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Modelling the effectiveness of measures applied in zones dedicated to stop the spread of African Swine Fever in wild boar when bordering with a region of limited control

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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, live wild boar may still be present in the WZ after its implementation 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 principal approach was established in the EU with regards to focal introductions. Here the special case is considered when the WZ approach is applied adjacent to an (potentially large) area with limited ASF control. The results of the spatially explicit individual-based simulations in different EU landscapes demonstrate that the WZ strategy becomes more complicated when applied in adjacency to areas with limited control. The failure rate and the hunting effort to implement the WZ increases compared to the focal scenario. The three WZ parameters, width, distance to core area and culling target density are tested in both situations and combined with carcass removal and fencing to facilitate effect comparison. Proactive approaches are simulated and the outcome was found to be dominated from the landscape and/or the WZ parameters chosen.

Key words: ASF, individual-based model, spatial-temporal simulation, white zone, population reduction, carcass removal, fencing

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1. Introduction

1.1. Background and Terms of Reference

The report details research activities under contract NP/EFSA/ALPHA/2021/03 contributing to EFSA's ASF Epidemiological Report (EFSA 2022).

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.

The Member States (MS), and the Commission are continuously updating the 'Strategic approach to the management of African Swine Fever for the EU' and the related legislation. There is knowledge, legislation, scientific, technical, and financial tools in the EU to effectively tackle ASF.

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 experience 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.

Effectiveness of different measures and their combinations as control approach has to be assessed in a wild boar population adjacent to populations subjected to limited control. The continued spread of ASF in limited control neighbourhoods alongside the white zone creates a novel strategic problem. In response EFSA seeks support in assessing the consequence of this constellation on the effectiveness of measures acknowledged for standard epidemiological settings (EFSA, 2021b).

Practical protocols of treatments must be modelled comprising implementation effort and impact on ASF.

1.2. Interpretation of the Terms of Reference, Objectives and 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 does enter from the adjacent ASF positive area (or not!). These measures entail the preparation of the WZ to act as buffer towards an even more distant ASF free area yet without management. The 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. 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.

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 and Lange (2017) investigate the effectiveness of pre-emptive measures applied in control areas adjacent to larger regions with epidemic wave like spread of ASF in wild boar. 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 fences around the infected inner part. Lange et al. (2021) addressed post-hoc the performance of WZ examples from previous ASF control activities in different MS and identified critical parameters of the WZ.

In this study the focus was on a particular epidemiological situation where the WZ had to be set-up adjacent to an ASF-affected area with limited control measures applied (Area of Limited Control, ALC). The objective of this study is the comparative evaluation of the effectiveness of WZ measures for the two epidemiological situations in wild boar populations.

2. Data and Methodologies

2.1. Data

The wild boar habitat model by ENETWILD et al. (2020) was used to map the spatial structure of the abundance of wild boar in the EU. The map was converted into the breeding capacity raster of 2x2km (Western and Central Europe) resp. 3x3km (Eastern Europe) according to the proportionality parameter BCconversion (BreedingCapacity [per cell] = BCconversion * RelAbundance [per km^2]).

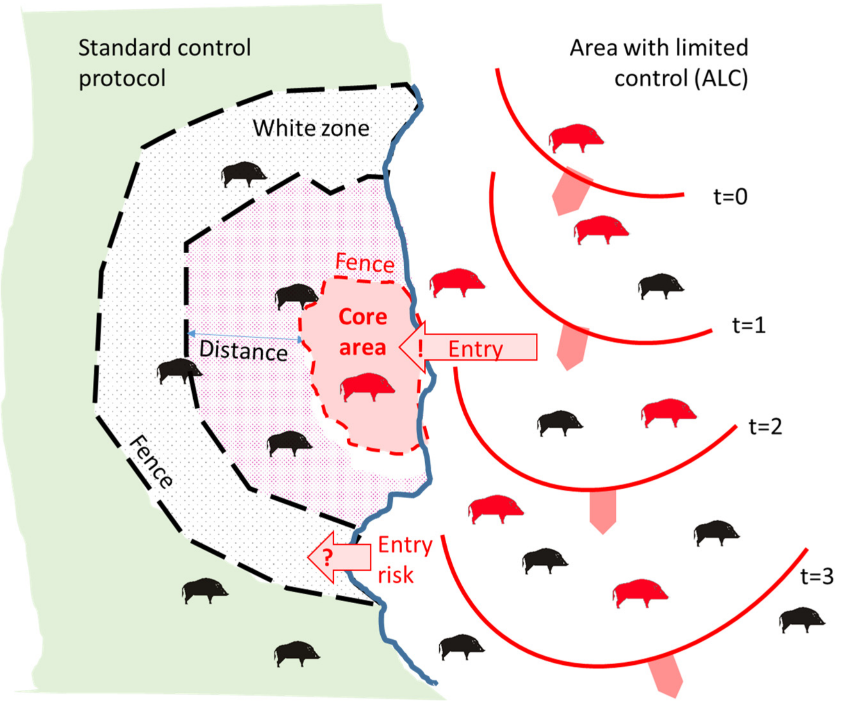
Hunting bag data from Germany and the Baltic countries were applied to validate the conversion of the ENETWILD input map.

