EXTERNAL SCIENTIFIC REPORT

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Modelling wild boar management for controlling the spread of ASF in the areas called white zones (zones blanche)

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Abstract

African Swine Fever (ASF) is an infectious lethal disease affecting domestic pigs and wild boar. In the EU the infection perpetuates predominantly in wild boar populations. ASF control comprises wild boar population reduction measures, e.g. pre-emptive culling in delineated zones, called white zones (WZ). These WZ are placed geographically adjacent to an area with ASF circulating in wild boar (ASF positive area). The ideal WZ would be depopulated of wild boar without possibility of recolonization. However, WZ may still harbour live wild boar after its establishment and the functionality of the WZ inherently foresees ASF entering it. But the spread of the infection is expected to stop within an effective WZ. The concept must not match legislative zones, likewise infected area, Part I, Part II, etc. In order to compare different approaches to implement a WZ (e.g. targets and speed of population reduction in the WZ, width of the WZ, and distance of the WZ from the ASF-positive area), an individual-based spatially explicit model was adjusted to four historic WZ-like situations in the EU, i.e. Estonia 2014, Latvia 2016, Czech Republic 2017, and France 2018. The model was used to simulate the reported spatio-temporal layout and targeted measures. The stochasticity of the model provided understanding of the general efficiency of these WZ. Alternatives of the local measures were simulated as scenarios to identify caveats of the settings and derive improvements in future applications. The simulation outcome suggests issues to be addressed in implementing future WZ: i) distance between ASF-positive area and the WZ was adequate if adapted to the speed of propagation according to the local wild boar density, and the time horizon of depopulation measures envisaged for the WZ; ii) the width of the WZ was adequately set if everywhere it was prevented that short infection chains already led out of the zone, iii) the WZ around focal introductions was most efficient if depopulated by culling the maximum of a defined (or fenced) population in shortest time with minimal disturbance, for instance, by trapping, sharp shooting or using silencers. Aspects of density, timing and spatial distribution in relation to the efficiency of WZ layout are explored.

Key words: African Swine Fever, wild boar, individual-based, spatial-temporal simulation, white zone, control measures, hunting, carcass removal, fencing, ASF-free management area

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Table of contents

1. Introduction

1.1. Background and Terms of Reference as provided by the requestor

This contract was awarded by EFSA to:

Contractor: Helmholtz – Zentrum für Umweltforschung GmbH – UFZ

Contract title: Modelling the effectiveness of measures applied in dedicated zones to stop the spread of African Swine Fever in wild boar and to assist in the development of an exit strategy.

Contract number: NP/EFSA/ALPHA/2020/09

1.2. Background and Terms of Reference

African Swine Fever (ASF) is an infectious lethal disease affecting domestic pigs and wild boar. It can be transmitted via direct animal contact or via dissemination of contaminated food or equipment. ASF has serious economic implications for the pig meat and related sectors, including indirect costs related to trade restrictions. The persistence of the disease in wild boar and the limited number of control measures available represents a challenge for the whole EU agricultural sector, in particular the pig farming industry. There is no commercially available vaccine or cure despite active ongoing research.

ASF free regions, neighbouring infected areas, are at higher risk of getting ASF infection via natural spread of the disease through wild boar. Based on previous EFSA reports and expert recommendations, geographical areas called white zones (zones blanches) were put in place to implement effective reduction of the wild boar population and enable disease surveillance through active search for carcasses. The task replied by this report, was to assess the effectiveness of measures in white zones using data on previous interventions in ASF-free management areas compatible with the concept of white zones, and the robustness and effectiveness of the boundaries used for the determination/demarcation of these areas.

1.3. Interpretation of the Terms of Reference, Objectives & Purpose

How to understand the strategic concept of White zones (in this report)? White zones (WZ) are meant to be geographically adjacent to an area with ASF circulating in wild boar (ASF positive area). The WZ will equivalently be called negative area (or ASF free management areas). None of these concepts must be confused with legislative zones, such as the ASF-infected area, Part I, Part II, etc. Geographical overlap between the two structures is not mandatory.

In a WZ, measures are undertaken to preventively reduce the wild boar population before ASF can possibly enter from the adjacent positive area (or not!). These measures entail the preparation of the WZ to act as buffer towards even more distant ASF free areas yet without management. The ideal WZ would be a defined area where wild boar is eradicated, and recolonization excluded. Because perfect implementation of such a zero-approach might be difficult in the field, a WZ may still harbour live wild boar after its establishment and population reduction measures implemented. The intended functionality of the WZ inherently foresees that ASF might enter but the spread of the infection is expected to stop inside the defined WZ. In other words, a white zone remains in function even if no longer "white", "ASF-free" or "negative" – the importance is whether eventually the infection chain ceases inside the demarcated area. Nonetheless, in practice, WZ usually will be extended once ASF enters, as a precaution.

This principle is the basis of the methodology described in the following sections and the assessment of the capability of WZ measures to control the spread of ASF.

The theoretic, model-based investigation of different ASF management zones in wild boar populations, including the WZ concept, their size, intensity of measures and timing of actions therein were reported elsewhere (https://ecoepi.eu/ASFWB). In particular Lange (2015), Thulke & Lange (2017) investigate the effectiveness of pre-emptive measures applied in WZ-like areas adjacent to a large infected wild boar region. Lange et al. (2018) provides the detailed investigation of effectiveness of population reduction measures in WZ around a focal introduction including an assessment of the robustness of the fences lines around the infected inner part.

Therefore, in this study the focus was on the analysis of the effectiveness of measures applied in areas understood as WZ in a certain historic context. The objective of this report is to model and simulate those particular situations covering alternative ecological situations and different control measures applied, in order to understand why certain combinations of activities are effective in achieving the aim of a WZ, i.e. stopping the spread of ASF inside.

In this report, technical details of the methodology and the structured output of the simulations including an uncertainty discussion are provided. The assessment section of this report is structured according to the four scenes of WZ that were established in EU member states with sufficient field data accessible at the time of writing this document. The interpretation boxes address issues, conclusions, and limitations of the study in each WZ.

The report details research activities of the NP/EFSA/ALPHA/2020/09 contributing to the EFSA output on an ASF Epidemiological Report (EFSA 2021a).

2. Data and Methodologies

2.1. Data

The wild boar habitat model by Pittiglio et al. (2018) was used to map the spatial structure of the relative wild boar abundance distribution. The map was converted into the breeding capacity raster of 3x3km (EE, LV, CZ) resp. 2x2km (FR) according to the proportionality parameter BCconversion (BreedingCapacity [per cell] = BCconversion * RelAbundance [per km²]).

Events of human-mediated ASF translocations were applied according to Lange et al. (2018) and based on ADNS notification data as of October 2018 provided by EFSA.

Geographical scenes, GIS layers and historic schedules of measures were used as immediate model input according to EFSA 2021a.

2.2. Methodologies

2.2.1. Field evidence

Field evidence of measures applied in WZ in different areas of the EU was taken from the Epidemiological Report (Table 8; EFSA, 2021a). Data were accessible for different periods of ASF management in the EU (as early as 2014 and at time when more experience was gained with the ASf epidemic five to six years later), different wild boar population structures (low to high density habitat affected) and alternative control situations (advancing epidemic front vs focal introduction). The data (Table 8 in EFSA 2021a) were applied as immediate input about spatial details of the WZ established as well as timing and planned intensity of measures applied therein. Data comprises the size, the time of establishment and timing of measures for WZ, fences used as demarcation, shot animals and carcasses found. Per member state (MS) scene one model landscape was developed.

2.2.2. Spatially explicit stochastic model

Next the detailed situation per MS was implemented in a spatially explicit stochastic individual-based model. The model is developed to simulate spread and control of ASF in wild boar in structured landscapes of wild boar habitat. The tool was used in support of previous EFSA output relating to ASF in wild boar and in particular for a principal assessment of the capacity to manage ASF spread in alternative scenarios (i.e. large-scale front, EFSA 2015 & 2017, or focal introduction EFSA 2018a). The disease component of the model was updated with knowledge on ASF infection and epidemiology as reviewed in EFSA (2021b). The updated standardised model documentation (ODD protocol; Grimm et al. 2006 Grimm et al. 2010) is available from http://ecoepi.eu/ASFWB/WZ.

The model framework has been developed and applied in the context of multiple infectious diseases of wild boar, i.e. CSF, FMD, and ASF. The model compiles (i) an ecological component detailing processes and mechanisms related to the ecology, sociology and behaviour of wild boar in natural free-roaming populations of the species Sus scrofa; (ii) an epidemiological component reflecting individual disease course characteristics and transmission pathways including direct contact transmission on different spatial scales and environmental transmission caused by ground contamination or contacts with carcasses of succumbed infected host animals; and (iii) a management component implementing surveillance and control scenarios in a spatio-temporal explicit manner. The model is stochastic in relation to all three components and parametrised using reported distributions from literature including variability and uncertainty. Model population emerges from birth and death probabilities depending on habitat quality on the level of individual social groups.

The component representing wild boar ecology was validated independently of ASF in terms of habitat use predicted by the model rules, regarding reproduction, breeding capacity and sub-adult dispersal. Validity of predictions was field-verified with spatial distribution of opportunistic sighting of wild boar in Denmark (Moltke-Jordt et al. 2016). Moreover, the model was shown to accurately predict geographical disease spread and time of infection circulation if the modes of infection and transmission are conceptually understood (EFSA, 2012; Dhollander et al. 2016).

The model uses habitat maps to represent population distribution and dynamics. These maps determine local reproduction and density variations. The structure of the model habitat is based on (Pittiglio et al. 2018) as abundance approximates, as ENETWILD was not yet readily available. Maximum abundance or density are calibrated to estimations provided by the MS for each region (EFSA, 2021a). Finally, the data provided by the MS regarding hunting records and carcasses found in and around the white zone were used to validate or adjust the population numbers emerging from the model habitats.

On the geographic landscape the spread of ASF is initialised according to the ADNS notifications and simulated considering relevant human-mediated translocation events until the date when the WZ was established. From there on, ASF spread is simulated, and control efforts applied to the white zone including fencing, ASF -related excess hunting, depopulation activities and carcass search/removal. The purpose is to investigate each white zone under the epidemiological situation where it was established, and where one possible outcome was already known from the field.

Model output is aggregated to derive:

- the likelihood of the observed outcome with a particular white zone (post-hoc),
- the probability of successful control over time of the applied measures, and
- potential amendments to the previous suggestions on measures in ASF-free management zones (EFSA 2015, 2017, 2018a).

Dynamic visualisations of example simulation output are available from http://ecoepi.eu/ASFWB/WZ.

2.2.2.1. Transmission model of ASF infections in wild boar

The basic principle of transmission relates to the number of adjacent/in contact animals and carcasses using event probabilities, i.e. each infectious object provides a chance of transmission to every susceptible animal sufficiently close.

Wild boar is acknowledged to organise in a matriarchal structure with female groups of strong kinship and satellite solitary movement and temporary aggregation of males with sow groups. Consequently, the wild boar-ASF-system comprises three potential modes of transmission, i.e. between live animals of the same social group (within group transmission), between live animals of different groups (between group transmission) and between carcasses of animals succumbed to the infection and live animals (carcass-mediated transmission). The conceptual framework of multi-modus transmission was established during past usage of the model (Kramer-Schadt et al. 2009; Lange & Thulke 2017; Lange et al. 2018) and recently validated by an ecological study of contact frequency within and between social groups (Podgorski et al 2017). Details of the modes of transmission related to ASFV were studied also by Pepin et al. (2020).

Parametrisation of the modes of transmission is based on multiple sources. Quantitative experimental data is accessible for within-group transmission, i.e., animals in permanent contact with groupmates (transmission trials; see review in EFSA 2021b). Between group transmission was parameterised relative to the within group transmission and reversely calibrated against the speed of propagation (Lange et al. 2018). Evidence regarding the role of carcasses of animals dying as consequence of an ASF infection is very experimental, including the potentially contaminated soil thereunder (Probst et al. 2017; Probst et al. 2020). Given the assumption that carcass-mediated transmission is relevant, insights exist on the likely volume of carcass-based transmission in the spread of ASF (Pepin et al. 2020). Based on the reverse parametrisation procedure by Lange & Thulke (2017), ubiquitous access to dead animals (i.e. not hiding or retreating due to morbidity) but very seldom actual contacts that may warrant transmission (blood, secretions or body fluids) has to be modelled to reconstruct adequate spatial spread patterns.

2.2.3. Simulation protocol

The simulations were performed on real habitat geography. Habitat maps for all scenes (i.e. EE, LV, CZ and FR) are derived from the habitat model according to Pittiglio et al (2018).

The landscape is further calibrated to the overall population density in the WZ prior to ASF, based on data input by the MS. Respective lower and upper alternative density scenarios were constructed to understand sensitivity of the outcome to the exact density input per WZ.

The infection was released according to the first ASF notifications in wild boar in each scene following ADNS data since 2014 and continued spread simulated by the model. Particularly, human-mediated translocations of the infection previously identified from notification data (Lange et al. 2018) were forced to happen in the simulations before the historic date reported for the establishment of a particular WZ. After that date, no further human-mediated translocations were replayed. The motivation is that the infection in the field did jump due to human-mediated translocations into the white zone immediately after its establishment which would bias the testing of efficiency of measures targeting the wild boar spread.

The measures are implemented with two flexible attributes: 1. the <u>duration of campaigns</u> determines the time per measure to achieve a specified target, and 2. the <u>interval between campaigns</u> determines after what time horizon a repeated campaign with the same target will be applied. Fences are erected by the date reported in EFSA (2021a) using the provided geography of the fence-line. Fences are simulated with a permeability of 10% (see Lange & Thulke 2015). Special modifications (e.g. target female hunting) according to individual treatments are mentioned in the specific sections.

The resulting 18 parameter combinations (3 initial densities, 3 target densities, 2 time horizons of measure) were simulated each with 100 repetitions.

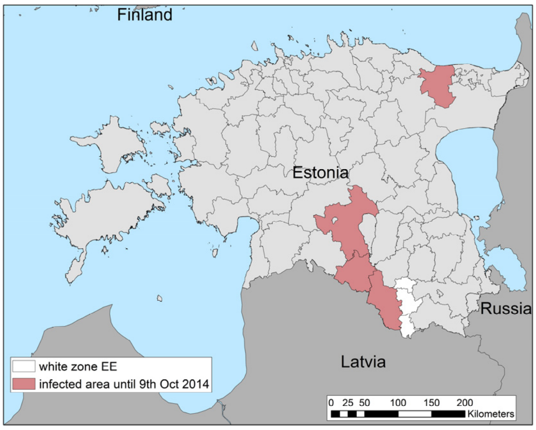
3. Results

3.1. Model scenes according to historical situation

The data provided by the MS facilitated the model-based analysis of four scenes. Two are negative areas (“white zone”) in front of the epidemic expansion on large scales (EE, LV) and two in the focal setting of local control measures (CZ, FR). The first scene from Estonia (EE) happened early in the European ASF genotyp II context. The second scene is from Latvia (LV) and already well into the time of ASF control in the EU. The third scene refers to the focal management of ASF entry into the Zlin region of Czech Republic (CZ), the first focal control application. The fourth scene addresses the French (FR) Zone Blanche, original of the concept, being a preventively managed zone in response to the focal situation across the border in Belgium.

3.1.1. WZ Scene EE

3.1.1.1. Data Input



A

Surface: 575 km²

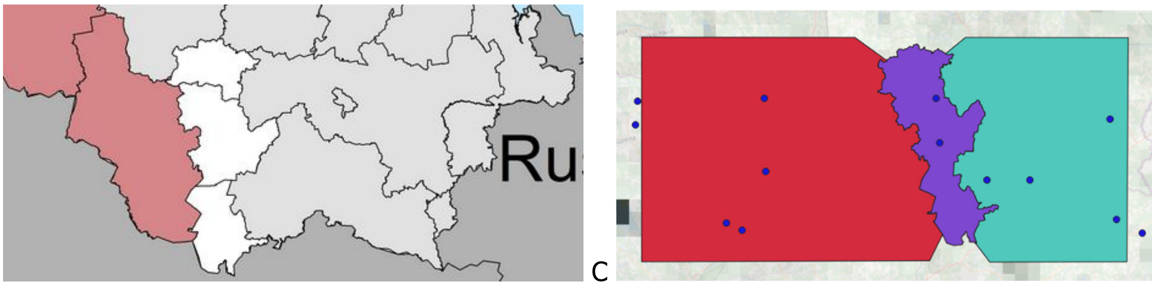
Established: 09.10.14 (Entry detected: 31.08.15)

Active samples: 136 (73 till 13.02.15)

Passive samples: none

Initial density: 1.5/km²

Target: normal hunting



B C

Figure 1. A-C. The WZ-EE established on Oct 9th, 2014.

