposure to highly virulent strains. Depending on the scenario and assumptions tested, infectiousness could persist for more than two years, highlighting a much longer epidemiological tail than would be expected under a purely acute high-virulence framework.

These findings are highly relevant for interpreting the Catalonia outbreak. Reports of seropositive wild boar, delayed carcass detection, variable mortality timing, and the possibility of progressive spread beyond the initial infection focus are all consistent with a scenario in which lower apparent virulence, prolonged survival, and heterogeneous post-infection states may be shaping transmission dynamics in the field. In practical terms, this means that carcass-based surveillance alone may underestimate the true extent and duration of viral circulation, and that epidemiological interpretation should account not only for acute mortality events but also for surviving, intermittently infectious, or only partially protected individuals. This biologically grounded framework substantially improves the realism of predictive analyses aimed at surveillance prioritisation, containment planning, and future scenario testing in Catalonia and comparable peri-urban wild boar systems.

Consequently, the Catalonia outbreak may represent an epidemiological configuration in which classical expectations derived from acute genotype II epidemics require careful reinterpretation within a broader virulence-spectrum framework.

3.3. Operational predictive platforms and decision-support modelling

Understanding ASF epidemiological dynamics in contemporary European landscapes increasingly requires modelling approaches capable of bridging theoretical transmission frameworks, experimental infection evidence, and real-world disease-management constraints. As discussed above, uncertainty regarding virulence expression, heterogeneous host survival patterns, and spatially complex transmission environments may substantially limit the operational interpretability of classical epidemiological projections when applied to rapidly evolving wildlife outbreaks. In this setting, decision-support platforms are needed not only to describe transmission processes, but also to translate epidemiological knowledge into spatially explicit and operationally relevant outbreak scenarios.

Within this perspective, the Wild Integrated Movement Boar Outbreak and Risk Dynamics (WIMBOARD) platform was conceived as an operational epidemiological modelling environment for risk assessment and outbreak management in wild boar-associated ASF. Its conceptual development began in 2020 in response to the need for a tool capable of integrating ASF epidemiology, wild boar ecology, host movement, landscape connectivity, and control interventions into a unified simulation framework. Functional development and methodological consolidation were subsequently achieved during 2022–2023 within Work Package 7 of the European Horizon 2020 VACDIVA project (`https://doi.org/10.3030/862874`), where WIMBOARD emerged as a translational modelling outcome linking experimental epidemiology, wildlife disease ecology, and quantitative decision-support analysis.

The platform was built through a strongly multidisciplinary collaboration involving expertise in veterinary epidemiology, wildlife ecology, animal health surveillance, and applied mathematics. In particular, its development was supported by contributions from researchers affiliated with the Universidad Complutense de Madrid (UCM), including the Department of Animal Health and the VISAVET Health Surveillance Centre, together with the research group UCM/MOMAT and the Instituto de Matemática Interdisciplinar (IMI). This integrative framework brought together complementary expertise from Jaime Bosch, Cecilia Aguilar-Vega, Satoshi Ito, and José Manuel Sánchez-Vizcaíno, together with Benjamín Ivorra and Ángel Manuel Ramos, among others, allowing the platform to evolve from a conceptual research tool into an operational modelling system applicable to complex epidemiological scenarios.

From a functional standpoint, WIMBOARD combines several interconnected modules within a single analytical environment. These include spatial spread simulation, host movement and landscape-connectivity analysis, wild boar population dynamics, and the implementation of configurable control scenarios under European field conditions. As a result, the platform can be used both as a scientific modelling platform and as a decision-support tool for risk assessment and outbreak management, enabling the comparison of alternative intervention strategies, the prioritisation of surveillance actions, and the evaluation of containment robustness under different epidemiological assumptions. Rather than focusing exclusively on pathogen persistence mechanisms, WIMBOARD translates epidemiological knowledge into management-oriented scenario exploration, including "what-if" analyses involving surveillance intensity, carcass detection, movement barriers, population management, and the timing of intervention deployment. In contrast to classical aggregated compartmental modelling approaches, the platform incorporates probabilistic host movement processes, explicit infection-progression dynamics including mortality and partial-immunity states, and scenario-based evaluation of control interventions such as carcass removal, population reduction, or bait-mediated vaccination strategies. This structure enables a more realistic representation of heterogeneous outbreak patterns and operational response conditions in free-ranging wild boar systems. By linking biological infection processes, wildlife ecological dynamics, and management-oriented intervention testing, the platform contributes to translating experimental efficacy into operational effectiveness under real-world outbreak conditions. In its current operational configuration, the platform can be readily adapted to diverse European epidemiological contexts through the incorporation of region-specific landscape, host-abundance, and surveillance parameters, allowing rapid scenario exploration in newly affected areas.

The operational maturity of the platform was progressively demonstrated through its application and evaluation in southern European contexts, including scenarios in northern Italy and Belgium, where its spatio-temporal projections were assessed against field epidemiological conditions. This translational trajectory was further reflected in its public presentation at the VACDIVA final technology-transfer workshop held in Brussels in November 2024, where WIMBOARD was presented as a functional European outcome for ASF preparedness and control (`https://vacdiva.eu/activities/vacdiva-final-world-technology-transfer-workshop-key-advancements-in-asf-control/`). The platform therefore represents not only a methodological development, but also a transferable scientific infrastructure intended to support institutions, veterinary authorities, wildlife managers, and epidemiologists engaged in transboundary disease preparedness.

Its relevance became particularly evident in the context of the Catalonia outbreak. On 1 December 2025, using the publicly available epidemiological information accessible at that time and assuming a plausible period of pre-detection viral circulation, an operational WIMBOARD simulation was implemented to explore potential spatial spread trajectories and short- to medium-term risk scenarios for the affected peri-urban wild boar population in Catalonia, Spain. This application generated monthly spatial risk maps and temporal spread outputs for the local epidemiological setting, thereby providing an early scenario-based assessment of possible outbreak trajectories. The resulting analyses were subsequently communicated publicly in Spain on 15 December 2025 through UCM scientific outreach channels, which described the contribution of a multidisciplinary team applying advanced modelling tools to anticipate spread, evaluate risks, and support decision-making during the emergency response (`https://www.ucm.es/analisis-peste-porcina-africana-cataluna?ver`). The same modelling framework and selected results were later disseminated internationally through an adapted technical interview submitted on 28 January 2026 and published in March 2026 in *Friend of Pig Farmers* (Japan), where the Catalonia case was presented as a source of operational lessons for ASF-free countries and preparedness planning (`https://w3.alpha-web.ne.jp/~chikutomo/youton.html`).

Importantly, WIMBOARD is currently configured around scenarios that have historically been dominated by highly virulent ASF strains, which makes it particularly suitable for many past European outbreaks. However, the biological and epidemiological insights derived from attenuated or mixed-virulence scenarios, including those described by Martínez (Martínez & Bosch et al., 2023), are being incorporated as an additional modelling layer to broaden the platform's applicability under more complex transmission conditions. In this sense, WIMBOARD should be understood as an evolving, yet already operational and spatially transferable, decision-support system for disease control, providing a platform for comparative scenario analysis, surveillance prioritisation, and outbreak management, capable of integrating experimental evidence, ecological realism, and applied epidemiological reasoning into a single operational framework.

This progressive integration of experimental epidemiology, landscape-based modelling, and operational decision-support tools reflects a broader paradigm shift in wildlife disease preparedness, in which anticipatory scenario analysis becomes as critical as reactive outbreak response.

4. Eco-epidemiological interpretation of WIMBOARD outputs in the 2025-26 Catalonia outbreak scenario

This section examines the ecological and epidemiological meaning of the spatial and temporal outputs generated by WIMBOARD under the Catalonia outbreak scenario. Rather than treating these outputs as purely mathematical projections, we interpret them as the epidemiological expression of interacting ecological, behavioural, landscape, and anthropogenic processes shaping African swine fever (ASF) spread in a fragmented peri-urban wild boar system. We first frame the main modelling outputs in biological and epidemiological terms, and then analyse how temporal epidemic dynamics, cumulative spatial risk, directional dispersal phases, monthly propagation patterns, and field observations together support a landscape-mediated interpretation of outbreak expansion. In this way, the section provides the ecological bridge between the predictive modelling framework presented above and its operational implications for surveillance, risk assessment, and outbreak management.