2.2. Methodologies

2.2.1. Principle scenario

The problem addresses a specific epidemiological situation which is new compared to previous literature and EFSA output. Although there will be different configurations, Figure 1 illustrates the general situation and sets definitions of concepts used in this tender.

The total management area is divided by the blue demarcation line into a limited control part (right) and a strategic control part (left). The left part applies different control schemes combining available measures in wild boar i.e. fencing, intensive population reduction, carcass removal. Within the right part limited control of ASF in wild boar does result in continued infected wild boars over time and infectious sources expand along the demarcation line between the right and left part. Additionally, the demarcation line might include a physical barrier e.g. fence line. Within the left part the standard (focal) approach applied in EU member states is depicted including a – usually fenced - infected core area (CA) with non-invasive measures only; and the white zone part – also usefully fenced – prepared for intensive population reduction in short time. The outer green area symbolises the part that should be protected from ASF incursion by the set of measures applied to the demarcated zones. Additionally, a lost zone (LZ) is shown between CA and WZ. The size is not yet understood (question mark in Figure 4). However, as reported by EFSA (2021b) there is the risk that the WZ does not halt the infection if it was placed too narrow to the CA so that finalisation of measures in the WZ is not accomplished before the infection approaches (Lange et al., 2021b). The problem of this epidemiological situation refers to the entry risk all over the lengths of the limited control area. The main question, therefore, is whether acknowledged approaches, i.e. width of WZ or distance between CA and WZ, can should be parametrised as suggested for the WZ design of the "true" focal approach.



The wild boar habitat is separated into a limited and a standard control area. Separation line between the two regions (bold blue line) symbolize certain demarcation e.g. using a fence. Red animals symbolise infection and waves the advance over time. Mobile or fixed fences (dashed lines) are established as response to an ASF intrusion in the wild boar habitat. The core area is demarcated and usually fenced area, set-up containing all notified ASF infections and meant to contain also all yet not detected infections. The green area is meant to be sheltered from ASF entry.

Figure 1: Schematic representation of the targeted epidemiological scenario

The schematic representation indicates the variable parameters that will be analysed in the following. Three parameters specify the effort put into the WZ implementation and the determine its reliability in stopping ASF inside the WZ: **width** of the WZ, the **targeted wild boar density** inside the WZ and the **time interval** during which the target must be reached. Additionally, the WZ can be surrounded by a **fence** which may have unknown **fence permeability**. The **distance between the WZ and the core area** is adjusted to the spread velocity of the ASF infection and the time interval until the WZ is prepared. **Carcass search and removal** is optionally considered.

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; 2010) is available from http://ecoepi.eu/ASFWB/.

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 ENETWILD (2020). Given ENETWILD structures, maximum abundance or density are calibrated to estimations provided by the MS for each region likewise in EFSA (2021a). Finally, the data provided by the MS regarding hunting records were used to validate the population numbers emerging from the model rules.

On the geographic landscape ASF spread is simulated, and control efforts applied to the white zone including fencing, ASF-related depopulation activities and carcass search/removal. The purpose is to investigate whether the epidemiological situation of ongoing ASF spread alongside the set-up WZ has an impact on the possible outcome of the WZ-based strategic approach.

Model output is aggregated to derive:

- the likelihood to fail with certain set of measures applied in the WZ,
- the relationship between depopulation effort (costs) and the strategy success (outcome).