Figure 1 shows the historic WZ in Estonia (WZ-EE) in the geographic context (A, B) and as schematic abstraction (C). The WZ-EE comprised two particularities. First, as this white zone was established very early after the entry of ASF into the EU, in 2014, no particular measures were implemented yet. Hence, the simulation without any efforts to control is the reference here. Second, the WZ is declared in accordance with notifications as shown by the red administrative units (A; as of Oct 8th, 2014). At the time of its establishment, the WZ-EE was a designation of risk of future ASF entry rather than an area dedicated to preventing further spread of the infection by certain (pre-emptive) control of the wild boar population. Therefore, it was not an issue that ASF might also spread theoretically "around" the WZ to the North of the WZ marked in the scene (B). To keep the testing principle, the simulated ASF was not allowed to spread "around" the WZ neither in the north nor in the south. Hence the analysis addresses the capacity to stop spread of the infection inside the WZ (C; lilac) on its way from left (red) to right (green).

3.1.1.2. Model landscape and zones

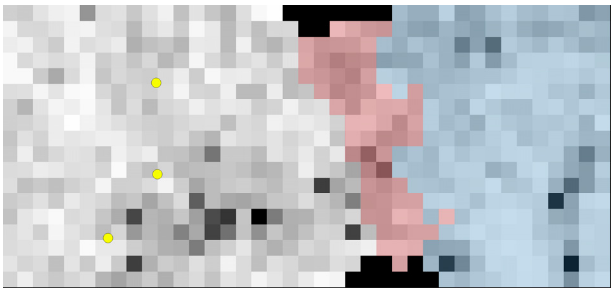


Figure 2. Simulation area representing the scene of the WZ-EE. Black squares represent virtual water bodies preventing ASF infection from bypassing the WZ to the north or south.

Figure 2 shows the details of the simulation landscape. Squared pixels represent wild boar group habitat patches of different quality according to the wild boar distribution model of Pittiglio et al (2018). According to the notifications (ADNS), the simulated ASF started from the west also considering human-mediated translocation events until Oct 9th, 2014. Hereafter the WZ is established (red cells in front of still ASF-free area to the east (blue shaded) and no further translocation was simulated.

3.1.1.3. Simulation outcome

Summary WZ-EE:

The layout of the WZ-EE resulted in 100% failure i.e. in all 100 simulations ASF did spread through this WZ.

Reason: No measures applied. **Note: Historically WZ-EE was not designed for taking measures.**

Video-Link: https://ecoepi.eu/ASFWB/WZ/#WZ-EE

Input:
- Area: 575 km²
- Density: ~1.5/km²
- Population reduction: no measures
- Time: no measures

Output:

Density per km² :: *release* 1.5 (1-2.4 90% central range); *incursion* unchanged

Time interval in years :: *release-establishment* 2 (input)

establishment-entry 0.7 (0.6-1.3)

entry-exit 0.4 (0-1)

Additionally hunted in WZ :: 0

Infected wild boar in WZ :: 850 (700-1000)

- *Density prior to ASF (release)*

The simulations started with levels of population density in the WZ suggested by input data (prior to ASF; boxed scenario in Figure 3A) although stochasticity and in particular annually varying living conditions, forced relevant differences between the simulation runs (Figure 3).

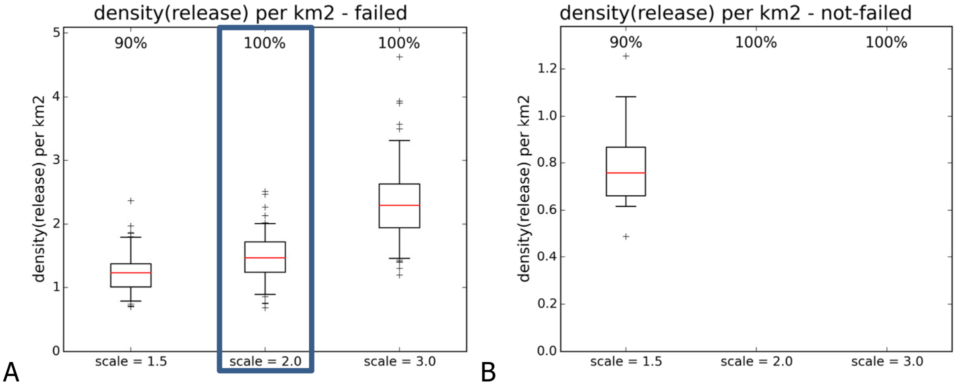


Figure 3 A-B. Wild boar density in the WZ-EE prior to management measures and ASF lethality read from model simulations for runs where the simulation ended in failure of the WZ to halt the spread of the infection, i.e. ASF infections occurred beyond the WZ (A) and runs ending with success of the WZ, i.e. ASF infections faded out inside the WZ (B). Top row values represent percentage of runs in which the managed WZ did fail to halt the spread of ASF. The blue box marks the scenario most similar to the input information.

The alternative habitat scenarios (scale 1.5; 2.0; 3.0) resulted in median population densities about 1.2, 1.5 and 2.3 animals per km². The values therefore cover the pre-ASF population density reported for

Estonia. There was a tendency but only small difference in effectively realised starting density for individual runs that did fail (Figure 3A) vs those not failing (Figure 3B).

- *Density at ASF entry to the WZ-EE*

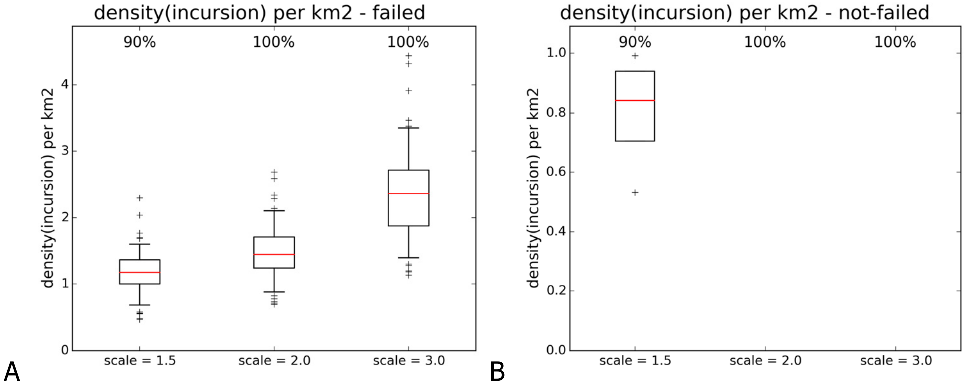


Figure 4 A-B. Wild boar density in the WZ-EE in the moment when ASF enters the WZ for runs where the simulated WZ failed to halt the spread of the infection, i.e. ASF infections occurred beyond the WZ (A) and runs ending with success of the WZ, i.e. ASF infections faded out inside the WZ (B). Top row values represent percentage of runs in which the managed WZ did fail to halt the spread of ASF.

The second density level of interest relates to the moment when ASF infection enters the demarcated and treated WZ (Figure 4). The potential difference between runs in which the WZ failed to stop ASF (Figure 4A) and runs where it was successful (Figure 4B) regarding the wild boar density in the WZ at entry could be considered to explain the different final outcomes, however, as the difference is due to stochastic nature of the modelled processes, the observation might have limited practical relevance in WZ design and planning.

- *Time interval from establishment to ASF entry into & from entry to break-out of the WZ*

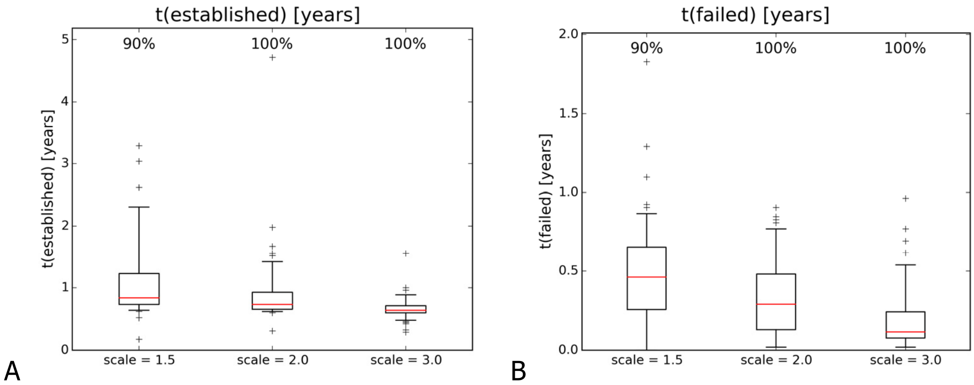


Figure 5 A-B. Time interval from establishment of the WZ-EE till the entry of ASF into the WZ (A) and from entry to the first ASF infection beyond the WZ area (B). Data are shown for three different starting densities (scale 1.5, 2.0 and 3.0; x-axis). Top row values represent percentage of runs in which the WZ did fail to halt the spread of ASF.

The simulation seeds infection according to notifications reported in ADNS falling into the simulation landscape. Subsequently, ASF spread is simulated stochastically until the historic date of establishment of the WZ-EE. Subsequent to establishment, measures are simulated in the WZ and spread simulation continued. Figure 5 evaluates the simulated ASF spread by the time segment before the infection approached the WZ-EE (established; Figure 5A) and the time segment ASF needed to leave the WZ (failed; Figure 5B). The greater the simulated density in the WZ was at entry, the faster the infection passed through the WZ (Figure 5B), i.e. the higher was the spreading velocity.

- *Number of infections in WZ*

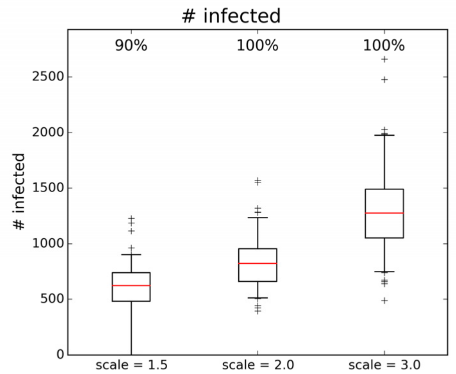


Figure 6. Number of infected wild boar in the WZ-EE. Data are shown for three different starting densities (scale 1.5, 2.0 and 3.0; x-axis). Top row values represent percentage of runs in which the managed WZ did fail to halt the spread of ASF.

The density of wild boar in the WZ influenced the spread velocity of the simulated ASF (Figure 5B). This could be considered to explain why the number of infected animals rather declines from left to right in Figure 6, although greater densities would imply more possible hosts. According to Figure 4A, at ASF entry into the WZ the median density was 1.2, 1.5 and 2.4. The area surface area input data was 575km² which leads to median number of susceptible hosts of 690, 860 and 1380 animals. During the median time needed to pass the WZ of 0.5, 0.3 and 0.15 (Figure 5B) there were about 120, 110 and 60 infections (Figure 6). The subsequent coverage of the whole simulation area (see Figure 7) indicates that substantially more infections inside the WZ happened after the failure of the WZ.

- *Spatial distribution of ASF*

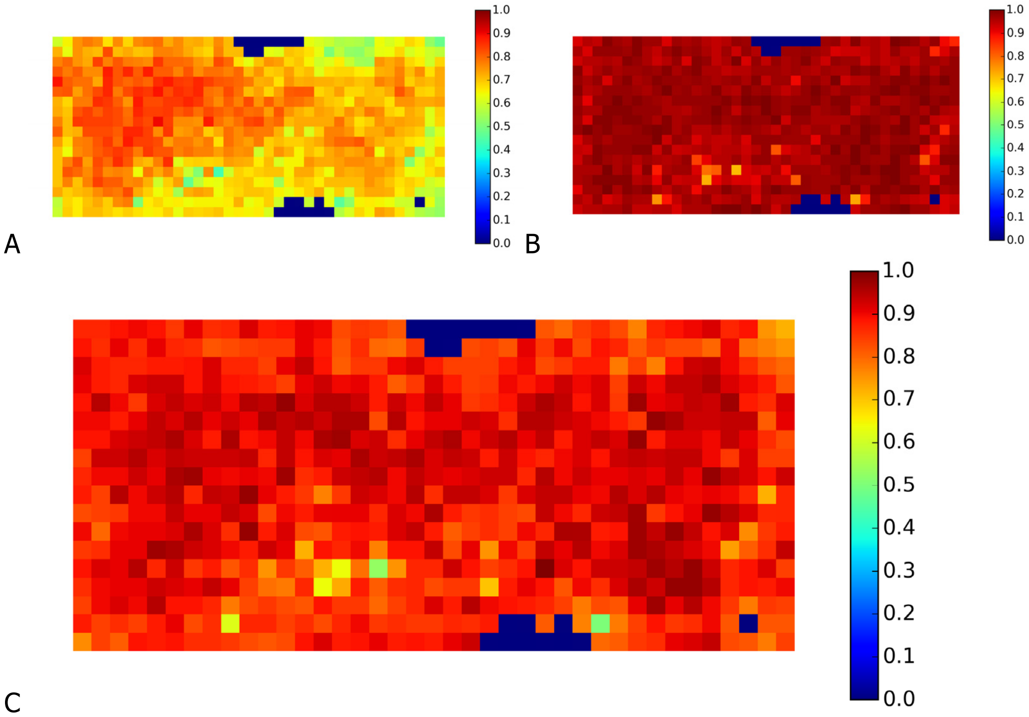
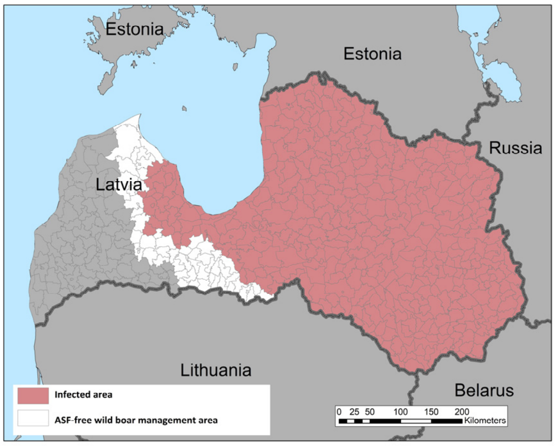


Figure 7 A-C. Heat map of ASF occurrence inside and adjacent to the WZ-EE. The greater value a wild boar habitat cell has, the greater the proportion of simulations runs in which the cell contained ASF-positive animals.

Figure 7 provides an overview of the impact of the WZ-EE on the spread of the infection. Given there are no measures foreseen, the expected outcome reveals no effect of the WZ for the three density scenarios low (1.5, Figure 7A), high (3.0, Figure 7B) and standard (2.0, Figure 7C). Note: The historic WZ-EE was not designed for wild boar population management at that time in context of ASF.

3.1.2. WZ Scene LV

3.1.2.1. Data Input



Surface: 5754 km²

Established: 12.08.16 (Entry detected: 23.10.16)

Active: see files

Passive: 10

Initial density: 1.1-2.0 WB/km²

Target: <0.5 WB/km², after 2 hunting seasons; selective on female

Note: (2016/1372/EU)

Figure 8. The WZ-LV established on Aug 12th, 2016.