4.1. Ecological and epidemiological framing of spatial modelling outputs

The spatial outputs generated by WIMBOARD under the Catalonia outbreak scenario should not be interpreted as purely mathematical projections detached from biological reality. Rather, they represent the epidemiological expression of interacting ecological, behavioural, landscape, and anthropogenic processes operating simultaneously in wild boar populations under outbreak conditions. In this sense, WIMBOARD functions not only as an operational modelling platform, but also as a decision-support tool for risk assessment and outbreak management, and as a spatially transferable decision-support system for disease control, capable of translating ecological complexity into operationally useful spatial scenarios.

In the Catalonia application, the model was initialised on 1 December 2025 using the coordinates of the first officially detected ASF-positive wild boar case and assuming, on the basis of field epidemiology and wild boar ecology, that infection had probably been circulating for some time before the first notification. This assumption was subsequently reinforced by the later detection of ASF-positive skeletal remains, which strongly suggests that the outbreak had begun before 26 November 2025 and that the observed epidemiological pattern likely reflects a partially delayed detection of a process already under way. Within this framework, WIMBOARD produced spatio-temporal outputs that included epidemiological curves, prevalence dynamics, cumulative spatial risk maps at 500 days, time-to-infection maps, and monthly infection-risk surfaces. Taken together, these outputs provide a coherent picture of a structured, directional, landscape-mediated epidemic rather than of a homogeneous radial spread.

4.2. Temporal epidemic dynamics and delayed detectability (detection lag)

The epidemiological curves derived from the simulation are especially informative in this regard. The disease dynamics shown in Fig. 1-left indicate a system dominated by susceptible, exposed, infected, and dead compartments, with recovery and immunity playing virtually no role under the current scenario. The corresponding prevalence dynamics shown in Fig. 1-right, in which the combined exposed and infectious compartments remain epidemiologically relevant while immunity remains essentially absent, are fully consistent with a highly virulent ASF framework. From an operational standpoint, this is important because it implies that the visible signal of the epidemic, especially when surveillance is largely based on passive carcass detection, may lag behind the true infection front. In wildlife systems, this temporal mismatch between infection and detection is critical. The area in which infection is already spreading is not necessarily the same as the area in which mortality has already become visible.

A more detailed temporal examination of the simulated epidemiological trajectories provides further insight into the internal structure of the outbreak dynamics. The disease dynamics shown in Fig. 1-left reveal a temporally structured progression in which exposed individuals initially decline during the early phase of the simulation, stabilise at low levels during an apparent epidemiological latency period, and then increase sharply after approximately day 300, reaching a peak around days 380–400. This increase in the exposed compartment is closely followed by a progressive rise in the infectious population, which reaches its maximum slightly later, around days 400–420. Such temporal coupling between exposed and infectious states reflects a spatially advancing infection front in which transmission occurs gradually through landscape-mediated contact processes rather than through abrupt mass-infection events.

Mortality dynamics display a markedly delayed but dominant pattern. The number of disease-related deaths begins to increase significantly after the infectious peak, rising steeply between approximately days 380 and 450, and reaching the highest proportional values towards the end of the simulation period. This delayed mortality signal suggests that large portions of the infected population remain mobile and epidemiologically active for a considerable period before succumbing to the disease. In contrast, recovered and immune compartments remain negligible throughout the simulation, indicating that long-term population-level immunity is unlikely to play a significant regulatory role under the epidemiological assumptions currently represented in the modelling framework.

The prevalence dynamics shown in Fig. 1-right further support this interpretation. The combined exposed-plus-infectious prevalence remains very low during the first half of the simulation, followed by a rapid escalation after approximately day 320, peaking near day 390. After this peak, prevalence stabilises at moderately elevated levels with oscillatory behaviour, suggesting persistent spatial transmission pressure rather than a short-lived epidemic pulse. Importantly, the virtual absence of an immune-prevalence signal reinforces the interpretation of a system dominated by ongoing transmission and delayed mortality rather than rapid epidemic burnout.

From an ecological perspective, these temporal patterns may be interpreted in light of the fragmented urban-agro-natural landscape structure characteristic of the Catalonia outbreak area. Wild boar populations in such environments often exhibit modified movement routines, reduced predictability of long-range dispersal, and complex contact networks structured by anthropogenic resources and habitat discontinuities. These factors may contribute to a more gradual spatial diffusion of infection and to a prolonged phase of sub-detectable epidemiological circulation. Although WIMBOARD simulations currently assume highly virulent acute ASF epidemiological parameters, the comparatively moderate mortality signal observed in the early stages of the simulated dynamics may be compatible either with landscape-mediated transmission constraints or with the potential involvement of a strain with altered virulence characteristics, as suggested by preliminary laboratory observations.

Operationally, these results have important implications for surveillance design. When mortality signals lag behind infection spread, passive surveillance based primarily on carcass detection may underestimate the true spatial extent of viral circulation. Delayed detectability may therefore lead to systematic underestimation of the true spatial extent of ASF circulation in wildlife populations. Consequently, areas that appear epidemiologically quiet may already be undergoing active transmission processes. Integrating ecological interpretation of movement behaviour, landscape connectivity, and temporal prevalence dynamics therefore becomes essential for anticipating future spread directions and prioritising targeted surveillance interventions.

The Catalonia outbreak supports the interpretation of ASF spread as a case of landscape-mediated epidemiological modulation in a fragmented peri-urban wildlife system. This dual ecological-operational interpretation is particularly relevant in peri-urban Mediterranean landscapes such as the Barcelona urban-natural gradient, where wildlife behaviour, landscape fragmentation, urbanisation, and human-modified ecological interfaces interact to produce eco-epidemiologically plausible patterns of ASF spread.

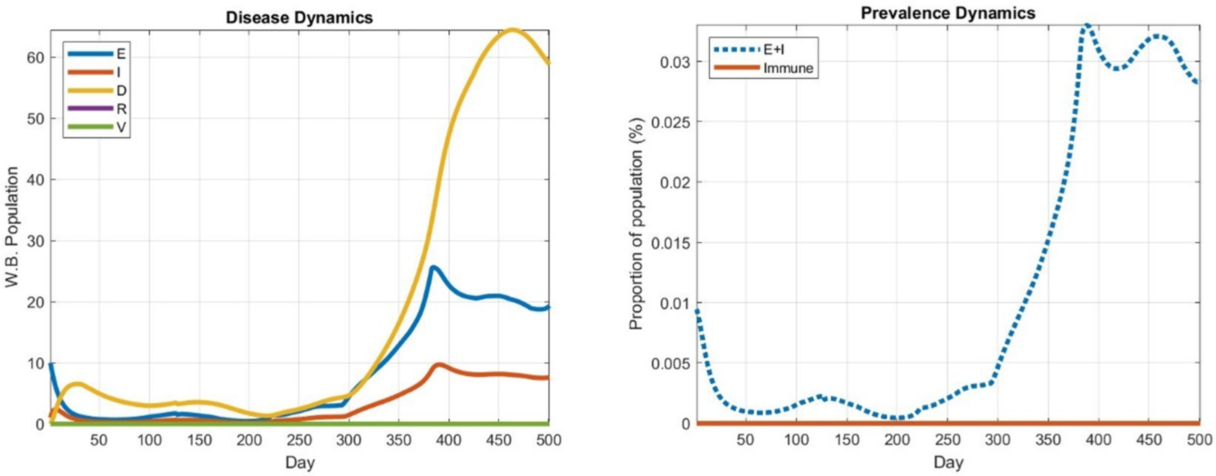

Figure 1: Simulated epidemiological and prevalence dynamics of African swine fever (ASF) in wild boar populations under the Catalonia outbreak scenario over a 500-day simulation period. **Left:** simulated disease dynamics showing the temporal evolution of the exposed (E), infectious (I), dead (D), recovered (R), and immune (V) compartments. The modelled dynamics indicate delayed mortality relative to infection progression, with negligible recovery and immunity, consistent with an acute high-virulence epidemiological configuration. **Right:** simulated prevalence dynamics showing the temporal evolution of exposed-plus-infectious prevalence (E+I) in comparison with immune prevalence. The results highlight low early detectability followed by a progressive escalation of infection pressure, supporting the interpretation of delayed epidemiological visibility under carcass-based passive surveillance systems.