3.1.2.2. Model landscape and zones

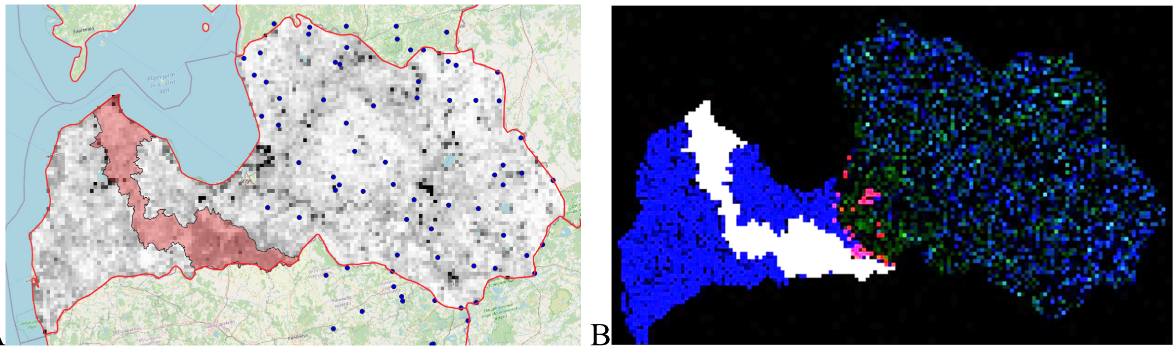


Figure 9 A-B. Simulation area representing the scene of the WZ-LV (A) and snapshot of the simulation at the moment of establishment of the WZ-LV (B).

Figure 9A shows the details of the simulation landscape. Squared pixels represent wild boar group habitat patches of different quality (varying grey shade) according to the wild boar distribution model of Pittiglio et al (2018). The simulation starts from the east, equivalent with the historic notifications (ADNS) including forced events until Aug 12th 2016 (blue dots). Hereafter the WZ is established (red cells) in front of still ASF-free area to the west. Further simulation of the ASF spread considers the changes to the wild boar population emerging from management measures applied to the WZ (here hunting to reduce the density e.g. to 0.5 per km² within two hunting seasons). The snapshot in Figure 9B reveals the distribution close to the WZ (reddish coloured wild boar groups) resulting from the simulation. The particular allocation of infected wild boar is from one arbitrary simulation run and varied between repetitions due to the stochastic nature of the model.

3.1.2.3. Simulation outcome

Summary WZ-LV:

The layout of and the target measures within the WZ-LV resulted in 94% failure i.e. in only 6 out of the 100 simulations ASF did not spread through this WZ.

Reason: Inhomogeneous thickness of the WZ along its lengths ranging between x and y km perpendicular to the direction of ASF spread.

Video-Link: https://ecoepi.eu/ASFWB/WZ/#WZ-LV

Input:
- Area: 5754 km²
- Density: ~1.5/km²
- Population reduction: at 0.5/km²
- Time: Two hunting seasons

Output:

Density per km² :: release 1.5 (1-2 90% central range); incursion 1.1 (0.6-1.8)

Time interval in years :: release-establishment 2 (input)

establishment-entry 1 (0-1.5)

entry-exit 2 (1-4) [94 of 100 runs]

Additionally hunted in WZ :: 5000 (2500-12000) // per km² 0.87 (0.4-2.1)

Infected wild boar in WZ :: 1200 (500-2000)

Female hunting: The short time available between WZ establishment and entry by ASF violates the concept of targeted female hunting as measure for population control. The results are worse than for arbitrary population reduction (ref time interval establishment-entry of less than 2 years).

- *Emergent density (range prior to ASF)*

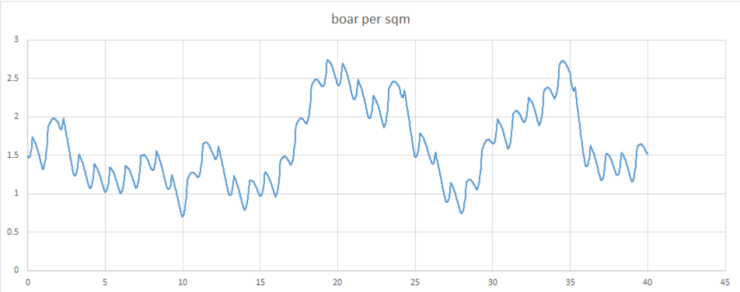


Figure 10. Variation of wild boar population density within the WZ-LV over several years of simulations reflecting the stochastic variation between different years.

- *Density prior to ASF*

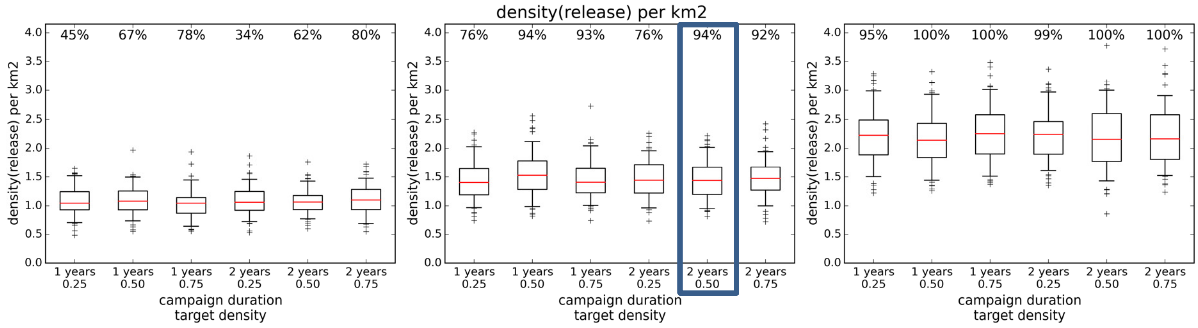


Figure 11. Wild boar density in the WZ-LV prior to management measures and ASF lethality. Data are shown for three different starting densities (diagrams left to right about 1, 1.5 and 2 wild boars per km²) and alternative management scenarios (x-axis, determined by duration and intensity of the programme). Top row values represent percentage of runs in which the managed WZ did fail to halt the spread of ASF. The blue box marks the scenario most similar to the input information.

The values of population density in the WZ at release of the infection (Figure 11) report the wild boar density across simulations without impact of measures or ASF lethality.

- *Density at ASF entry to the WZ-LV*

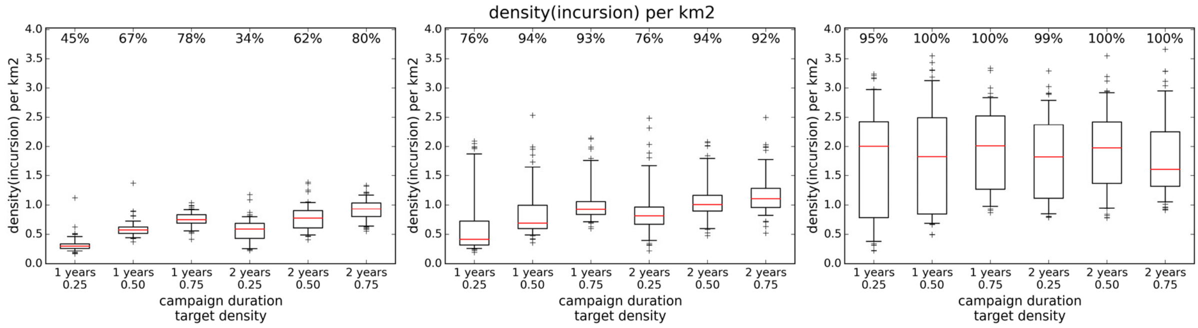


Figure 12. Wild boar density in the WZ-LV at the moment of ASF entry, i.e., after measures were applied since date of establishment of the WZ. Data are shown for three different starting densities (diagrams left to right) and alternative management scenarios (x-axis). Top row values represent percentage of runs in which the managed WZ did fail to halt the spread of ASF.

The values of population density in the WZ at entry report to what extend the targeted management aims were in place yet, i.e. whether population reduction plans were completed (Figure 12). The fulfilment of the density target inside the WZ varies from adequate population reduction (Figure 12 left diagram) to unreliable impact on the population by the measures (Figure 12 right diagram). Therefore, it appeared useful to detail the temporal aspect of the WZ, i.e. the period between establishment of the WZ-LV (fixed date according to input) and the eventual approach of the infection at the WZ (stochastic simulation outcome).

- *Time interval between release of ASF and entry to the WZ*

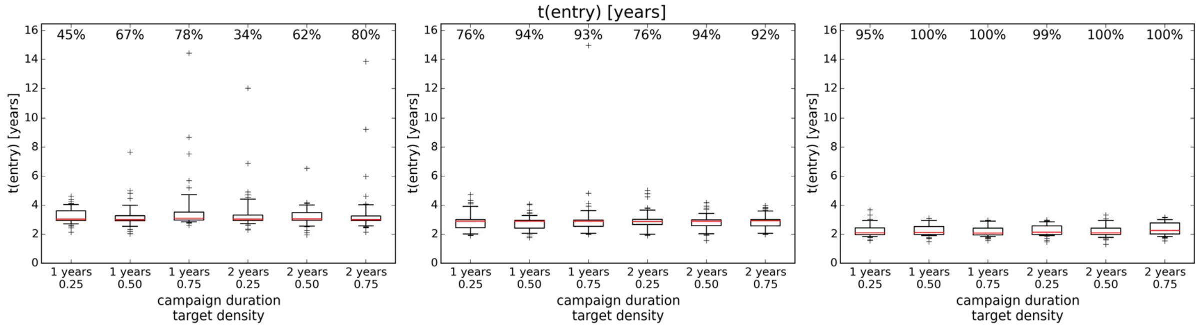


Figure 13. Time interval between release of ASF and entry into the WZ-LV. Data are shown for three different starting densities (diagrams left 1/km² to right 2/km²; Figure 11) and alternative management scenarios (x-axis). Top row values represent percentage of runs in which the managed WZ did fail to halt the spread of ASF.

Reasonably, the time interval between release of the infection and entry into the WZ does not vary between alternative management plans (Figure 13; x-axis, per diagram); but does shorten with increasing density at start, indicating slightly faster speed of propagation in areas with greater wild boar density (Figure 13; diagrams from left to right).

- *Time interval between establishment of and entry to the WZ*

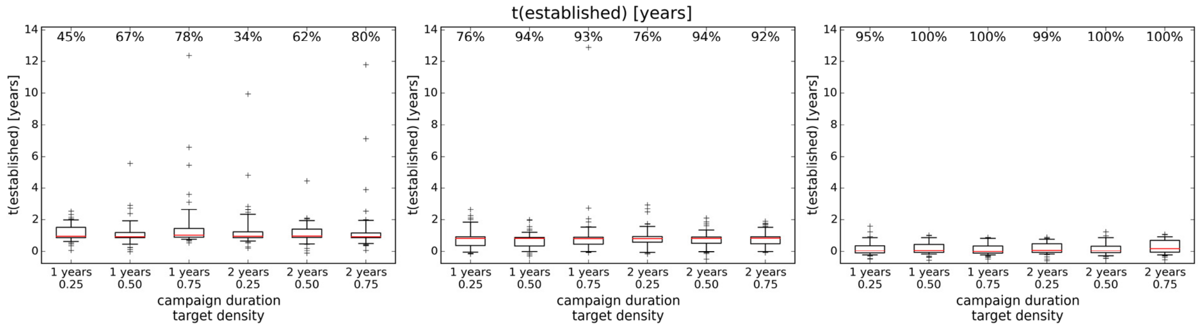
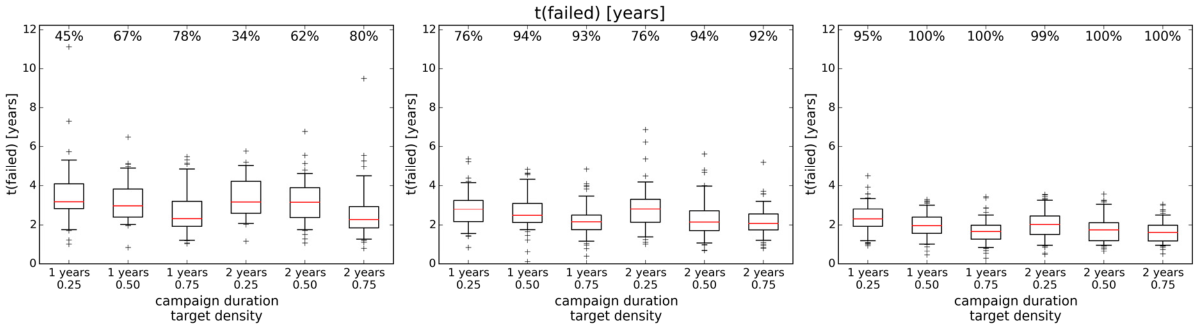


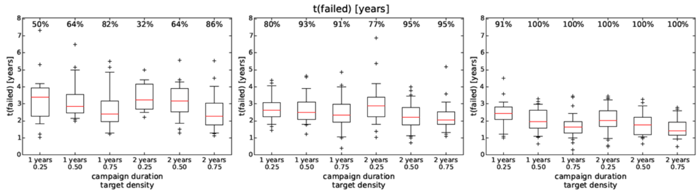
Figure 14. Time interval between establishment of and ASF entry into the WZ-LV. Data are shown for three different starting densities (diagrams left 1/km² to right 2/km²; Figure 13) and alternative management scenarios (x-axis). Top row values represent percentage of runs in which the managed WZ did fail to halt the spread of ASF.

Figure 14 shows that the time interval between declaration/establishment of and the entry of ASF into the WZ-LV again does not differ between alternative management scenarios because there is no other management simulated than the measures in the WZ. Figure 14 indicates that there was not sufficient time left after establishment of the WZ to complete a program of two hunting seasons before ASF reached the WZ.

- *Time interval between entry to and break-out of the WZ*

Figure 15 shows the duration of ASF spreading through the WZ-LV. Shorter time to fail indicates greater speed of propagation thorough the WZ. Interestingly, comparing the measures applied in either strategy reveals that lower target density corresponds with longer time interval between entry and first exit of the WZ. This implies that faster speed of propagation the more animals are left by the measures in the WZ. Since the simulation, after establishment of the WZ, did no longer replay historic human-mediated translocations, the realised speed is directly related to time and distance.



NB: 

Another 100 runs illustrating uncertainty.

Figure 15. Time interval between entry of ASF into the WZ-LV and the first ASF infection beyond the WZ area. Data are shown for three different starting densities (diagrams left to right, Figure 11) and alternative management scenarios (x-axis). Top row values represent percentage of runs in which the managed WZ did fail to halt the spread of ASF.

Figure 14 reported the effective time interval available to complete pre-emptive implementation of the planned measures (values given on the x-axis for campaign duration and target density). Even with the optimistic scenario (Figure 14 left diagram) less than two years were available and hence the aimed density in the WZ at the moment of entry was not yet reached for campaigns designed over two seasons (right three box-plots per diagram in Figure 12).

The time dimension related to the WZ-LV indicates the pitfalls of such zoning. First, the time between establishment of the WZ (start of measures) and the approach of the WZ by ASF was about one year (Figure 15; 0-1.5). Second, the time between ASF approaching the WZ and failure (i.e., exiting the WZ towards the free-region) lasted another 2 years (Figure 16; 1-4y in the central 90% range)

- *Number of excess hunted animals due to measures*

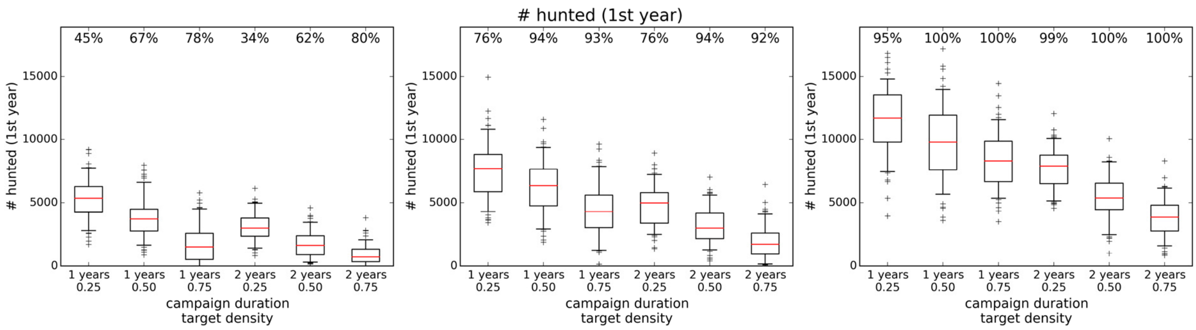


Figure 16. Wild boar hunted additionally to the normal hunting efforts during the first year after the establishment of the WZ-LV. Data are shown for three different starting densities (diagrams left to right, Figure 11) and alternative management scenarios (x-axis). Top row values represent percentage of runs in which the managed WZ did fail to halt the spread of ASF.