4.3. Landscape structuring of spatial infection risk

The cumulative spatial risk outputs at 500 days (Fig. 2) and the corresponding time-since-infection surface (Fig. 3) show that spread is neither isotropic nor simply distance-dependent. Instead, the model identifies clear directional asymmetries and differentiated phases of expansion. This is a major ecological result, as it indicates that the outbreak is being shaped by functional connectivity, habitat structure, barriers, corridors, and host ecology, rather than behaving as a simple diffusion process across homogeneous space. In other words, WIMBOARD does not merely generate a risk map; it reconstructs the likely geography of transmission through a biologically plausible landscape. The spatial pattern reconstructed by WIMBOARD is consistent with functional connectivity-driven spread rather than isotropic diffusion across homogeneous space (Goicolea et al., 2024; Bosch et al., 2017a).

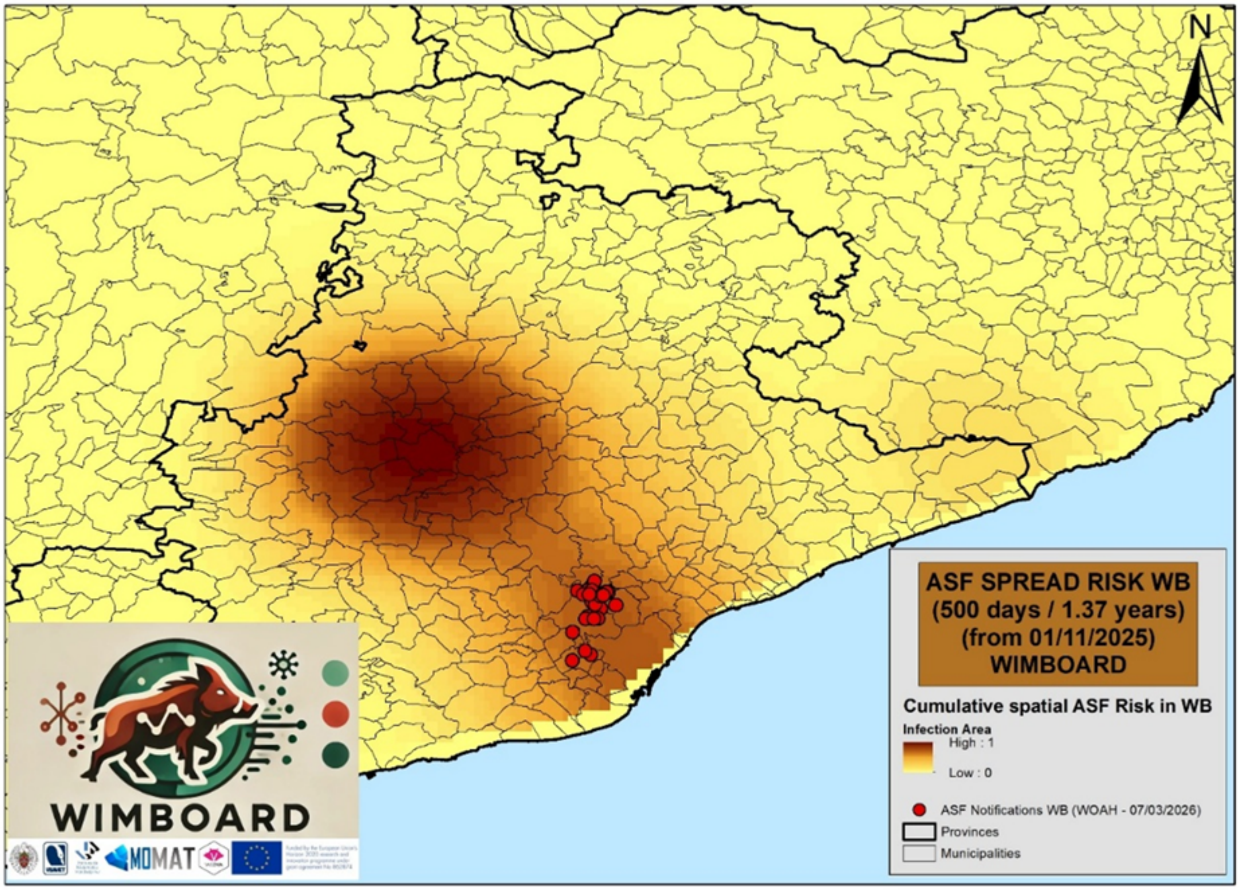

Figure 2: Cumulative spatial risk of African swine fever (ASF) infection after 500 days of simulated spread. Spatial distribution of normalised infection risk across the landscape, representing the integrated epidemiological pressure accumulated during approximately 1.37 years following the first notified infection. The spatial pattern reveals directional spread driven by functional connectivity rather than isotropic diffusion.