Figure 16 reflects the extra hunting effort necessary and applied in the simulations to achieve a certain population number target. Excess hunting starts only after establishment of the WZ.

The MS reported the historic target of a resulting density of 0.5/km² after two hunting seasons.

- *Number of infections in WZ*

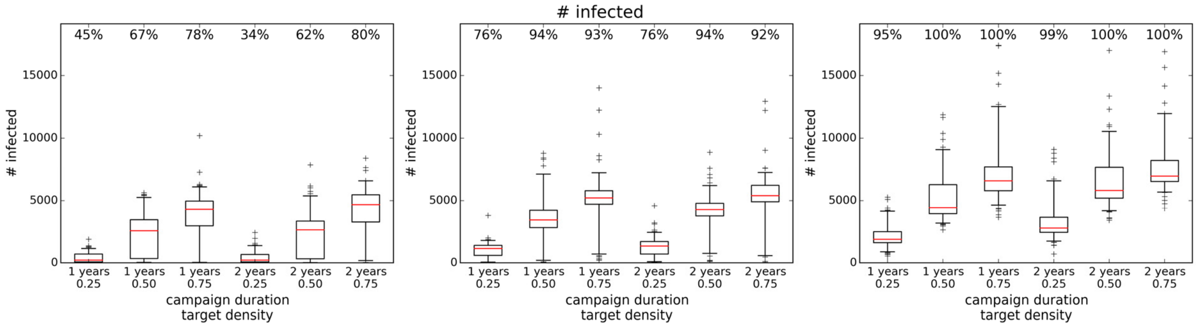


Figure 17. Number of infected wild boar in the WZ-LV. Data are shown for three different starting densities (diagrams left to right, Figure 11) and alternative management scenarios (x-axis). Top row values represent percentage of runs in which the managed WZ did fail to halt the spread of ASF.

- *Spatial distribution of ASF*

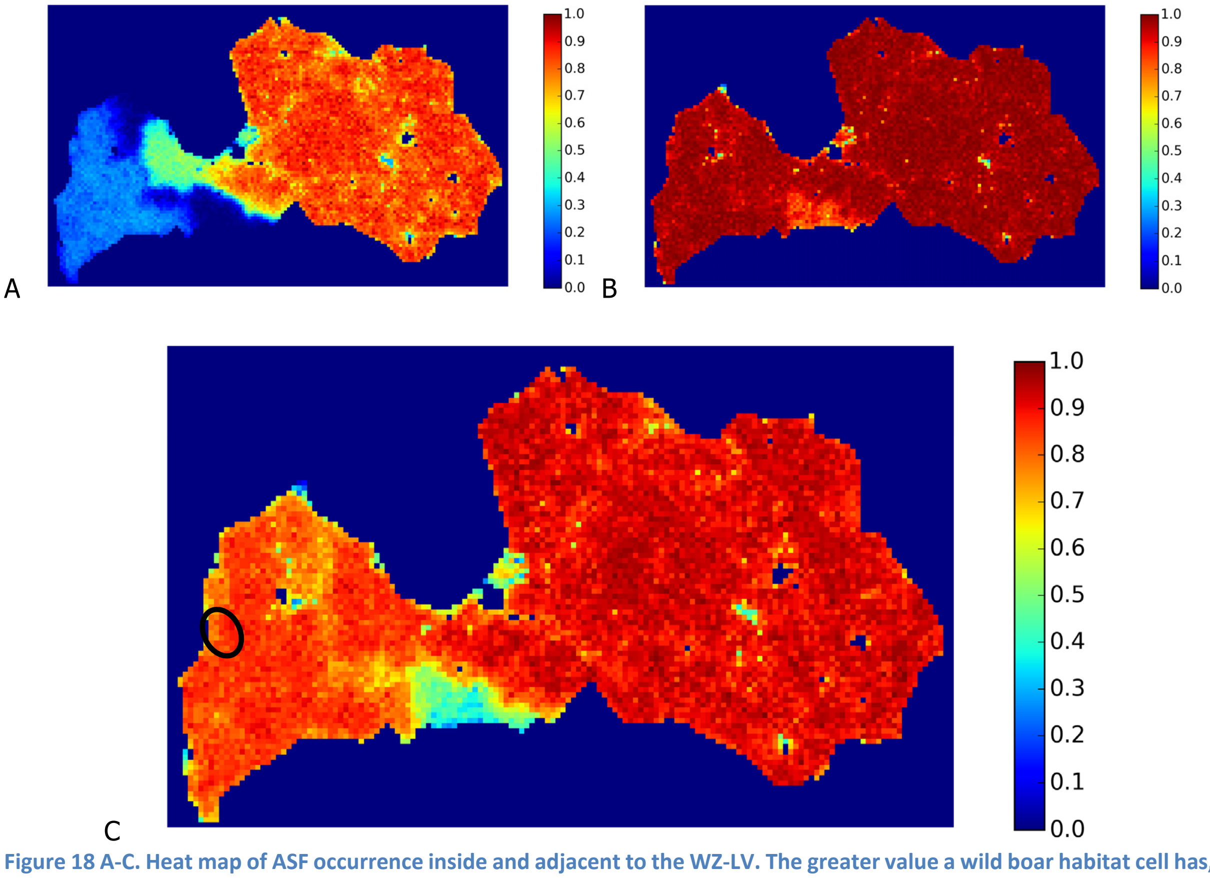


Figure 18 A-C. Heat map of ASF occurrence inside and adjacent to the WZ-LV. The greater value a wild boar habitat cell has, the greater the proportion of simulations runs in which the cell contained ASF-positive animals.

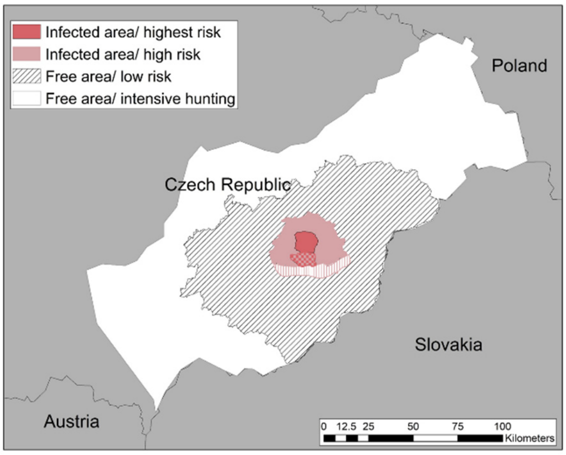
Figure 18 reveals the impact of the WZ-LV on the spread of ASF in wild boar using the heat map resulting from 100 runs per three scenarios. Top left the most optimistic with low starting density (~1/km²) and within one season down to 0.5/km² (Figure 18A). Top right the most pessimistic scenario with high starting density (~2/km²) and within two seasons down to only 0.75/km² (Figure 18B). The larger map shows the outcome of the main scenario i.e. starting density at 1.5/km² and within two seasons down to 0.5/km² (Figure 18C).

In particular optimistic scenarios (Figure 18A) reveal how the pre-emptive measures inside the WZ reduce the capacity of the infection to maintain continuous spread. However, the more wild boar inhabit the WZ the lower is the impact of the pre-emptive measures (Figure 18B+C). This insufficient effect relates to the thin design in the middle of the WZ, which is the location through which most of the runs failed (encircled in Figure 18C).

Interestingly, the basic effect of the WZ is clearly visible in the southern part of the standard scenario (yellow to blue values, Figure 18C) while the "bridge" due to thin layout in the middle section of the WZ facilitates final ASF spread into the left part of the simulation area in most runs.

3.1.3. WZ Scene CZ

3.1.3.1. Data Input



Positive area: 160 km² (58 fenced; 102 not-fenced) [Extended 1.2.18 following break-out]

Surface WZ: 9374 km² (low + intensive hunting zone)

Established: 26.06.17 (Entry detected: none)

Active: 14475+[6118] (positive: 648+[109]

Passive: 445+[200] (positive: 332{200+}+[88{12+}]

Initial density: uncertain, 3 up to 10 WB / km²

Target: intensive hunting

Figure 19. The WZ-CZ established on June 26th, 2017.

3.1.3.2. Model landscape and zones

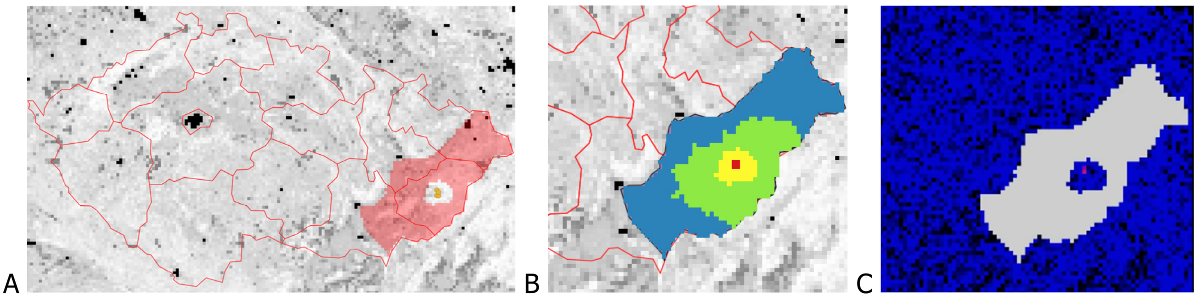


Figure 20 A-C. Simulation area representing the scene of the WZ-CZ (A), the four historic areas (B; red = core area fenced, yellow = core area not fenced, green + blue pre-emptively hunting area), and snapshot of the simulation at the moment of establishment of the WZ-CZ (C).

(Glossary: red = highest risk area fenced, yellow ~ high-risk area not fenced, green ~ low risk area, blue = intensive hunting area; after Feb 1 2018 slight interchanges between yellow and green apply in response to the breakout of ASF from the fenced red area; EFSA 2018b)

Figure 20 shows the details of the simulation landscape for the WZ-CZ. The square grid cells represent wild boar group habitat patches. Their quality increases with lighter shading, and the structure follows the wild boar distribution model of Pittiglio et al (2018). The simulated spread starts inside the fenced core area (red part Figure 20B). ASF infection can stochastically cross the fence. Additionally, in January 2018 ASF is seeded, according to history, outside the fence towards the south (but still inside the yellow section in Figure 20B). Culling, targeting depopulation of the core area (red + yellow in Figure 20B), started already 2.5 months after initial detection. At that moment, the yellow part of core area was still ASF free while fencing of the red part was established. The WZ-CZ combines the larger areas (green + blue, Figure 20B) around the core area and was treated by intensified hunting immediately after initial detection.

Note: From the simulations it became obvious, that in strict sense the non-fenced part of the core area (yellow) could have been considered as white zone instead. It is as well adjacent to the fenced ASF-positive area and was pre-emptively treated by depopulation culling. However, the planning of this study did address the WZ-CZ in the historic way where pre-emptively intensified hunting was addressing the green and blue part.

3.1.3.3. Simulation outcome

Summary WZ-CZ:

The layout of and the target measures within the WZ-CZ resulted 80% to 90% failure i.e. in only every 5th to 10th repetition of simulations ASF did not spread into and through this WZ. Here the maximum starting density considered was 4 animals per km² while in the input data 8-10 animals were recorded from the high-risk part – but not from the WZ.

Reason: Incomplete implementation of measures in the WZ due to the very short period between establishment and possible entry of ASF (NB: Historically the infection did not approach the WZ! However, this was most likely due to the intense (pre-emptive) culling efforts in the ASF-negative part of the core area surrounding the fenced ASF-positive part from only 2.5 months post detection onwards!)

Video-Link: https://ecoepi.eu/ASFWB/WZ/#WZ-CZ

Input:
- Area: 9374 km²
- Density: ~3/km²
- Population reduction: 50% additional harvest on top of pre-ASF hunting bag
- Time: one year (outcome, not pre-planned)

Output:

Density per km² :: release 4.0 (3.5-4.5 90% central range);
incursion 3.6 (2.8-4.1))

Time interval in years :: release-establishment 0.1
establishment-entry 0.15 (0-0.4)
entry-exit 0.5 (0.3-0.7)

Intensive Hunting in WZ year 1 :: 15000 (13500-16500) // per km² 1.6 (1.4-1.8)

Total hunted in WZ year 1 :: 25000 (13000-28000) // per km² 2.7 (1.4-3.0)

Infected wild boar in WZ :: 24000 (19000-28000)

- *Density prior to ASF*

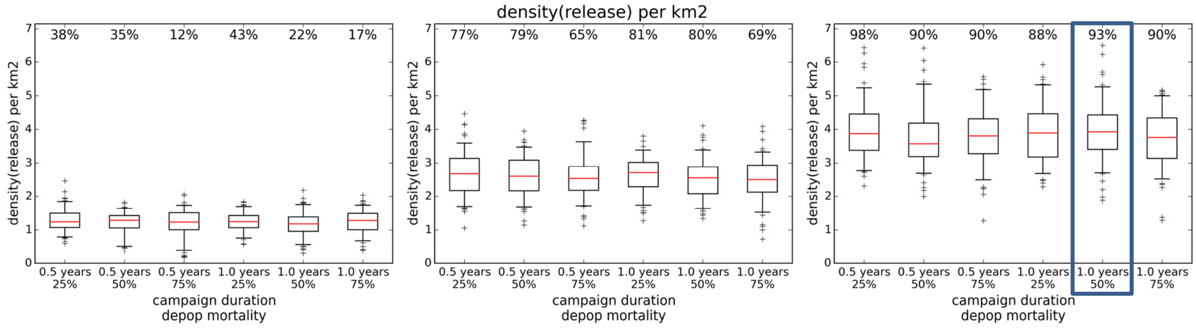


Figure 21. Wild boar density in the WZ-CZ prior to management measures and ASF lethality. Data are shown for three different starting densities (diagrams left to right about 1, 2.5 and 4 wild boars per km²) and alternative management scenarios (x-axis, determined by duration and intensity of the programme). Top row values represent percentage of runs in which the managed WZ did fail to halt the spread of ASF. The blue box marks the scenario most similar to the input information.

Wild boar density in WZ-CZ was rather uncertain. Depending on the zone evaluated, the hunting bag of one year suggested density of above 3/km² (WZ area; green+blue in Figure 20B) or even above 10/km² (red+yellow in Figure 20B i.e. "high" & "highest risk area"). Simulations cover three alternative scenarios resulting in 1, 2.5 and 4 wild boar per km² prior to ASF (Figure 21), which corresponds to wild boar family groups of up to 16 animals before reproduction. Differences of the resulting densities between different control scenarios (x-axis per density diagram) are only due to stochasticity of the population model. Now, Figure 22 shows the impact of the applied measures on the density in the WZ-CZ achieved during the period between start of measures and ASF entry into the WZ.