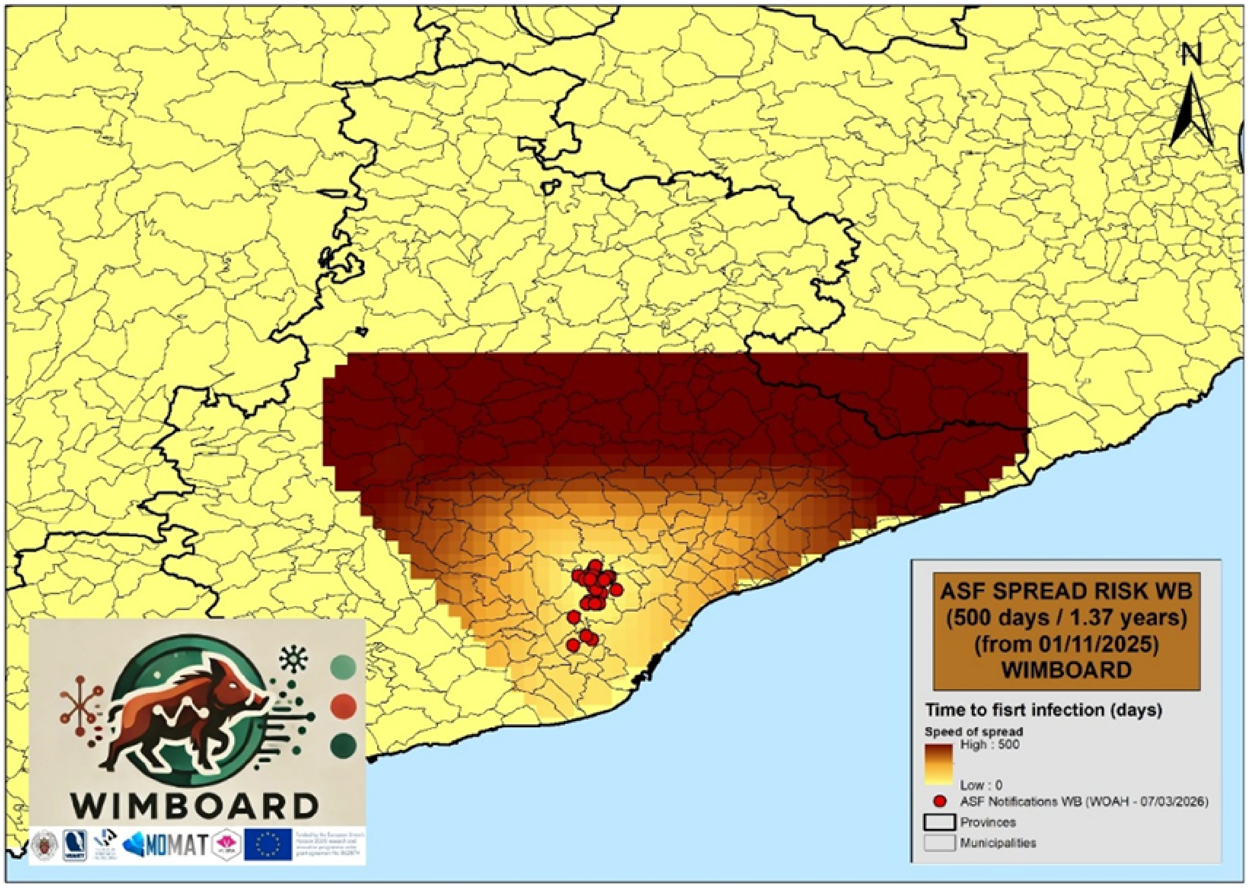

Figure 3: Time-since-infection surface after 500 days of simulated African swine fever (ASF) spread. Spatial distribution of the estimated timing of infection across the landscape, showing differentiated phases of epidemic expansion from the initial notified focus. The resulting pattern highlights marked directional asymmetries and supports the interpretation of a landscape-mediated transmission process structured by functional connectivity rather than by homogeneous distance-based diffusion.

4.4. Directional dispersal phases and regional amplification scenarios at landscape level

Under the Catalonia scenario, the outputs describe three main dispersal phases over a 500-day horizon. The first phase is directed southwards, approximately during the first 30 to 60 days and extending to around day 90, towards the Collserola system and the peri-urban southern sector. The second phase, occurring roughly between days 250 and 350, is oriented towards the north and northwest and represents the most important phase in terms of overall infection pressure and cumulative epidemiological impact. The third phase, between approximately days 400 and 490, is directed towards the northeast and appears less important than the previous one in terms of overall pressure. These phases are not arbitrary modelling artefacts. Rather, they are ecologically interpretable as successive expressions of how wild boar movement, local transmission, environmental contamination, and landscape structure interact over time.

The second dispersal phase identified by the model, oriented towards the northern and north-western sectors between approximately days 250 and 350, represents the most epidemiologically consequential expansion scenario within the simulated outbreak dynamics.

According to the WIMBOARD outputs, this phase corresponds to the period of highest potential infection pressure and spatial amplification. Unlike the initial southward signal, which unfolds within a highly fragmented peri-urban landscape, the northern sector is characterised by comparatively higher wild boar habitat quality, greater population abundance, and stronger functional landscape connectivity across broader spatial scales (Bosch et al., 2017b; Goicolea et al., 2024; Faustini et al., 2025). Habitat-suitability analyses for the region have previously shown that this northern mosaic contains some of the most favourable ecological conditions for sustained wild boar presence and movement, including extensive agro-forestry interfaces and structurally continuous habitat patches (Bosch et al., 2017b).

From a spatial epidemiology perspective, this configuration may act as an epidemiological amplification landscape. In practical epidemiological terms, this highly connected ecological matrix may function as a landscape-scale transmission basin facilitating regional-scale spread beyond the peri-urban interface. Increased host density, more homogeneous terrain permeability, and multiple corridor-mediated connections towards adjacent territories may facilitate multidirectional transmission diffusion rather than the more channelled propagation observed in peri-urban sectors. Under such conditions, infection spread could transition from a structured wavefront process to a broader regional expansion dynamic, potentially increasing persistence, spatial unpredictability, and long-term control difficulty. The WIMBOARD projections therefore suggest that, if ASF transmission becomes established within this northern connectivity network, containment efforts could become substantially more complex, with implications extending beyond the immediate outbreak area and potentially affecting the wider epidemiological stability of the Iberian wild boar system and associated domestic pig production sectors. This configuration may substantially increase the probability of long-term epidemiological persistence at the regional scale. The northern sector may therefore be interpreted as an epidemiological amplification landscape with increased potential for multidirectional spread and long-term persistence.

Importantly, this interpretation does not imply deterministic epidemic escalation, but rather highlights a scenario of heightened systemic vulnerability in which landscape structure, host ecology, and delayed detection dynamics converge. Within a precautionary risk-analysis framework, such projections support the prioritisation of anticipatory surveillance, early containment buffers, and targeted population-management strategies along predicted northern spread corridors.

The third dispersal phase identified by the simulation, corresponding to a lower-pressure northeastward expansion between approximately days 400 and 490, represents a later-stage expansion scenario characterised by comparatively lower cumulative infection pressure but continued spatial progression. In contrast to the northern amplification landscape, this phase appears to reflect a more attenuated diffusion dynamic in which transmission advances through progressively connected habitat elements rather than through large-scale connectivity networks. From an eco-epidemiological standpoint, this north-eastern signal may be interpreted as a secondary expansion front emerging once the primary transmission system has stabilised in earlier affected sectors. Although its projected epidemiological impact is lower than that of the north-northwest expansion, the persistence of directional spread at this stage highlights the potential for long-term spatial maintenance of infection within heterogeneous peri-regional landscapes. Consequently, this phase reinforces the need for sustained surveillance intensity beyond the initial outbreak period, as delayed expansion processes may continue to generate new transmission foci even after the main epidemic wave has progressed.

4.5. Peri-urban ecological modulation of transmission dynamics

A further layer of interpretation emerges when cumulative spatial risk patterns (Fig. 2), time-to-infection gradients (Fig. 3), and the dynamic monthly infection-risk surfaces (Fig. 4) are analysed together. These outputs illustrate landscape-mediated transmission dynamics and support anticipatory surveillance prioritisation in fragmented peri-urban wildlife systems. While the cumulative map provides a structural representation of the long-term geography of epidemiological pressure, the monthly outputs reveal the progressive and wave-like nature of the epidemic front, highlighting a spatially modular propagation process rather than a synchronous landscape-wide outbreak.

This pattern supports an eco-epidemiological hypothesis grounded in landscape ecology, whereby the fragmented peri-urban Mediterranean environment of the Barcelona urban–natural gradient may act as a landscape-mediated modulator of ASF transmission dynamics. In such systems, wildlife populations adapted to human-modified environments often display altered movement routines, flexible habitat use, and restructured contact networks driven by anthropogenic resources. These behavioural adaptations may reduce large-scale synchronous transmission events while favouring progressive spatial diffusion through semi-connected habitat patches and ecological corridors.

A further eco-epidemiological interpretation can be proposed when considering the role of anthropogenic resource distribution and peri-urban refuge habitats within the Barcelona urban–natural gradient. In highly human-modified landscapes, wild boar frequently exploit predictable waste-derived food sources, urban green infrastructure, and semi-protected peri-urban refugia, generating spatially heterogeneous aggregation patterns and behaviourally buffered movement dynamics (Aguilar-Vega et al., 2024; Amici et al., 2012; Hidalgo-Toledo et al., 2025; Pérez-González et al., 2025). Such landscape-mediated behavioural buffering may reduce synchronised mass-contact events while promoting modular, stepwise dispersal across semi-connected habitat patches. As a consequence, infection transmission may occur through a progressive wavefront mechanism characterised by spatial persistence, delayed mortality clustering, and increased surveillance uncertainty. This eco-epidemiological configuration is consistent with the temporal decoupling observed between early prevalence signals (Fig. 1), cumulative risk structuring (Fig. 2), directional spread velocity (Fig. 3), and the monthly propagation sequence described by the dynamic risk maps (Fig. 4), reinforcing the interpretation of ASF spread in peri-urban wildlife systems as a landscape-mediated epidemiological process rather than a purely density-driven epidemic expansion. In peri-urban systems, behaviourally buffered spatial diffusion may slow synchronised transmission while prolonging epidemiological persistence.