- *Density at ASF entry to the WZ-CZ.*

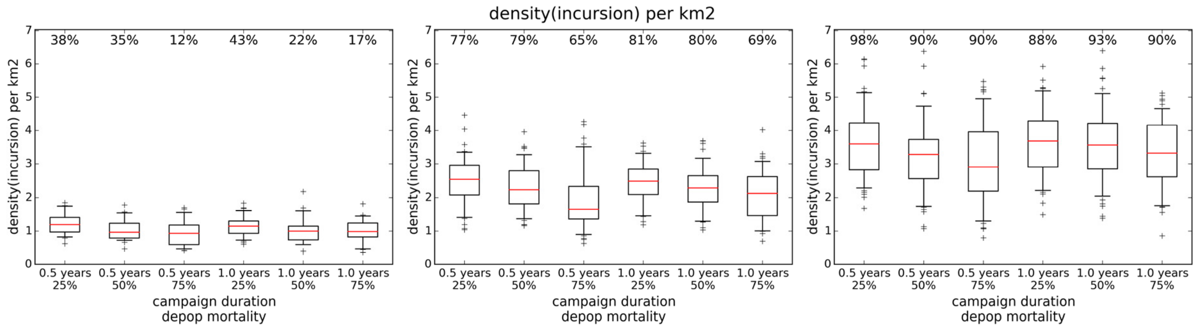


Figure 22. Wild boar density in the WZ-CZ at the moment of ASF entry, i.e. after measures were applied beginning with the date of establishment of the WZ. Data are shown for three different starting densities (diagrams left to right; see Figure 21) and alternative management scenarios (x-axis). Top row values represent percentage of runs in which the managed WZ did fail to halt the spread of ASF.

At the time when ASF entered the WZ-CZ the population density therein (Figure 22) was marginally reduced compared to the situation prior to ASF (Figure 21). This is reasonable as the inner ASF-positive area is of limited dimension (160km² or about 7km radius) which is swiftly covered by the infection (Figure 23) once it left the fenced centre area ("highest-risk area").

- *Time interval between establishment of and entry to the WZ*

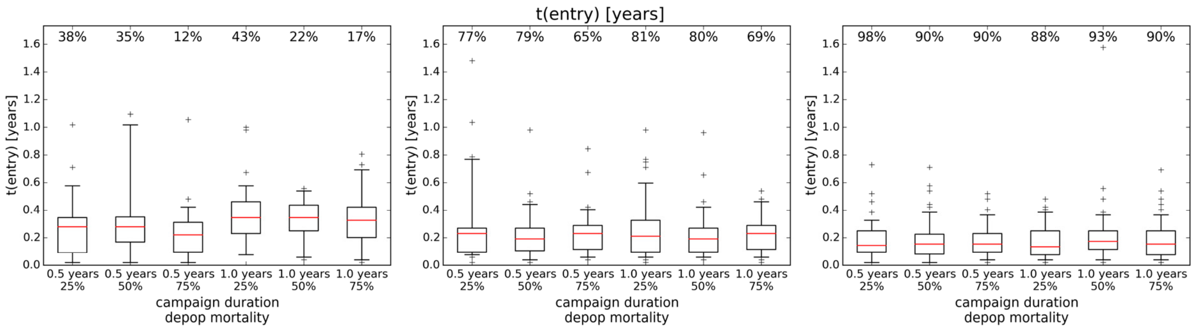


Figure 23. Time interval between establishment of and ASF entry into the WZ-CZ. Data are shown for three different starting densities (diagrams left to right) and alternative management scenarios (x-axis). Top row values represent percentage of runs in which the managed WZ did fail to halt the spread of ASF.

Due to the short distance from the centre of the situation to the WZ-CZ it took only about 2 months (0,15 years) that the infection entered the WZ (0-0,4 years, 90% central interval).

- *Time interval between entry to and break-out of the WZ*

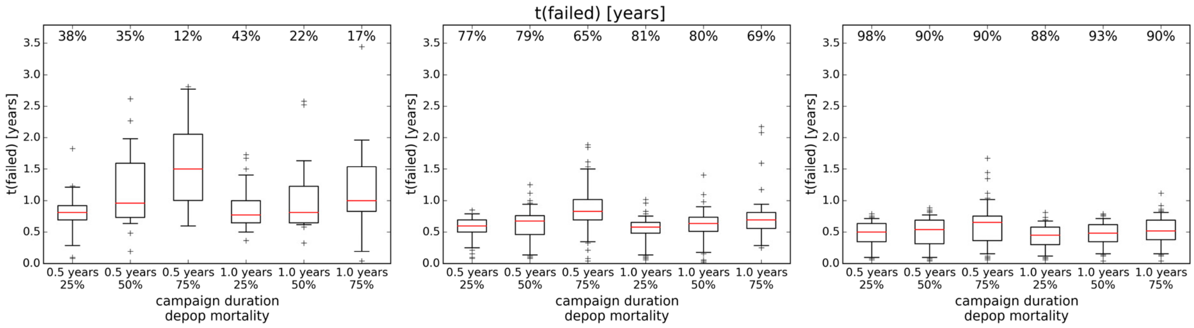
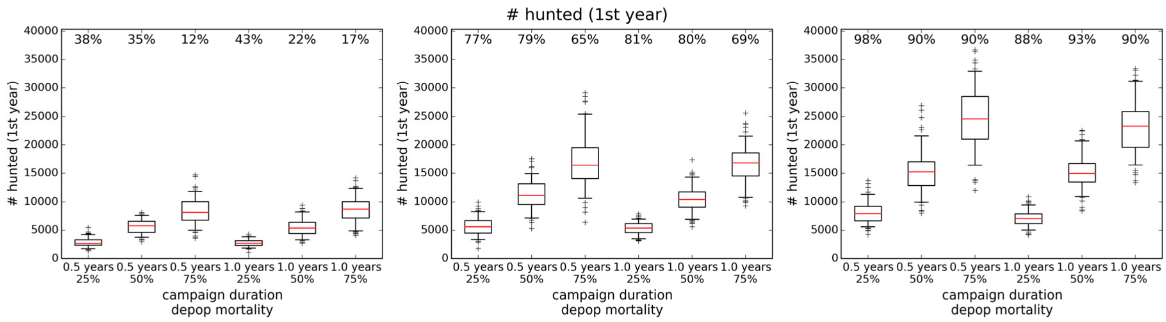


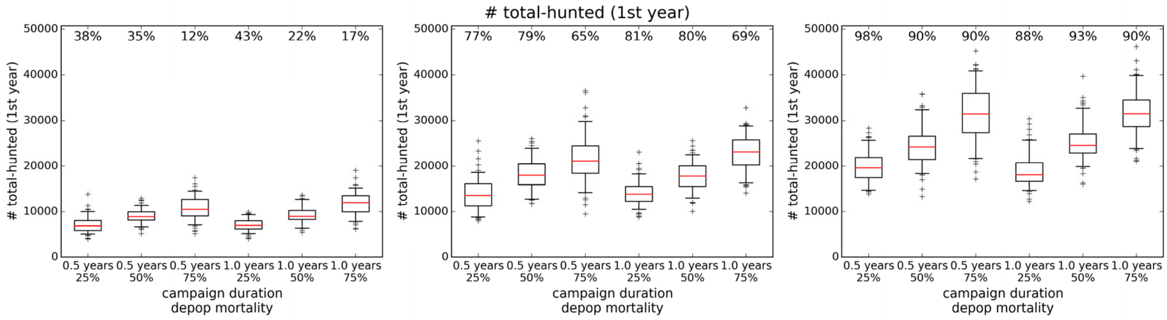
Figure 24. Time interval between ASF entry into the WZ and subsequent break-out from the WZ-CZ. Data are shown for three different starting densities (diagrams left to right) and alternative management scenarios (x-axis). Top row values represent percentage of runs in which the managed WZ did fail to halt the spread of ASF.

Once the infection reached the WZ-CZ it took the infection another half year to cross the WZ (Figure 24). This means, between establishment and failure in total about 0.7 years did pass (i.e. less than 9 months). Consequently, sustainable hunting intensity (e.g. additional removal of 75% of all animals that would have not been hunted otherwise) could not get effective before the WZ already did fail.

- *Number of hunted animals*



A

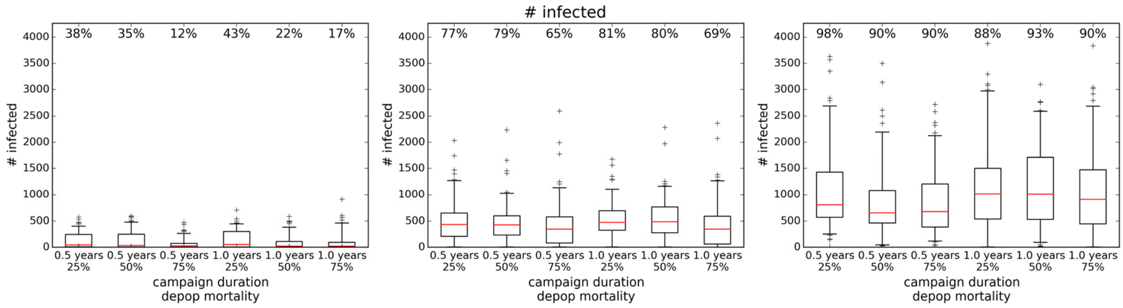


B

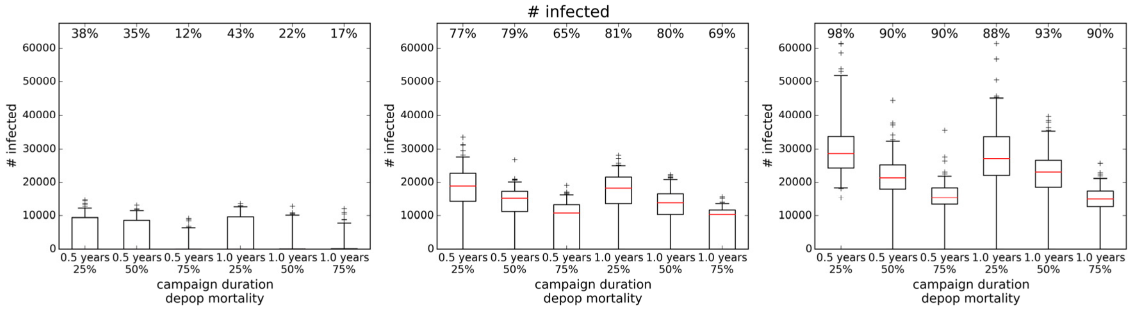
Figure 25 A-B. Wild boar removed within the WZ-CZ (green+blue Figure 20B) additionally due to the measures implemented in the WZ (A) and all hunts including normal activity in the WZ (B). Data are shown for three different starting densities (diagrams left to right, Figure 21) and alternative management scenarios (x-axis). Top row values represent percentage of runs in which the managed WZ did fail to halt the spread of ASF.

Figure 25 details the number of hunted animals in the simulation. The diagrams compare the excess hunting intensity in the WZ-CZ due to intensified efforts (Figure 25A) and the total hunted animals (Figure 25B). Interestingly, the amount of excess hunted animals in the most similar scenario (about 15.000 animals) corresponds to the records from CZ i.e. about 14.000 animals.

- *Number of infections in WZ*



A



B

Figure 26 A-B. Number of infected wild boar within the core area (A; red+yellow Figure 20B), and the WZ-CZ (B; green+blue Figure 20B). Data are shown for three different starting densities (diagrams left to right) and alternative management scenarios (x-axis). Top row values represent percentage of runs in which the managed WZ did fail to halt the spread of ASF.

- *Spatial distribution of ASF*

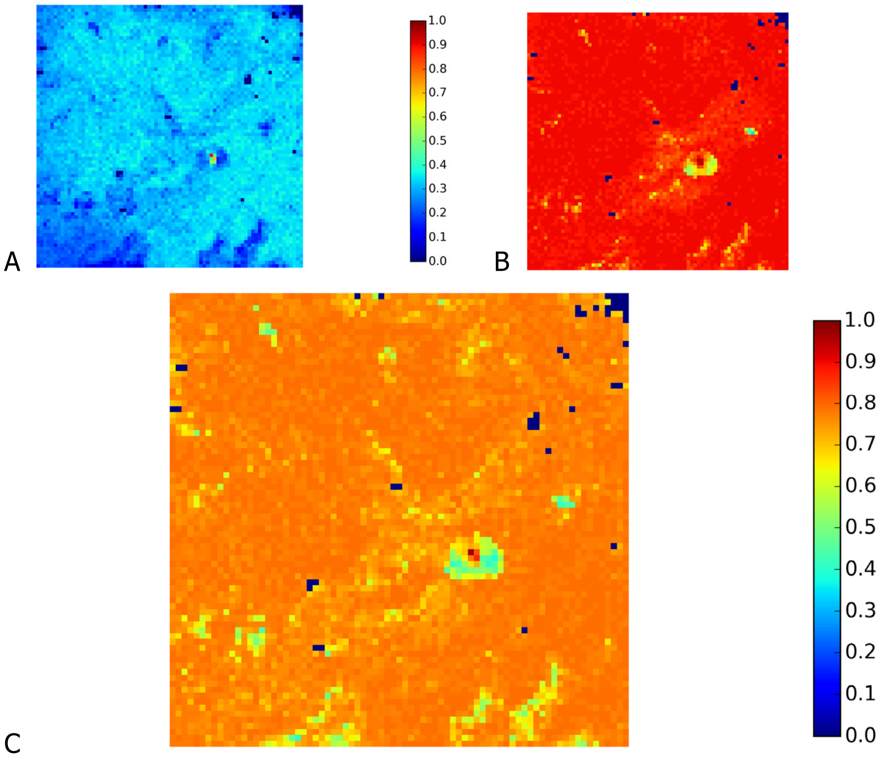


Figure 27 A-C. Heat map of ASF occurrence inside and adjacent to the WZ-CZ. The greater value a wild boar habitat cell has, the greater the proportion of simulations runs in which the cell contained ASF-positive animals.

Figure 27 demonstrates what would have happened, if ASF would have escaped the infected part (red in Figure 20B) of the core area (red+yellow; in Figure 20B). The more reddish a particular wild boar habitat cell is coloured, the greater the proportion of simulations runs in which the cell contained ASF-positive animals. From the uniform, orange coloured heat map (wild boar group infected in about 70 to 80% of simulation runs) follows that the measures in the white zone would not have stopped the infection from spread into and further out of the WZ.

However, as detailed in Table 1, Table 1there was different contribution by simulated management measures inside the core area (red+yellow; in Figure 20B). Dependent on the initial density, in 36%, 77% and 92% of the simulation runs ASF reached the WZ (Table 1 third column). Hence, in 64%, 23% and 8% of the runs the infection was stopped already inside the ASF-positive area. Only 23%, 2%, and 0% of those runs, which ever entered the WZ, did actually stop inside the WZ (Table 1 last column). The reason is the timely depopulation of the area around the fenced centre (yellow in Figure 20B) – in which wild boar was culled starting 2.5 months after initial detection and during about three months period.

Table 1: Table 1. Contribution of ASF-positive area and WZ-CZ to the overall success

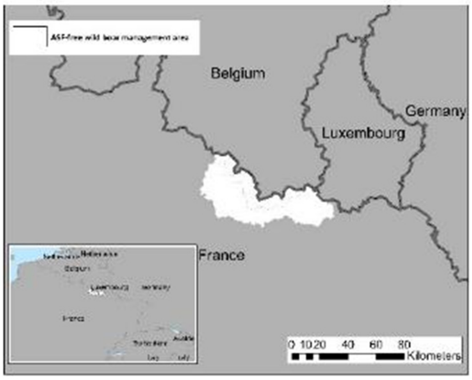
Density factor	Approach WZ	% Runs	Leave WZ	Stop in WZ	% Runs	% Runs approaching WZ
2	214	36%	164	50	8%	23%
4	459	77%	451	8	1%	2%
6	549	92%	549	0	0%	0%
Total	1222	68%	1164	58	3%	5%

According to Figure 27C the southern segment of the non-fenced core area (yellow; in Figure 20B) became involved in a lower proportion of runs (less than 50%; green scale) then the demarcated WZ-CZ (more than 70%). This implies that in the simulation entry into the dedicated WZ-CZ usually happened to the north - although there was intentionally release to the south of the fence in every simulation (repeating the field situation). Hence, simulated spread after imputed escapes to the south did rarely arrive at the WZ. The simulated fence has a homogeneous permeability. Thus, the observed directionality must be understood from the width of the northern segment of the non-fenced core area and the habitat structure therein, an insight worth exploring further to improve placement of fences and WZ in future occasions.