Consequently, infection spread may become temporally prolonged and spatially structured, generating comparatively lower early observable mortality signals while potentially increasing long-term persistence and epidemiological complexity. This interpretation is consistent with the temporal decoupling observed between infection prevalence dynamics (Fig.1) and cumulative spatial risk accumulation (Figs. 2–3), and provides a biologically plausible framework linking landscape fragmentation, wildlife urban adaptation, and ASF landscape epidemiology.

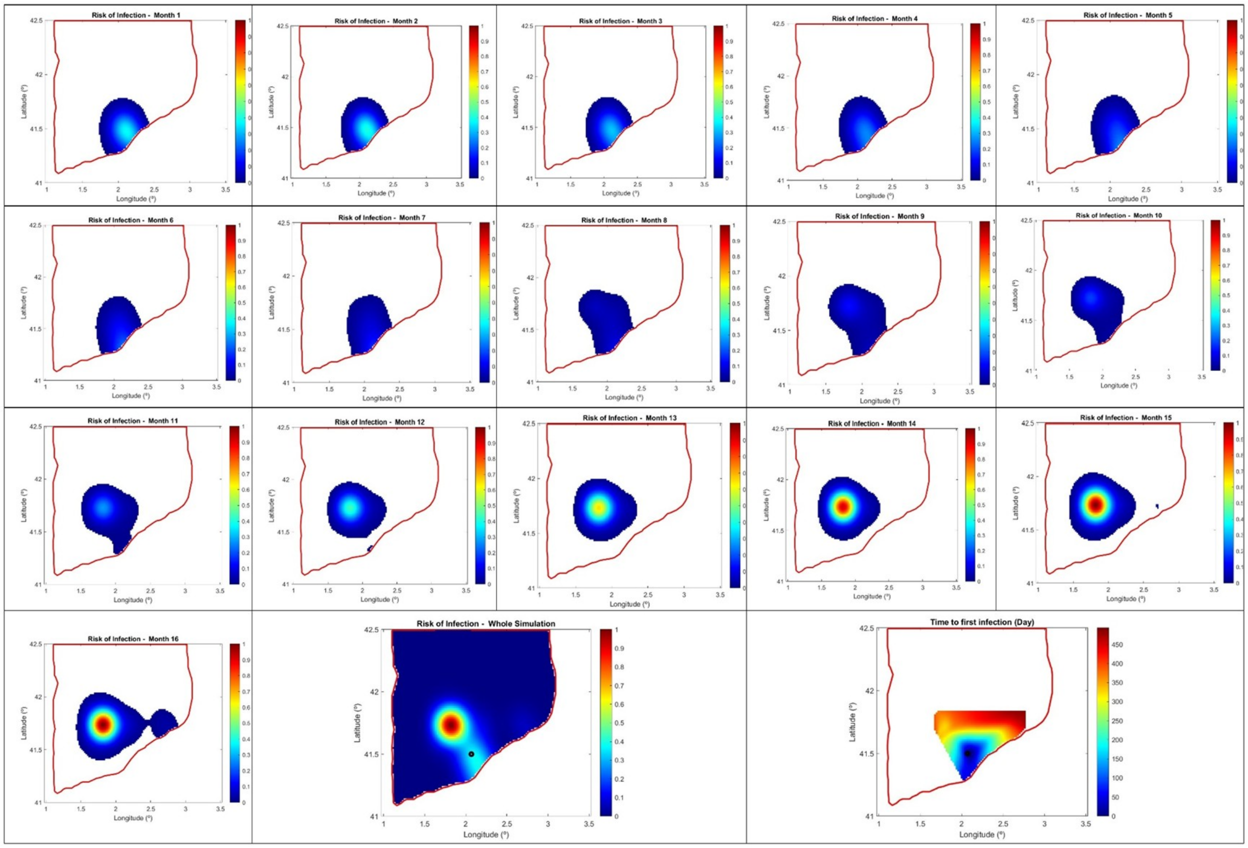

Figure 4: Monthly infection-risk dynamics of African swine fever (ASF) spread in wild boar populations under the Catalonia scenario. Sequence of spatial risk maps showing the normalised monthly infection probability relative to the maximum risk value observed across the full simulation scenario. The maps illustrate the progressive eco-epidemiological wavefront of disease spread during the 500-day modelling period, highlighting shifting spatial amplification zones, the delayed emergence of visible infection fronts, and temporally structured surveillance windows.

4.6. Monthly wavefront dynamics and surveillance timing

At monthly resolution, the dynamic infection-risk maps (Fig. 4) show that the outbreak behaves as a moving eco-epidemiological wavefront rather than as a fixed infected area. Risk does not expand uniformly across the landscape, but progresses through temporally shifting pockets of amplification and persistence that reflect local connectivity, environmental suitability, and corridor-mediated spread. This monthly sequence helps identify ecological timing in the epidemic process: some areas act as early transmission bridges, others as delayed amplification zones, and others as residual persistence pockets after the main front has advanced. From an operational perspective, this is particularly valuable because it defines shifting surveillance windows in space and time. Monthly risk surfaces define anticipatory surveillance windows by identifying areas that may become epidemiologically critical before visible mortality is detected. Areas with only moderate risk in one month may become epidemiologically critical shortly afterwards, especially in fragmented peri-urban systems where visible mortality may remain delayed. Interpreting ASF spread through these monthly surfaces therefore strengthens anticipatory surveillance, targeted carcass search, and the adaptive deployment of control measures along likely acceleration corridors.

At a finer temporal resolution, the monthly infection-risk maps (Fig. 4) further reinforce the interpretation of the epidemic as a moving spatial wave, illustrating how localised transmission pulses may precede visible epidemiological signals and thereby supporting anticipatory surveillance beyond the currently affected core. The monthly progression reflects successive local transmission events, movement through connected cells, carcass-associated environmental persistence, and the delayed emergence of visible infection fronts. This temporal progression also shows how localised transmission pulses can precede visible epidemiological signals, reinforcing the need for anticipatory surveillance targeting areas predicted to enter higher-risk phases. For outbreak management, this is highly relevant. Surveillance should not focus only on the currently positive core, but should also target areas that, according to the model, are likely to enter a higher-risk phase in the near future. This is where WIMBOARD becomes especially valuable as a practical tool: not because it predicts the future deterministically, but because it helps allocate attention in time as well as in space.

4.7. Field validation and functional connectivity evidence

Importantly, early field observations provide ecological support for these modelled dynamics. The early southward phase is particularly relevant because it closely matches the observed field evolution during the first weeks of the outbreak, including the appearance of positive detections towards Sant Cugat del Vallès and the southern Collserola sector. This early agreement between model outputs and field observations reinforces the operational credibility of the simulation. More importantly, it supports the interpretation that the southern signal is not necessarily an anomalous jump, but can instead be understood as a realistic early dispersal phase following ecologically favourable routes within a highly fragmented, yet still functionally connected, urban–natural system.

This interpretation becomes stronger when considered together with previous connectivity analyses developed for the same region. Least-cost path modelling and functional landscape-connectivity assessments have shown that the outbreak area is structured by habitat patches connected through non-obvious but epidemiologically relevant corridors, including riparian strips, agroforestry mosaics, peri-urban vegetation belts, and residual connective elements between infrastructure barriers. In particular, the least-cost route linking the initial outbreak area near the UAB/Bellaterra sector with the southernmost positive detection runs very close to a functional corridor previously identified in connectivity analyses (Goicolea et al., 2024). This corridor crosses riparian vegetation, agroforestry patches, and infrastructure interfaces, including the AP-7 area. From an eco-epidemiological standpoint, this is highly significant: the modelled direction of spread is consistent with a landscape in which movement is channelled through residual permeability rather than prevented by formal barriers.

This has direct implications for interpreting the southernmost positive live wild boar detected several kilometres south of the initial cluster. In a fragmented urban–peri-urban system such as Barcelona–Vallès, a positive live wild boar does not necessarily imply an abrupt epidemiological leap. More parsimoniously, it may represent the detectable edge of an infection process that has been moving through ecologically functional space before becoming visible to surveillance. This is particularly plausible if one considers that wild boar movement in such systems is not linear in Euclidean terms, but tortuous, patch-dependent, and strongly mediated by cover, resource availability, disturbance, and social structure. A distance of approximately 5–6 km in a straight line is therefore fully compatible with a longer, non-linear path through mosaics of natural cover, riparian habitat, agroforestry patches, or linear infrastructures.

The ecology of the urban–natural wild boar system is central to this interpretation. Wild boar in the Barcelona–Collserola–Vallès setting are neither purely urban animals nor purely forest animals. Rather, they occupy a hybrid ecological gradient in which urban areas function primarily as feeding grounds, while nearby natural patches provide structural refuge, social stability, and reproductive space. Habitat modelling based on Quality of Available Habitat has shown that agro-urban and agricultural resources located within approximately 2 km of natural habitat edges significantly increase the probability of recurrent wild boar use (Bosch et al., 2017b). This means that urban presence is rarely independent; it is usually sustained by nearby high-quality ecological cores. Therefore, the southern positive case should not be interpreted as urban spread detached from landscape ecology, but rather as spread rooted in a connected urban–natural wild boar system.

This urban–natural gradient fundamentally alters ASF ecology and surveillance. Compared with predominantly natural systems, peri-urban outbreaks involve higher human mobility, greater access to waste-derived resources, more opportunities for indirect transmission, and more socially constrained control measures. At the same time, they often offer greater carcass detectability because of increased human presence. Catalonia is therefore not simply a wild boar outbreak in a forest patch; it is an outbreak at the wildlife–urban interface, where ecological connectivity and anthropogenic pressure coexist. This hybrid configuration helps explain why risk can remain spatially structured even under intense fragmentation.

Hydro-ecological structure adds a further layer of ecological realism to the interpretation of WIMBOARD outputs. The relationship between ASF-positive wild boars and water-associated habitats has been documented in multiple contexts. In South Korea, Ito et al. (2024) found a very strong negative correlation between ASF-positive wild boars and distance to watercourses, identifying rivers and streams as priority areas for surveillance. Morelle et al. and subsequent European studies have also shown that carcasses are often found in cool and moist habitats, which may function both as preferred deathbeds and as areas of increased environmental persistence. In the Barcelona–Vallès case, the southern detection appears spatially associated with a non-permanent stream system that becomes functionally relevant during the wet season. This is especially important between November and March, when temporary streams regain hydrological continuity, riparian vegetation becomes denser, and valley-bottom routes may offer a combination of cover, moisture, and lower movement resistance.

In this context, the identified least-cost route is not only a connective path in abstract landscape terms; it also overlaps with a hydrologically structured corridor. Moreover, this route passes through the topographically lowest point beneath the motorway, where runoff is concentrated and where geomorphological conditions may favour both water flow and animal passage. This convergence between hydrology, topography, and least-cost connectivity is not trivial. It suggests the existence of a genuine functional corridor in which ecological movement, forced crossing, and potentially enhanced environmental suitability for ASF persistence coincide. The fact that WIMBOARD includes environmental and landscape variables implicitly related to topography, habitat structure, and movement resistance strengthens this interpretation. Thus, the clustered risk patterns observed in the model should be interpreted as reflecting, to a substantial extent, the influence of these ecological structures. The ecological discussion therefore goes one step further: it helps explain why the spatial outputs take the form they do.

The role of rail infrastructure also deserves attention. When habitual passages are closed, wild boar do not simply stop moving; they may redirect their movement towards alternative linear structures. Railway margins, embankments, and fenced corridors can, under certain conditions, function as unintended movement guides, especially if access is possible through local fencing failures, drainage points, or erosion gaps. In the Catalonia outbreak area, this possibility is ecologically plausible and should not be dismissed. It does not necessarily replace riparian or agroforestry connectivity, but may complement it, especially under conditions in which known wildlife crossings have been closed and movement becomes concentrated into fewer residual routes. From a modelling perspective, this is precisely why directionality matters: it helps identify where epidemiological pressure is likely to be re-routed even if the exact micro-corridor used by an individual cannot be observed directly.

4.8. Strain-dependent epidemiological interpretation

The risk outputs must also be interpreted in light of the biological characteristics of the strain involved. In its current operative configuration, WIMBOARD is primarily parameterised for highly virulent ASF strains, which is appropriate for most historical and emerging genotype II scenarios. This is fully consistent with the simulated epidemiological structure shown in Fig. 1, where recovery and immunity remain negligible and mortality becomes a dominant component of epidemic expression. In this context, the current projections may be interpreted as a conservative modelling scenario under acute-strain epidemiological assumptions applied to a highly anthropised and spatially heterogeneous landscape.

Such a configuration may partly explain the apparent discrepancy between the modelled high-virulence epidemic structure and the comparatively moderate early observable mortality signal detected in the field. Rather than contradicting the modelling framework, this divergence highlights the importance of landscape-mediated epidemiological modulation and behavioural buffering processes in peri-urban wildlife systems. Consequently, the Catalonia scenario should be interpreted as representing a biologically plausible interaction between strain characteristics, host ecology, and human-modified landscape structure, reinforcing the need for an adaptive interpretation of model outputs as new genomic and epidemiological evidence becomes available.

However, under the current Spanish epidemiological scenario, there are reasons to consider the possibility that the detected virus may not behave exactly like a classical highly virulent genotype II strain. The observed pattern has been interpreted as potentially compatible with lower transmissibility, lower apparent virulence, or an altered acute/subacute dynamic. Field observations further support this cautious interpretation, including the detection of seropositive wild boar and the confirmation of ASF-positive animals that were still mobile at the time of capture or selective removal, whether by trapping or targeted shooting. This indicates that at least some infected individuals may remain alive and epidemiologically active for longer than would be expected under a strictly classical acute high-virulence scenario. If this were confirmed, then the current WIMBOARD projections should be interpreted as potentially conservative, because infected animals surviving for longer could move further, excrete virus over longer periods, and generate a more diffuse transmission pattern before detection.

This does not weaken the model. On the contrary, it clarifies its interpretative framework. The current outputs provide a robust baseline scenario under acute-strain assumptions and current European control conditions. At the same time, the platform is being expanded through the incorporation of a specific module for attenuated-strain dynamics, drawing on previous work conducted with real experimental data from wild boar (Martínez & Bosch et al., 2023) . This future integration will allow the platform to represent both acute and attenuated epidemiological scenarios and to compare their spatial consequences more explicitly. For the Catalonia outbreak, the key implication is that field interpretation must remain adaptive: the present model outputs are highly informative, but should be read alongside new genomic, ecological, and surveillance evidence as it becomes available.

4.9. Integrated decision-support synthesis

Beyond its role as a spatial simulation framework, the Catalonia application demonstrates how the integrated interpretation of temporal epidemiological dynamics, cumulative spatial risk structuring, directional spread patterns, and monthly propagation sequences can provide a coherent eco-epidemiological understanding of ASF emergence in complex peri-urban wildlife systems. Rather than representing isolated modelling outputs, these results collectively support the interpretation of ASF spread as a landscape-mediated epidemiological process shaped by functional connectivity, host behavioural adaptation, and delayed detectability dynamics. In this context, WIMBOARD operates not only as a predictive modelling platform, but also as an operational decision-support framework capable of identifying ecological transmission windows, anticipating spatial amplification scenarios, and guiding adaptive surveillance prioritisation, including the potential emergence of landscape-scale transmission basins in highly connected ecological sectors. This temporal framing also reinforces the operational value of anticipatory surveillance targeting future risk zones beyond currently affected areas. Such an integrative interpretation strengthens proactive risk governance by translating multi-scale ecological processes into actionable spatial intelligence for wildlife disease management under conditions of environmental heterogeneity and anthropogenic pressure. WIMBOARD thus translates eco-epidemiological complexity into operational spatial intelligence for anticipatory wildlife disease management. Table 1 summarises the integrative conceptual framework combining modelling outputs, epidemiological dynamics, and landscape-mediated wildlife ecology within a peri-urban ASF outbreak scenario.