In the model simulations the failure was hop-or-top regarding the eradication of the infection in the non-fenced and fenced core area ("highest- and high-risk part") and not related to the efforts in the WZ-CZ. Due to the historically concise dimension of the core area particular to the North success outcome became exceptional for larger population densities. From the analysis of the simulation outcome (Figure 27C) the widened non-fenced part of the core area (yellow; in Figure 20B) would have served as better WZ, while subjecting it to the pre-emptive population culling after fencing the inner part, instead of relying on the intensified hunting in the WZ-CZ.

3.1.4. WZ Scene FR

3.1.4.1. Data Input



Surface WZ: 1035 km² (Fenced inside ~300km²)
Established: 19/10/2018 (Entry detected: none)
Fenced: Early January 2019
Initial density: ~2.8/km²
Target: Total depopulation

Figure 28. The WZ-FR established since October 19th, 2018 with extensions (ASF trigger 13.09.2018).

3.1.4.2. Model landscape and zones

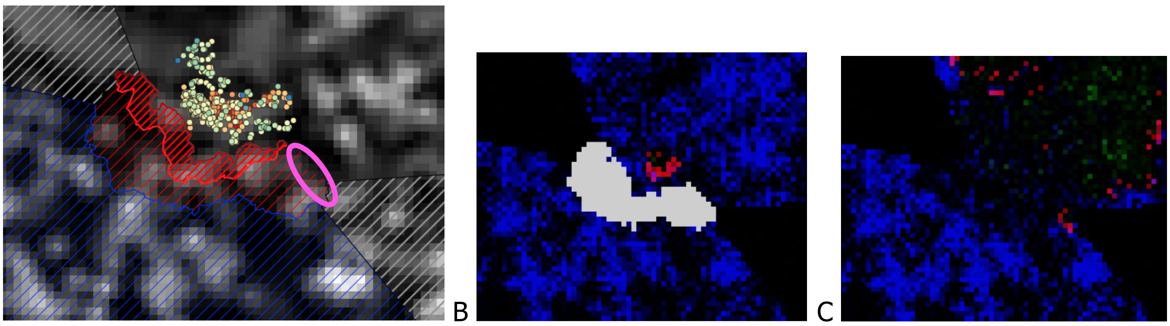


Figure 29. Simulation area representing the scene of the WZ-FR (intense red hashed) and the cumulated ASF notification in BE wild boar (A). Simulation snapshot at the moment of establishment of the WZ-FR and start of population measures therein (B). Simulation snapshot at the moment when ASF bypasses the WZ-FR if no artificial barrier was placed (C).

Figure 29 reflects the spatially explicit design of the simulation landscape for replaying the WZ-FR. The intensely hatched red area (~300 km²) is fenced towards France while all red area (1024 km²) is subjected to depopulations. The pink ellipse at the French-Luxembourgian border symbolises artificially placed barriers to prevent ASF from bypassing the WZ-FR in the east where a 4-lane highway and an urban area is suggested to act as barrier of wild boar movements. Without that manipulation, the WZ would have produced mostly failure results.

3.1.4.3. Simulation outcome

Summary WZ-FR:

The layout of and the target measures within the WZ-FR resulted in only 20% to 30% failure dependent of the exact starting population (i.e. varied for 2.8 +/-25%) and the rigorous depopulation per year.

Reason: First, the gap at the French-Luxembourgian border was closed in the simulations. Second, the fence and repeated drastic population measures early in the year prepared the WZ for a potential ASF entry. (NB: Historically the infection did not approach the WZ! Most likely due to the intervention measures on the Belgian side of the border.)

Video-Link: https://ecoepi.eu/ASFWB/WZ/#WZ-FR

Input:
- Area: 1035 km²
- Density: ~2.8/km² (Pittiglio et al. 2018)
- Population reduction: 80% additional harvest on top of pre-ASF hunting bag
- Time: Jan-Mar each year (according to population estimation data)

Output:

Density per km² :: release 2.9 (2-4.6 90% central range)
incursion 0.3 (0.2-0.6)
Time interval in years :: release-establishment 0.35
establishment-entry 0.5 (0.25-1.5)
entry-exit 1 (0-2)
Additionally hunted in 1st year of WZ :: 750 (600-900) // per km² 0.73 (0.6-0.9)
Infected wild boar in WZ :: 10 (0-40)

- *Density prior to ASF*

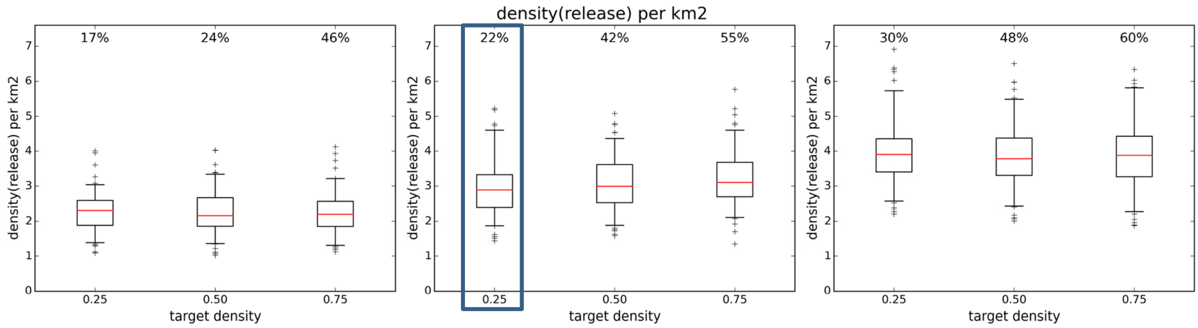


Figure 30. Wild boar density in the WZ-FR prior to management measures and ASF lethality. Data are shown for three different starting densities (diagrams left to right about 2.2, 3 and 4 wild boars per km²) and alternative management scenarios (x-axis). Top row values represent percentage of runs in which the managed WZ did fail to halt the spread of ASF. The blue box marks the scenario most similar to the input information.

- *Density at ASF entry to the WZ-FR*

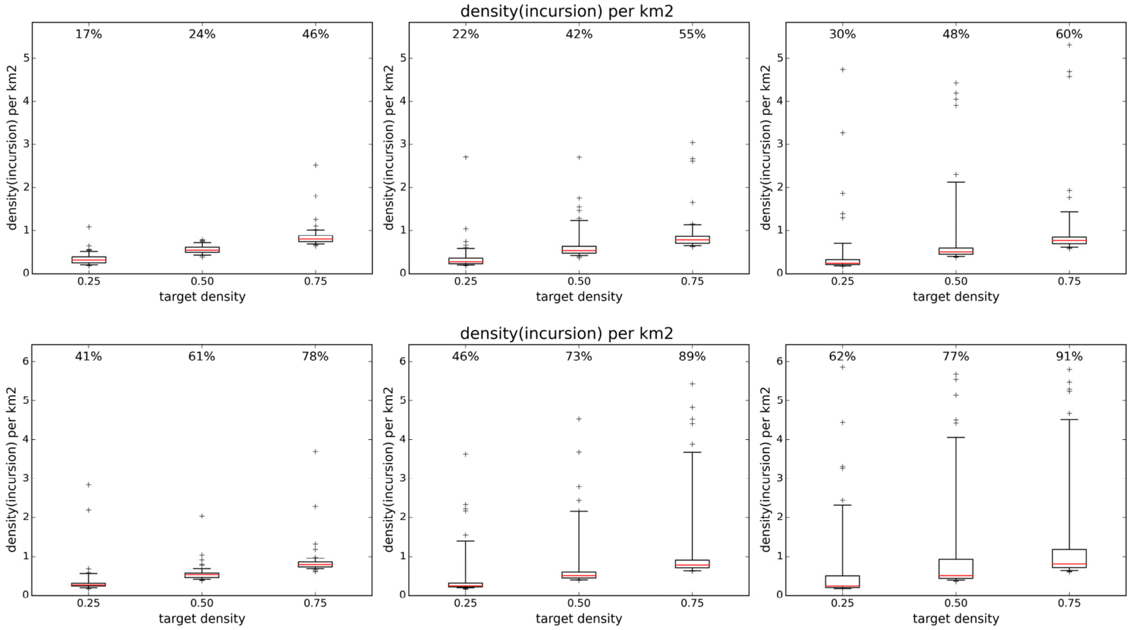


Figure 31 A-B. Wild boar density in the WZ-FR at the moment of ASF entry, i.e. after measures were applied since date of establishment of the WZ with fixed fence (A) and without fixed fence effect (B). Data are shown for three different starting densities (diagrams left to right; Figure 30) and three different management scenarios (x-axis). Top row values represent percentage of runs in which the managed WZ did fail to halt the spread of ASF.

The depopulation measures applied inside the WZ-FR, drastic and concentrated early before reproduction, resulted in a sustainable effect leading to low densities as intended by the design of the WZ (Figure 31A). Interestingly, the effective densities did not differ much between the scenario with fence (Figure 31A) and without fence (Figure 31B). However, the failure rate was 1.5 to 2.5 times worse in simulation without fence. Hence, even with lowest managed population size the fixed fence has an important impact on the efficiency of WZ measures.

- *Density after measures in the WZ-FR*

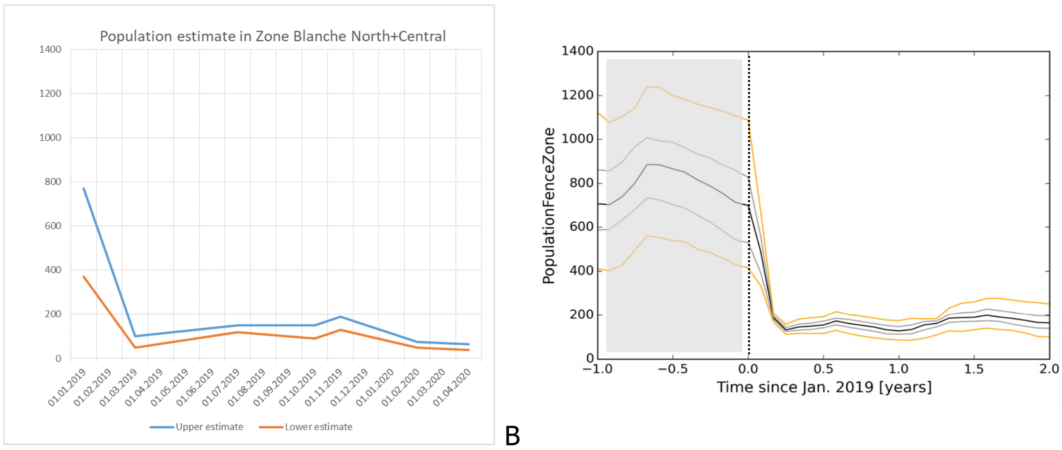


Figure 32 A-B. Development of the population size inside the fenced part of the WZ-FR (intense hatched red in Figure 29)

Figure 31 revealed the drastic effect of the depopulation measures on the population numbers in the WZ-FR. Were the simulations realistic? The input data of population estimate in the fenced part of the WZ in FR were used to illustrate the observed dynamics (Figure 32A). The simulations were calibrated with the overall population density in the region (~2.8 per km²; Pittiglio et al. 2018) and a simulated

80% reduction in intense hunting campaigns during January-March each year. With these two basic inputs the model adequately reproduced the population size in the fenced part of the WZ, the steep decline after the first depopulation campaign, the smooth regrowth over the reproductive season and the next dip early in 2020 (Figure 32B).

- *Time interval between establishment of and entry to the WZ*

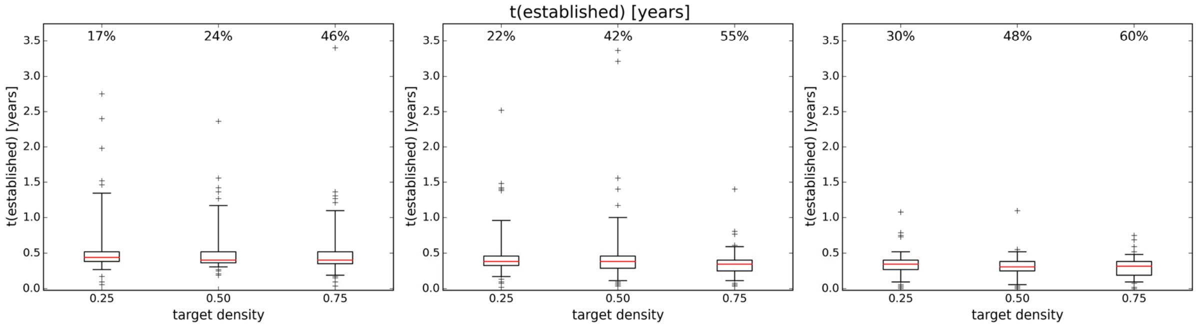
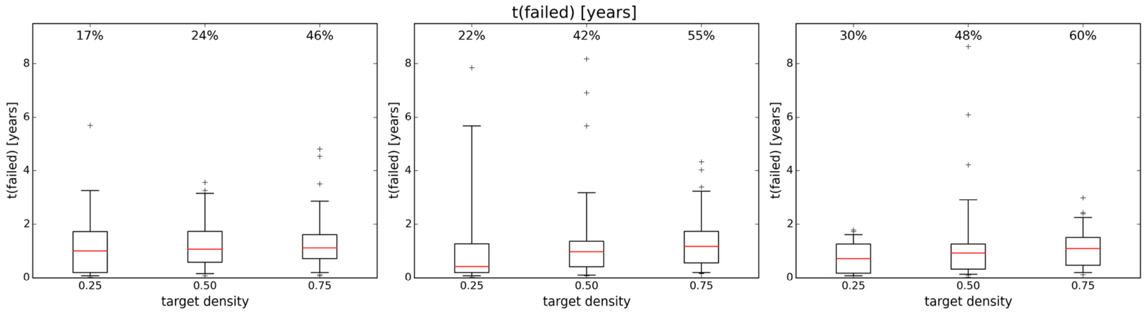
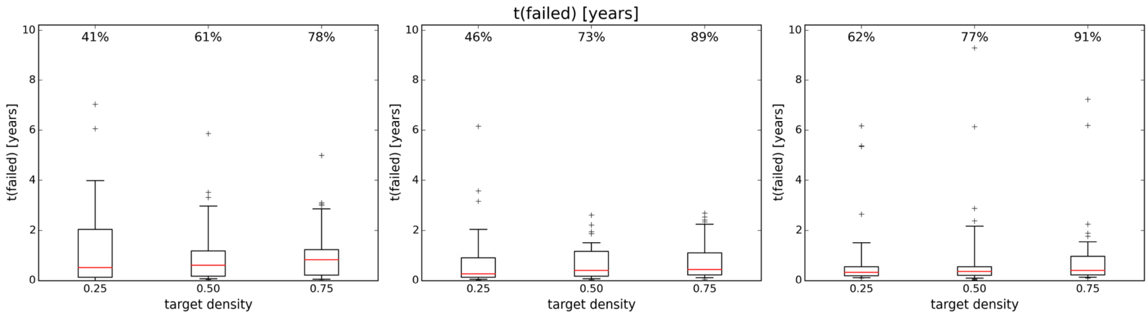


Figure 33. Time interval between establishment of and ASF entry into the WZ-FR. Data are shown for three different starting densities (diagrams left 2.2, middle 3 and right 4/km²; Figure 30) and alternative management scenarios (x-axis). Top row values represent percentage of runs in which the managed WZ did fail to halt the spread of ASF.

- *Time interval between entry to and break-out of the WZ*



A



B

Figure 34 A-B. Time interval between entry of ASF into the WZ-FR and the first ASF infection beyond the WZ area with fixed fence (A) and without fixed fence effect (B). Data are shown for three different starting densities (diagrams left to right, Figure 30) and alternative management scenarios (x-axis). Top row values represent percentage of runs in which the managed WZ did fail to halt the spread of ASF.

For simulation runs with WZ failing to halt ASF spread, the median time of failure is shorter than six months (extreme variation up to 6 years; Figure 34A). If there was no fixed fence simulated, the period and variation is generally shortened (about halved; Figure 34B), highlighting the delaying effect of the fence.