Table 1: Conceptual eco-epidemiological interpretation integrating modelling outputs, wildlife behavioural ecology, and landscape structure under the Catalonia ASF scenario.

Component	**Landscape-ecological mechanism**	**Expected eco-epidemiological effect**	**Operational implication**
Landscape fragmentation (urban-agro-natural mosaic)	Reduced habitat continuity and spatial compartmentalisation of wild boar subpopulations	Progressive rather than explosive transmission dynamics	Need for spatially differentiated surveillance buffers
Wildlife urban adaptation	Modified movement routines and flexible resource exploitation (modular functional mobility adapted to a human environment)	Altered contact networks and asynchronous infection spread (altered/restructured wild boar social/contact networks)	Surveillance must include peri-urban interfaces and waste-related hotspots
Anthropogenic food resources	Aggregation around predictable human-derived food sources	Localised infection persistence and recurrent transmission foci	Targeted carcass search and communication strategies in human-modified areas
Corridor-mediated connectivity	Functional ecological links despite infrastructure barriers	Directional and wave-like epidemic expansion	Strategic placement of fencing, traps, and population-management actions
Behavioural buffering and modular mobility	Stepwise dispersal between semi-connected habitat patches	Lower initial observable mortality but prolonged epidemiological pressure and persistence; less synchronised epidemiological contact and more structured spatial diffusion	Anticipatory surveillance based on the predicted spread sequence
Integrated modelling interpretation	Coupling temporal prevalence dynamics with cumulative spatial risk surfaces	Landscape-mediated epidemiological modulation	Use of WIMBOARD as an operational decision-support tool

4.10. Operational implications and translational relevance

From a management perspective, the implications are direct. The model outputs indicate that surveillance should be intensified not only within the initial cluster, but also along ecologically plausible directions of spread; that carcass search should prioritise functionally connected corridors, riparian belts, and barrier interfaces; that fencing strategies should focus on residual permeability points rather than on assumed barrier lines; and that selective population control should be timed before spring reproductive amplification, particularly under scenarios in which virus establishment in wild boar remains a risk. In highly anthropised systems, this must be complemented by waste management, public communication, access control, and strict attention to indirect human-mediated transmission pathways.

Ultimately, the Catalonia case illustrates the main strength of WIMBOARD: its outputs become most useful when interpreted ecologically. The model does not merely indicate where infection may occur. It shows how outbreak risk is shaped by the interaction between host behaviour, landscape structure, hydrological interfaces, environmental persistence, and human modification of ecosystems. This is why its value is translational. It converts multidisciplinary knowledge into operational geography. Applied mathematics provides the simulation architecture; veterinary epidemiology defines transmission dynamics; ecology explains host behaviour and habitat use; landscape analysis clarifies connectivity; and field response gives the results operational meaning. In this combined sense, WIMBOARD is not only a predictive tool, but also a practical framework for linking ecological interpretation with outbreak control in complex wildlife disease systems.

At its current level of operational maturity, WIMBOARD has been deployable across European landscapes since 2023, enabling large-scale spatial epidemiological modelling while delivering fine-scale, operationally actionable intelligence for outbreak interpretation and risk management. As a new-generation operational spatial epidemiology platform, WIMBOARD has the capacity to support coordinated cross-border disease-intelligence frameworks across Europe and beyond, and to be rapidly transferred to diverse regions worldwide. Its mature and scalable modelling infrastructure allows immediate uptake in real-world management environments, while its flexible architecture facilitates adaptation to heterogeneous ecological systems, epidemiological dynamics, and governance structures across diverse global contexts. By explicitly integrating and capturing the ecological and epidemiological role of wild boar in pathogen circulation, environmental contamination pathways, and long-term reservoir persistence, WIMBOARD provides a strategic preparedness and response platform extending beyond African swine fever to a broader spectrum of wildlife-mediated disease threats of global relevance.

Importantly, WIMBOARD is itself the product of a multidisciplinary effort and is not delivered as a static analytical tool, but as an operational decision-support framework embedded within a multidisciplinary implementation process. Its deployment is supported by a multidisciplinary expert team providing targeted technical advisory services tailored to specific epidemiological, ecological, and management contexts. This expert support accompanies platform implementation through context-driven model calibration that incorporates local wildlife-management realities, landscape constraints, surveillance infrastructures, and institutional and governance decision-making needs. Through this adaptive, interactive, and context-sensitive co-implementation model, WIMBOARD enables continuous system refinement and improvement, strengthens evidence-based policy responses, and maximises the effectiveness, acceptability, and long-term sustainability of disease-mitigation strategies across diverse geographic and epidemiological settings. As such, WIMBOARD constitutes a ready-to-use strategic instrument for authorities seeking to enhance preparedness, optimise resource allocation, and strengthen proactive wildlife-disease governance at multiple spatial scales.

By bridging advanced spatial modelling, operational decision support, and adaptive technical implementation, WIMBOARD contributes to redefining how wildlife-associated disease risks are anticipated and managed in complex socio-ecological systems, particularly under conditions of landscape-mediated epidemiological modulation and wildlife urban adaptation that fundamentally reshape transmission dynamics across human-modified environments.

5. Conclusions

The Catalonia outbreak illustrates how African swine fever (ASF) spread in wild boar populations within highly anthropised peri-urban environments cannot be fully understood through simplified assumptions of homogeneous diffusion or purely reactive outbreak interpretation. The integrated analyses presented in this work support the interpretation of ASF spread as a landscape-mediated epidemiological process shaped by functional connectivity, host behavioural adaptation, fragmented urban-agro-natural mosaics, and delayed detectability dynamics.

Within this framework, the application of WIMBOARD provided a coherent eco-epidemiological reconstruction of outbreak dynamics by linking temporal epidemic behaviour, cumulative spatial risk structuring, directional dispersal phases, and monthly wavefront propagation. The resulting outputs consistently indicate that infection spread is structured, directional, and ecologically modulated, rather than isotropic, and that visible mortality may substantially lag behind the true spatial extent of viral circulation. This has direct implications for outbreak interpretation, surveillance prioritisation, and the design of anticipatory control strategies.

A particularly relevant result is the identification of differentiated dispersal phases, including a southward early signal consistent with field observations and a north-northwest expansion scenario with increased potential for regional amplification and long-term epidemiological persistence. These findings reinforce the importance of interpreting ASF dynamics through the lens of functional landscape connectivity and peri-urban wildlife ecology, especially in systems where host movement, anthropogenic resources, ecological corridors, and delayed mortality visibility interact.

More broadly, this study highlights the translational value of WIMBOARD as an already operational decision-support platform for ASF preparedness, risk assessment, and outbreak management. Beyond the Catalonia case, the platform offers a spatially transferable framework capable of integrating experimental epidemiological evidence, ecological realism, and scenario-based modelling in support of proactive disease governance. In this sense, WIMBOARD contributes to translating eco-epidemiological complexity into operational spatial intelligence for anticipatory wildlife disease management under real-world conditions.

References

Aguilar-Vega, C., Sánchez-Vizcaíno, J.M., Bosch, J., 2024. Identifying sites where wild boars can consume anthropogenic food waste with implications for african swine fever. PLOS ONE 19, e0308502. doi:`10.1371/journal.pone.0308502`.

Amici, A., Serrani, F., Rossi, C.M., Primi, R., 2012. Increase in crop damage caused by wild boar (Sus scrofa l.): the "refuge effect". Agronomy for Sustainable Development 32, 683–692. URL: `https://dspace.unitus.it/handle/2067/35075`.

Barrios-García, M.N., Ballari, S.A., 2012. Impact of wild boar (Sus scrofa) in its introduced and native range: a review. Biological Invasions 14, 2283–2300. doi:`10.1007/s10530-012-0229-6`.