- *Number of excess hunted animals due to measures*

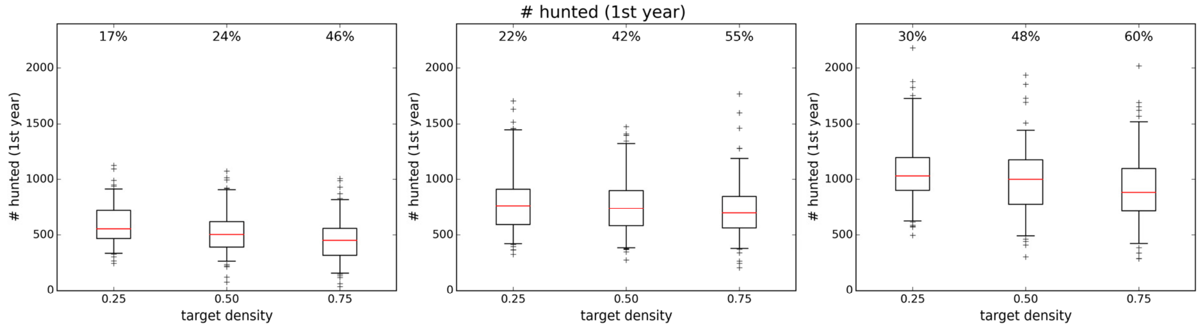


Figure 35. Wild boar hunted additionally to the standard hunting bag during the first year of the WZ-FR. Data are shown for three different starting densities (diagrams left to right, Figure 30) and alternative management scenarios (x-axis). Top row values represent percentage of runs in which the managed WZ did fail to halt the spread of ASF.

- *Number of infections in WZ*

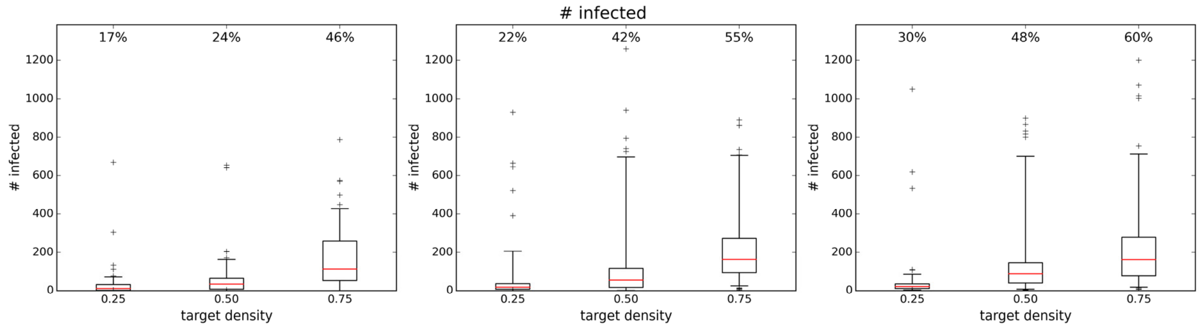


Figure 36. Number of infected wild boar simulated in the WZ-FR with fixed fence. Data are shown for three different starting densities (diagrams left to right, Figure 30) and alternative management scenarios (x-axis). Top row values represent percentage of runs in which the managed WZ did fail to halt the spread of ASF.

In accordance with the limited failure rate of the WZ-FR (Figure 36 top row values), only limited numbers of infected animals must be recorded inside the WZ (Figure 36).

- *Spatial distribution of ASF*

Figure 37 reveals the impact of the WZ-FR on the spread of ASF in wild boar using the heat map resulting from 100 runs per scenario. Top row shows the scenario most similar to input information with starting density (~2.8/km²) and target density of depopulation at 0.25/km²; comparing the simulations with fence (Figure 37A) and without fence (Figure 37B). Bottom row shows the most pessimistic scenario simulated with high starting density (~4/km²) and target of depopulation only at 0.75/km²; again comparing the simulations with fence (Figure 37C) and without fence (Figure 37D).

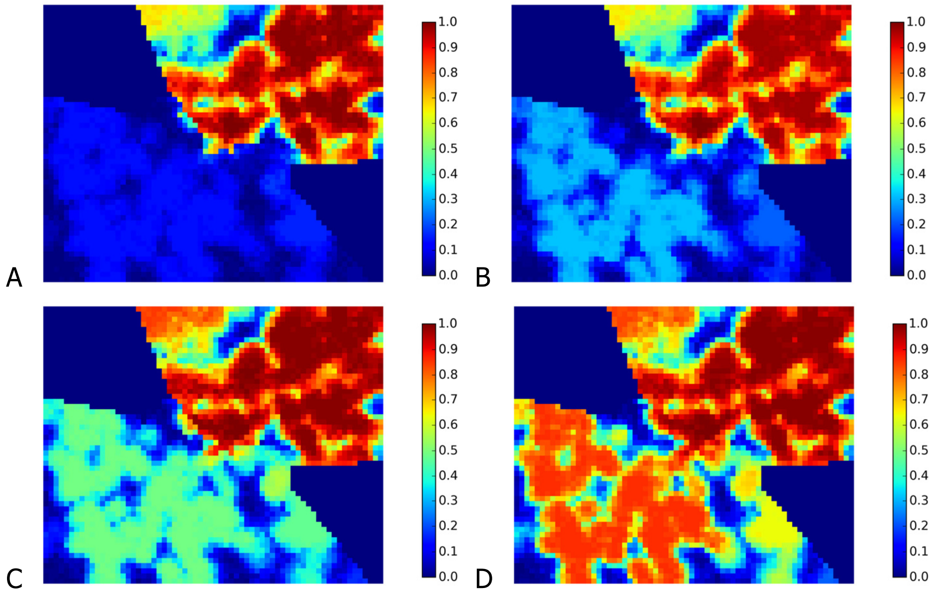


Figure 37 A-D. Heat map of ASF occurrence inside and adjacent to the WZ-FR. Failure rate (A) 22%, (B) 46% with fence, (C) 60% and (D) 91% without fence.

4. Discussion

4.1. Relationship between density and timing of WZ

The simulations addressed standard settings of historic WZ layout. Here we are interested to further detail the relationship between density and time intervals involved in the functioning of a WZ. In particular we did observe that both densities are relevant the initial pre-ASF and the effective density achieved after measures in the WZ when ASF enters. After recognising the influence of density values on the speed of propagation it becomes evident that fixed time intervals created by placing the WZ distant to the ASF-positive area or to complete the population measures, are important to understand the success of a WZ.

Figure 38 uses a subset of all 1800 simulation runs for the WZ-LV to demonstrate general aspects of evaluating the effectiveness of measures implemented in a WZ. The simulation runs comprise three different starting densities (1; 1.5; 2 per km² coloured graphs in Figure 38) and one design of population reduction measures (target density of 0.25/km² within one hunting year of 52 weeks since establishment of the WZ).

First, the data reveal why in the low-density scenario fewer failing runs were recorded. Indeed, only in the low-density scenario (orange dots) the target population density was achieved before the infection entered the WZ.

Second, the data show how the start of the reproductive season between Q1-Q2 each year bounces the density up which implies the need for continued year-round or repeated short-term depopulation measures to maintain an achieved depopulation level (or even improve it).

Third, in the same landscape and temporal setting, runs with greater initial density (orange < grey < blue dots) are related to shorter periods between the date of WZ establishment (fixed by history at simulation week 289) and first approach of the WZ by ASF (x-axis). This reveals the greater speed of propagation the higher the density is prior to ASF – which in turn shortens the time left to complete implementation of measures before ASF enter the WZ again reflected in the increasing level of density at incursion (y-axis).

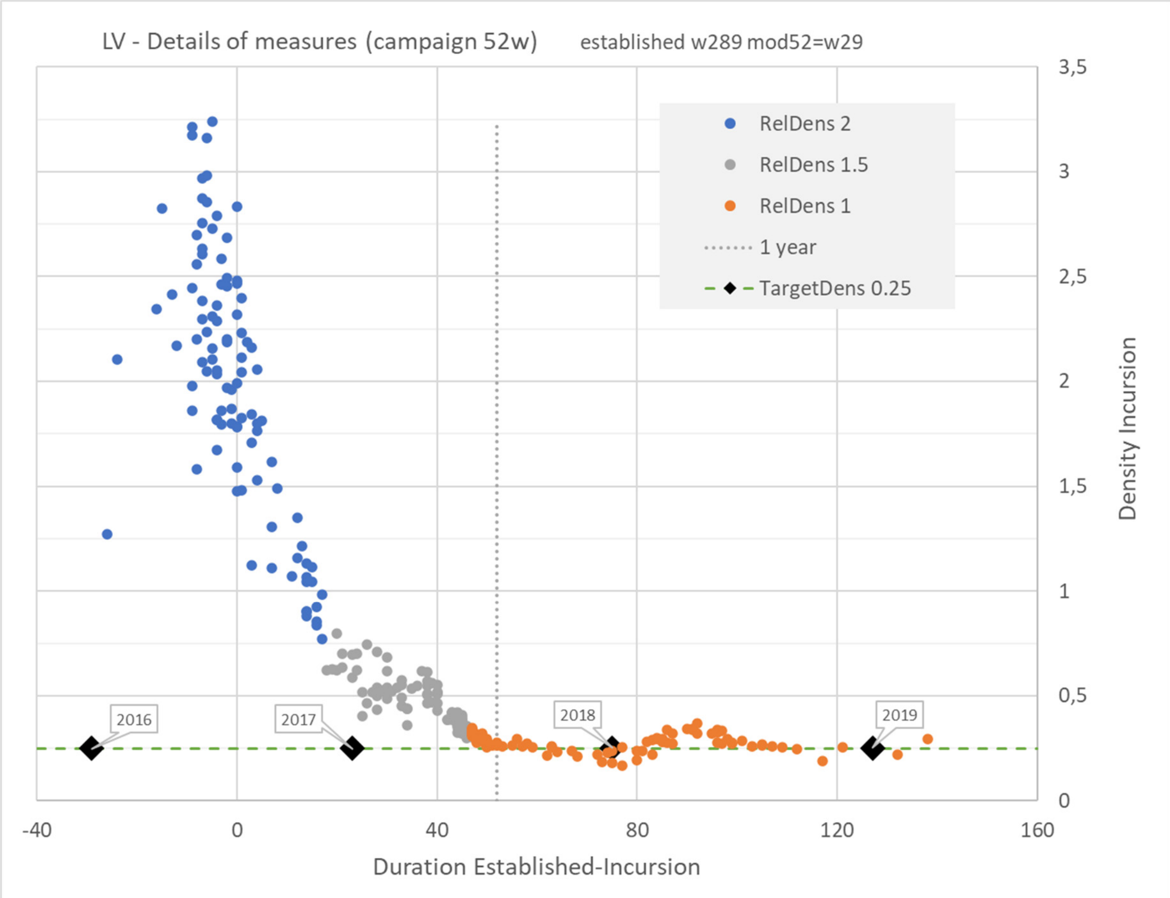


Figure 38. Simulation outcome regarding density and time intervals related to functionality of WZ. Simulation runs (individual dots) are shown for three starting densities (blue, grey, orange) by their time interval between WZ establishment and ASF entry to the WZ (x-axis) and the achieved density in the WZ at entry (y-axis). The hatched line represents the target density of 0.25/km². The dotted line marks the end of the first year after establishment of the WZ. Moreover, the diamonds mark the 1st week of the historic year for the WZ-LV which was established mid-August 2016 (week 26).

Figure 39 illustrates the practical importance of adequate distance of the planned WZ from ASF infections at the moment of establishment/start of measures. The population measures simulated in the modelled WZ aimed at a target density of 0.25km² within one year/hunting season. The diagram compares runs failing (orange) vs succeeding (blue) in stopping ASF spread by the WZ. The cumulative distributions are plotted for the length of time since its establishment (x-axis). Negative values reflect runs with ASF already inside the WZ when it was established. The longest interval was beyond 2.5 years (138 weeks since establishment). The upper values refer to the actual years in the simulation to allow synchronisation with the wild boar year. In particular, the juvenile dispersal in late autumn results twice in increased number of failure but also once for success stratum. The early increase are runs where the infection enters the WZ around its establishment when measures just started and thus leading later to failure. The second reflects how dispersal affected the entry time no matter what the outcome finally was. Beyond the shortest time intervals, effectively around zero, there is no predictive capability of the time interval regarding success (after about 10 weeks length both curves run in parallel).

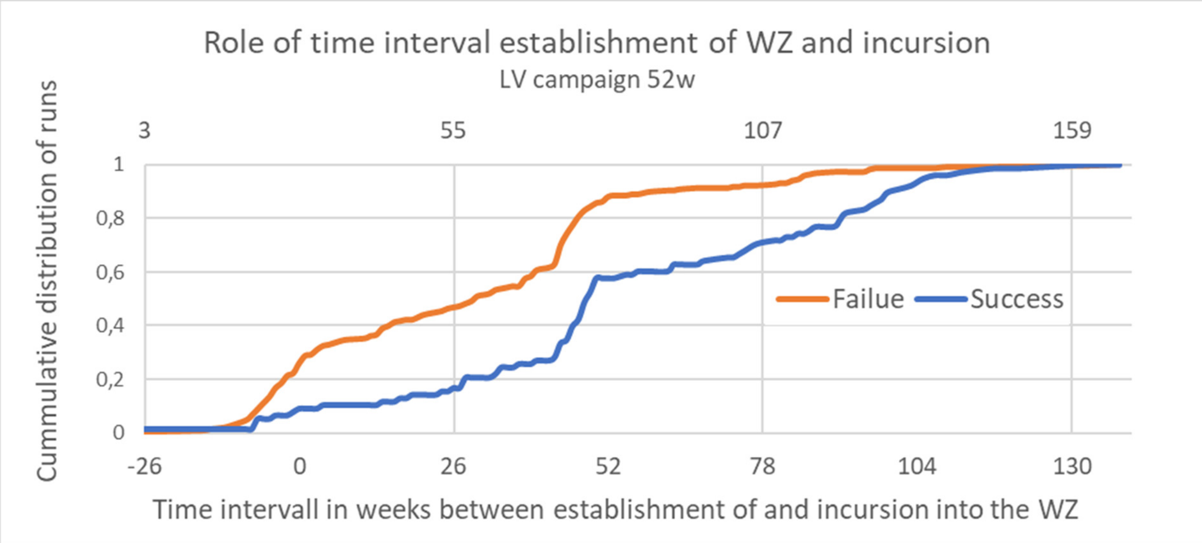


Figure 39. Time interval in weeks between establishment of the WZ and the ASF entry into the WZ (x-axis) as predictor for WZ failure.

Nonetheless, of runs that ended with successful eradication 40% had a time between establishment of the WZ and entry of at least the duration targeted to accomplish measures (here 52 weeks) whereas only 10% of failing runs were so.

> ***Interpretation***: *Critical drivers of WZ designs were seen from the investigation of historic layouts and practices:*
>
> - *Time period to complete implementation of planned measures should coincide with the expected speed of propagation of the infection. Speed of propagation varies with initial density around the WZ – greater densities require greater distances between ASF and the WZ to complete measures compared with low density situations.*

4.2. Issues of the WZ evaluation addressed with the model

Issue: Did the simulations of the WZ suggest an improved understanding of the issue of density thresholds for successful ASF eradication by measures addressing population numbers?

The request for density threshold of ASF spread in wildlife, reported for other infectious diseases by model approaches that abstract heterogeneous and stochastic contact networks into average event rates, is pertinent in the context of ASF control in European wild boar populations. Several scientific outputs reveal the difficulty in determining a quantitative density threshold usefully predicting if ASF spread in wild boar will stop once density is below the threshold value. Here, we compared for the Latvian scene (3.1.2) runs that i) entered vs did not enter the WZ regarding their initial density; and similarly, ii) runs that entered the WZ and finally failed vs succeeded to stop ASF inside the WZ by their density at incursion (after measures were applied).

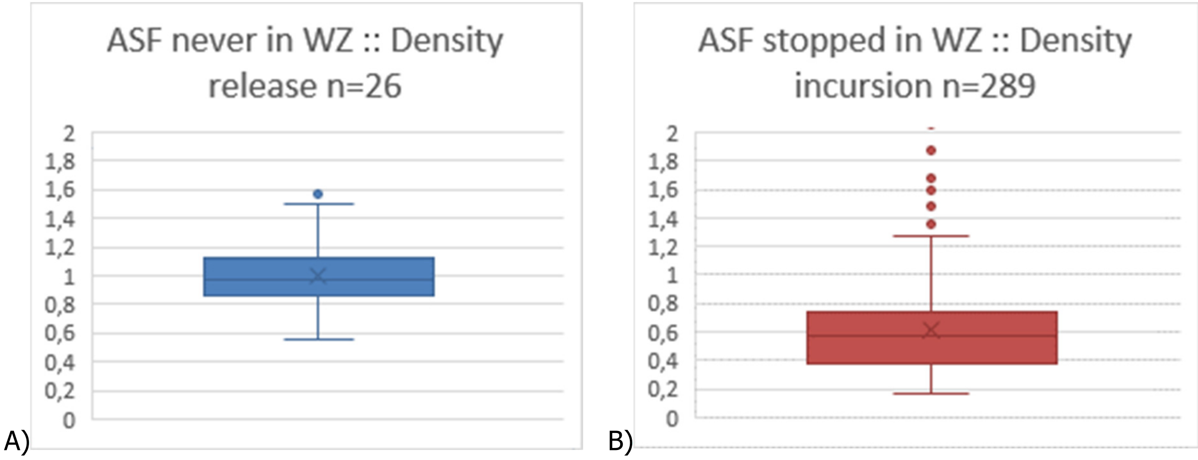


Figure 40 A-B. Density distribution of runs that stopped either before entering the WZ (A) or inside the WZ (B).

Figure 40 confirmed the relationship established in literature that lower wild boar density associates with lower probability of ASF to spread. It shows the distribution of effective population density for all runs that did stop spreading either before entering the WZ ("normal" density at release, Figure 40A) or inside the WZ ("reduced" density at incursion, Figure 40B). All but one run of those fading out before reaching the WZ had the lowest initial density of 1/km² (n=25+1 of 600). Of runs that stopped inside the WZ (success), most were from the low-density scenario, i.e. sc 1.0 (209; 35%), sc 1.5 (74; 12%) and sc 2 (6; 1%) respectively.

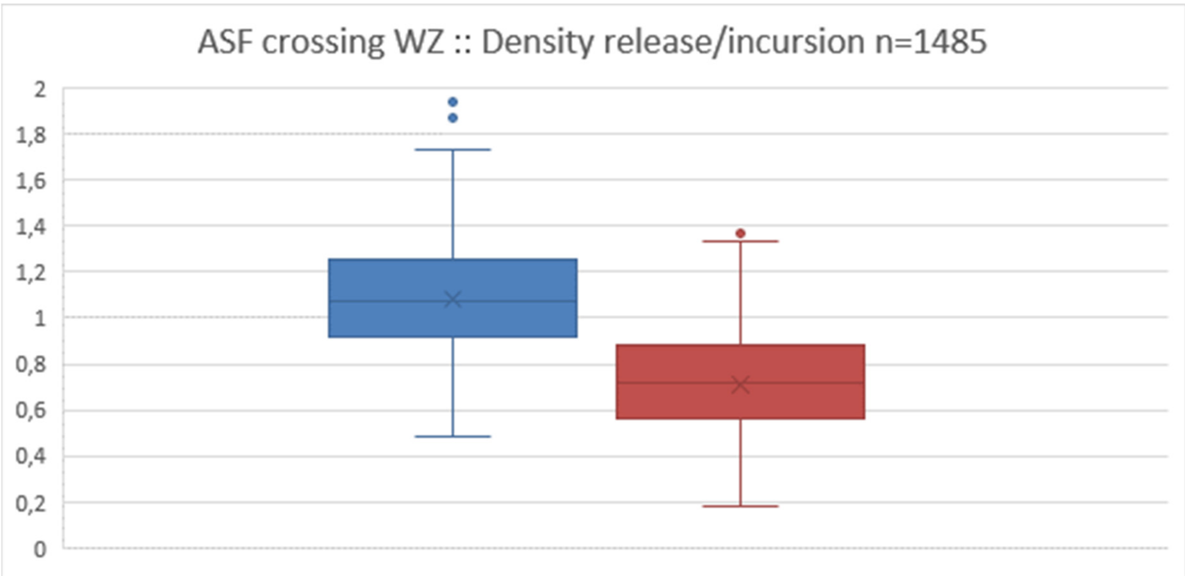


Figure 41. Density distribution at release (blue) and incursion (red) of runs that actually crossed the WZ, i.e. ended with failure.

The comparison of those runs that eventually spread beyond the WZ (failure; Figure 41) revealed great variation of density values both at start of ASF spread and at entry into the WZ. Moreover, the runs that ended with failure (Figure 41 blue) started in the same range of the release density compared to those that succeeded in stopping WZ (Figure 40A). The situation is slightly changing when the density at incursion of failing runs (Figure 41 red) is compared to the same output from non-failing runs (Figure 40B). Although the two distributions largely overlap, there is an apparent shift to slightly lower densities at incursion (central 50% interval 0.55-0.9 vs 0.4-0.75). If there is such a tendency in density it appears worth to understand the effect of density values for those runs in which ASF was stopped due to the measures inside the WZ (see Figure 40B).

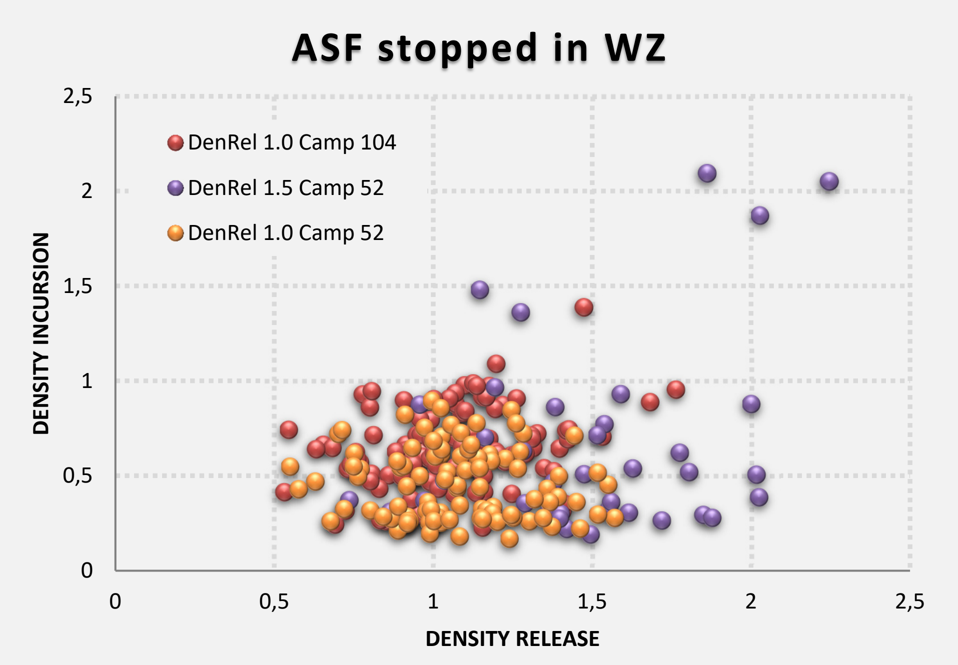


Figure 42. Density values at release and incursion for individual runs that stopped inside the WZ does not suggest a tendency. Colours indicate different scenarios combining density at release (DenRel) with time horizon planned for population reduction (Camp).

The plot in Figure 42 answers the question whether starting density (DenRel 1; 1.5) and intensity of density reduction (Camp over 52 or 104 weeks) provides better understanding of WZ success. However, the runs in which the WZ-LV did succeed in stopping ASF spread are filling by compatible completeness ranges of density values and no tendency can be identified. Regarding threshold one only may conclude that a potential threshold value below which ASF may no longer spread in wild boar should be expected below 1 animal per km². This imprecise result adds to other indications that density per se does not create a typical threshold feature to forecast spread vs fade-out of ASF in wild boar. The reasoning would argue that the slow spread gets dominated by stochasticity because at low average density few animals are left while ASF lethality acts synchronised on the level of wild boar families, i.e. creates “gaps” in the landscape regarding host coverage.

***Interpretation**: In summary there is further plausibility-based evidence that the stochastic nature of ASF spread (regarding landscape structure, natural short-term population level variations and carcass-mediated ASF infection chain) results in extreme variability of the apparent densities at which spread is more likely to stop than continue.*

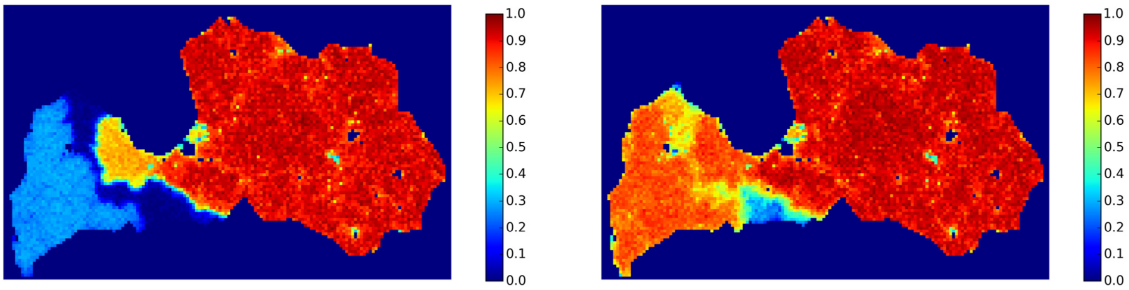
Reduced densities are beneficial in supporting ASF control and eradication from wild boar populations (e.g. less carcasses potentially in an area buffering fade-out; slower replication of the infection across the landscape with less homogeneous transmission networks). However, the final density values at which certain measures led to success vary as wide that a potential functional relationship was not accessible. This argues that after reaching densities of 1 or less animals per km² the infection may or may not fade out for several other factors more important than tiny differences in density values.

Issue: Do the simulations of the WZ without the removal of carcasses show a wrong picture of its effectiveness?

The carcass removal in WZ only comes into play once ASF entered and likely will improve the performance. But in that case the issue is about control measures in areas already acknowledged as ASF-positive. The central importance of carcass removal for ASF control in ASF-positive areas was already sufficiently demonstrated in literature (EFSA 2017, 2018a; Croft et al., 2020; O'Neill et al., 2020).

The standard simulations in this report address the population measures applied pre-emptively in the WZ and their individual efficiency when ASF enters the WZ. Therefore, the study protocol excluded carcass removal. However, after the infection did enter the WZ, in reality, reactive control measures like carcass removal should apply in support of the pre-emptively achieved population reduction.

To characterise the impact of carcass removal, a side experiment was simulated with the WZ-LV as an example. Additional simulations were performed as in section 3.1.2 but considering carcass removal inside the WZ (outside the WZ conditions were kept as in Figure 18C, i.e. time periods, density and spread).



A B

Figure 43 A-B. Heat map of ASF occurrence inside and adjacent to the white zone in Latvia. As Figure 18C (failure rate 94%) but simulation additionally includes carcass removal inside the WZ assuming a detection efficiency of 20% (A; failure rate 34%) and 2% (B; failure rate 90%). The greater value a wild boar habitat cell has, the greater the proportion of simulations runs in which the cell contained ASF-positive animals.

Figure 43 confirms the carcass removal as efficient measure to support the WZ in halting the spread of the infection when compared with Figure 18C. However, it is also clear that high carcass detection efforts (here 20%; Figure 43A) are required to improve the situation. The more routine level of carcass detection (here 2%; Figure 43B; EFSA 2021b) cannot compensate the issues discussed as limiting the efficiency of the WZ-LV.

Interpretation*: In summary carcass removal does not add to the pre-emptively achieved sustainability of the WZ against ASF spread. Nonetheless, carcass removal will evidently support the control of ASF spread once the infection entered the WZ.*

However, routine intensity of carcass detection, e.g. 1 carcass per 1000km² per year (EFSA 2021b), will not suffice as supporting reactive control measure. Intensified removal rates would be needed.

4.3. Pertinent queries to the issue of WZ for ASF management

Based on data and modelling output, this document addresses principal aspects of WZ effectiveness along four historic examples. The evaluation of the particular WZ settings, however, also led to undiscussed issues and new questions that cannot yet be answered by the data collected within the time frame of this report. These questions should be tackled by further elaborations.

Q1: Which level of carcass search and testing would be target-oriented in the WZ fostering early detection of ASF entry?

Q2: What is the functional relation between wild boar distribution (including density) and distance a WZ should be placed in front of ASF positive areas?

Q3: What is an adequate width of the WZ given wild boar distribution, time horizon and planned measures?

5. Conclusions

- Historic white zone designs based on standard or intensified hunting as a population management measure were more likely to fail than halting spread of ASF in wild boar.
- Historic WZ designs which included both fencing AND drastic, fast depopulation measures by any means could more often halt the spread of ASF than fail.
- A relative definition of population reduction measures is less useful as the results are not comparable across areas which may have different initial densities. Hence, similar relative depopulation targets may still result in different abundance numbers.
- Tangible, absolute population reduction targets in terms of numbers wild boar per km2 in the white zone after a certain management period should be specified or the related absolute number of hunts per km² prescribed, even if (annual) field estimation of population numbers is known to be noisy.
- Reason for failure was:
    - A short distance of WZ to the non-free area relative to the period foreseen to complete target measures.
    - A (partially) small dimension (width) of the WZ that could not stop ASF spread even though target measures were completed, and wider segments successfully prevented ASF from spreading across the WZ.
    - Insufficient population reduction speed in WZ nearest to the risk area.
    - Unavoidable leaks over time in longer fence lines.
- WZ must be in sufficient distance from the non-free area to allow final implementation of targeted population management measures before entry may be expected (spread velocity, EFSA 2019).
- WZ should be designed with sufficient thickness to prevent the infection passing through by short infection chains (e.g. EFSA 2015/2017) as usually a wild boar free WZ will not be possible.
- WZ in focal context needs reliable fence protection towards the risk area or extreme culling measures that allow fast depopulation of the WZ because in the focal context the WZ will always be close to the risk area by distance and therefore also regarding exploitable time lag.
- The success of the focal approach in the CZ scene most likely was due to early depopulation measures inside the non-fenced part of the core area and not due to the WZ (low-risk + intensive hunting area). In model runs with ASF infection spreading beyond the core area into

WZ-CZ no reliable success to stop ASF was observed. Evidence from field is lacking as ASF never entered the WZ-CZ.

- The apparent success of the WZ in France could have relied on the closure of adjacent wild boar habitat at the French-Luxembourgian border.
- The model results require attention as it was deemed that the WZ established around the core area will develop sufficient capacity to stop ASF if population in the WZ would be intensively hunted. The effect is weakened by the large Wz required and the trade-off between enlarged WZ and necessary resources to complete population reduction.
- Minimised width of the WZ and fast-term (silent) population culling soon after fencing of the core area was more promising than large scale, continuously intensified hunting.
- The advice on long-lasting hunting ban in the core area should be clearer regarding that "long-lasting" might be as short as few weeks (e.g. only 2.5 months in CZ) and that depopulation should immediately follow once the area with infections was reliably fenced. Long waiting times (several months) till clearance of the core area and the WZ were already suggested as of limited value for the overall outcome (EFSA 2018a). The hunting ban phase includes not only the building of reliable fences but also identification of the infected area by intensive carcass search.
- For comparison, in units of 1.000-5.000 km² ASF infections did peak only after more than 1.5 years (EFSA 2021b). Finalising the reliable fence encircling the ASF-positive area appears usually faster than that. Therefore, the finished fence is the more appropriate decision criterion for starting culling in the adjacent WZ, compared to awaiting the pass of the epidemic peak inside the fence.
- Carcass removal is a measure to eliminate ASFV sources from an infected area, this is not a pre-emptive measure. Hence, carcass removal must come into play only after ASF entry to the WZ. The yet ASF-negative WZ does not include carcass removal, nonetheless, carcass detection and testing will add to early detection and control of ASF after possible incursion in the white zone

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