Bosch, J., Iglesias, I., Muñoz, M.J., De la Torre, A., 2017a. A cartographic tool for managing african swine fever in eurasia: mapping wild boar distribution based on the quality of available habitats. Transboundary and Emerging Diseases 64, 1720–1733. doi:`10.1111/tbed.12559`.

Bosch, J., Ivorra, B.P.P., Aguilar-Vega, C., Ito, S., Sánchez-Vizcaíno Rodríguez, J.M., Ramos del Olmo, Á.M., 2026. African swine fever in spain (catalonia, november 2025): Lessons learned from science, surveillance, and field response. URL: `https://docta.ucm.es/entities/publication/4a994792-9c99-4264-abb4-960382b7dc3d`.

Bosch, J., Peris, S., Fonseca, C., Martinez, M., De la Torre, A., Iglesias, I., Muñoz, M.J., 2012. Distribution, abundance and density of the wild boar on the iberian peninsula, based on the CORINE program and hunting statistics. Folia Zoologica 61, 138–151. doi:`10.25225/fozo.v61.i2.a7.2012`.

Bosch, J., Rodríguez, A., Iglesias, I., Muñoz, M.J., Jurado, C., Sánchez-Vizcaíno, J.M., De la Torre, A., 2017b. Update on the risk of introduction of african swine fever by wild boar into disease-free European Union countries. Transboundary and Emerging Diseases 64, 1424–1432. doi:`10.1111/tbed.12527`.

Faustini, G., Soret, M., Defossez, A., Bosch, J., Conte, A., Tran, A., 2025. Habitat suitability mapping and landscape connectivity analysis to predict african swine fever spread in wild boar populations: A focus on northern italy. PLOS ONE 20, e0317577. doi:`10.1371/journal.pone.0317577`.

Goicolea, T., Cisneros-Araújo, P., Vega, C.A., Sánchez-Vizcaíno, J.M., Mateo-Sánchez, M., Bosch, J., 2024. Landscape connectivity for predicting the spread of ASF in the european wild boar population. Scientific Reports 14, 3414. doi:`10.1038/s41598-024-53869-5`.

Hidalgo-Toledo, S.P., Pérez-González, J., Hidalgo-de Trucios, S.J., 2025. The landscape of fear and wild boar (Sus scrofa) spatial use in a peri-urban area from west-central spain. Land 14, 1845. doi:`10.3390/land14091845`.

Ito, S., Bosch, J., Aguilar-Vega, C., Jeong, H., Sánchez-Vizcaíno, J.M., 2024. Geospatial analysis for strategic wildlife disease surveillance: African swine fever in south korea (2019–2021). PLOS ONE 19, e0305702. doi:`10.1371/journal.pone.0305702`.

Kawaguchi, N., Aguilar-Vega, C., Sasaki, M., Orba, Y., Sawa, H., Sánchez-Vizcaíno, J.M., Isoda, N., Bosch, J., Ito, S., 2025. Risk mapping of african swine fever in domestic pigs and wild boars to enhance management and surveillance in asia. Transboundary and Emerging Diseases 2025, 8850856. doi:`10.1155/tbed/8850856`.

Martínez, M.A., Bosch, J., Ivorra, B., Ramos, Á.M., Ito, S., Barasona, J.Á., Sánchez-Vizcaíno, J.M., 2023. Epidemiological impacts of attenuated african swine fever virus circulating in wild boar populations. Research in Veterinary Science 162, 104964. doi:`10.1016/j.rvsc.2023.104964`.

Pérez-González, J., Hidalgo-Toledo, S.P., Martínez, R., Hermoso-de Mendoza, J., Gonçalves, P., Hidalgo-de Trucios, S.J., 2025. Demography, peri-urban presence, and male-biased dispersal in an expanding wild boar (Sus scrofa) population in western spain. European Journal of Wildlife Research 71, 149. doi:`10.1007/s10344-025-02030-2`.

De la Torre, A., Bosch, J., Iglesias, I., Muñoz, M.J., Mur, L., Martínez-López, B., Sánchez-Vizcaíno, J.M., 2015. Assessing the risk of african swine fever introduction into the european union by wild boar. Transboundary and Emerging Diseases 62, 272–279. doi:`10.1111/tbed.12129`.

Appendix A. Supporting resources and dissemination

This research was supported by the Horizon 2020 program of the European Union through the European Project H2020 “VACDIVA - A Safe DIVA vaccine for African Swine Fever control and eradication” project (grant agreement no. 862874). This work was also funded by project PID2023-146754NB-I00, funded by MCIU/AEI/10.13039/501100011033 and by the European Regional Development Fund (FEDER, EU), and by project PCI2024-153478 under the European M-ERA.Net programme, funded by MCIU/AEI/10.13039/501100011033 and the European Union.

VACDIVA
Funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No 862874
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
Cofinanciado por la Unión Europea
AGENCIA ESTATAL DE INVESTIGACIÓN

Appendix A.1. European research framework and operational modelling platform development (WIMBOARD)

VACDIVA — A safe DIVA vaccine for African Swine Fever control and eradication

Grant Agreement No. 862874 (Horizon 2020, European Commission)
Project duration: October 2019 – December 2024
Project DOI: `https://doi.org/10.3030/862874`

The VACDIVA project aimed to develop innovative tools for African swine fever (ASF) control and eradication, including vaccine research, epidemiological preparedness strategies, wildlife disease-management frameworks, and decision-support modelling systems. Within this multidisciplinary European research environment, the WIMBOARD platform was conceived and operationally developed as a spatial epidemiological modelling and decision-support framework for ASF outbreak risk assessment and management in wild boar populations.

The final World Technology Transfer Workshop of the VACDIVA project was held on 12 December 2024 in Brussels at the European Economic and Social Committee (EESC). The event brought together scientists, policymakers, international organisations, and livestock-sector representatives to present and discuss the project's main technological and scientific advances for improving ASF prevention, preparedness, and control. New epidemiological tools were also showcased, including the WIMBOARD ASF Risk and Vaccination Assessment Platform, an innovative online decision-support tool designed to optimise ASF surveillance and vaccination strategies. The platform attracted strong interest from international organisations because of its potential to enhance field implementation and monitoring, particularly as a translational outcome developed within Work Package 7 of the VACDIVA project.

Project information and dissemination resources

`https://cordis.europa.eu/project/id/862874`
`https://vacdiva.eu`
`https://vacdiva.eu/activities/vacdiva-final-world-technology-transfer-workshop-key-advancements-in-asf-control/`

Appendix A.2. Public communication and dissemination of WIMBOARD modelling applications

Public outreach describing the application of WIMBOARD to the Catalonia outbreak scenario and related modelling results was disseminated through Universidad Complutense de Madrid channels on 15 December 2025:

- `https://www.ucm.es/momat/news`
- `https://www.ucm.es/analisis-peste-porcina-africana-cataluna?ver`
- `https://www.ucm.es/imi/file/noticia-peste-porcina?ver`

International technical dissemination was later carried out through the contribution entitled *African Swine Fever in Spain (Catalonia, November 2025) – Lessons Learned from Science, Surveillance, and Field Response*, prepared in January 2026. This work was submitted on 28 January 2026 to *Friend of Pig Farmers* (*Yōton no Tomo*, Japan), published in the March 2026 issue, and made available in English through the following resources:

- **Friend of Pig Farmers (Japan)**
  Submitted: 28 January 2026
  Issue: March 2026
  `https://w3.alpha-web.ne.jp/~chikutomo/youton.html`
- **English full-text version (Docta UCM)**
  `https://docta.ucm.es/entities/publication/4a994792-9c99-4264-abb4-960382b7dc3d`
- **ResearchGate dissemination**
  `https://www.researchgate.net/publication/400983538_African_Swine_Fever_in_Spain_Catalonia_November_2025_-_Lessons_Learned_from_Science_Surveillance_and_Field_Response`