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

2.2.2.1. Transmission model of ASF infections in wild boar

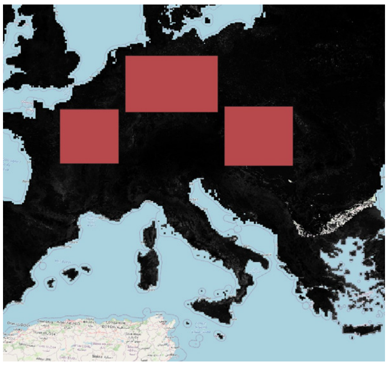
The basic principle of transmission relates to the number of adjacent/in contact animals and carcasses using event probabilities, i.e. each infectious object provides a chance of transmission to every susceptible animal sufficiently close.

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 and Thulke, 2017; Lange et al., 2018) and 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 and 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.

2.2.1. Simulation protocol

The simulations were performed on real habitat geography. Habitat maps for selected terrestrial Europe (Figure 2) are derived from the habitat model according to ENETWILD (2020). The landscape is calibrated to generate the ENETWILD information in terms of spring population density in the WZ prior to ASF. For every scenario and parameter combinations, either all model runs were performed on one selected landscape (fixed landscape), or one model run per 1,000 randomly selected landscapes (randomized landscape). In all simulations, however, the size of the simulation area is equal. This facilitates the direct comparison of model outputs while adjusting for the possible space-time interaction in one selected finite simulation area.

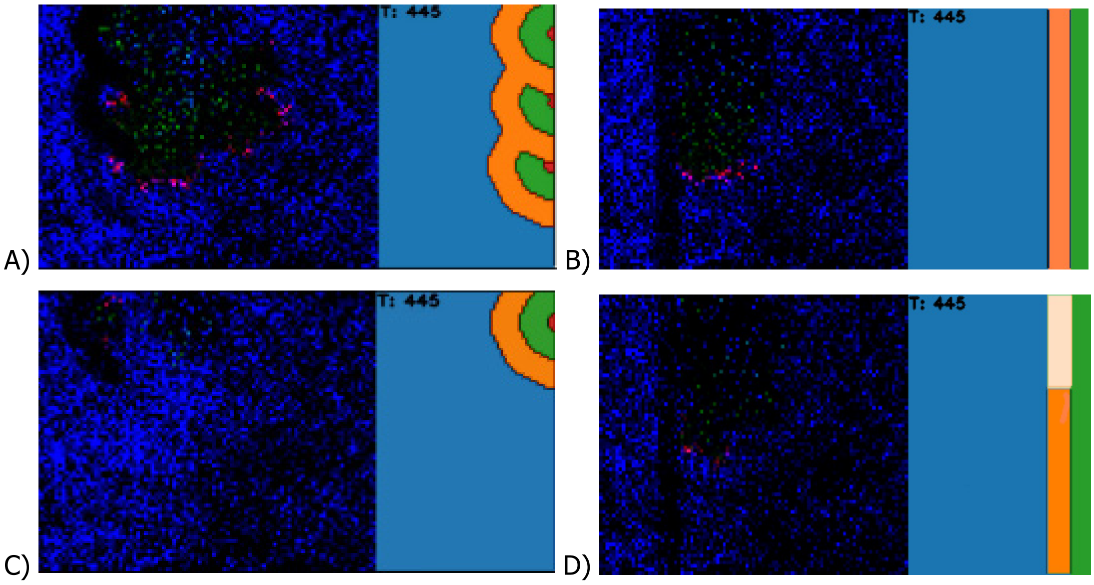


Without randomised simulation landscape the model refers to one arbitrarily chosen rectangle in the middle box.

Figure 2: Map of Europe with boxes indicating the terrestrial regions from which the simulation landscape was randomly chosen

The infection was released in the north-eastern part of the simulation landscape. Simulated spread generated westwards and southwards waves with continuous approach towards the demarcation line (see Figure 1). When the infection was close enough the WZ were declared, and measures implemented so that after the pre-set time horizon a pre-set population density was steadily reached.

The population reduction measures are implemented with two parameters: 1. the duration of campaigns determines the time per measure to achieve a specified target, and 2. the interval between campaigns determines after what time a repeated campaign with the same target will be re-applied to maintain the population inside the WZ at the target density. Fences are optionally erected both around der CA and the WZ. Fences are simulated with different fence permeability of 0, 10, 100% (see Lange and Thulke, 2015).



Left in each panel the model landscape of wild boar (blue – brighter colour equals more individuals) shaped by the infection (infectious red, seropositive green) and succumbed respective culled animals (black); the right side of the panels shows the location of the management zones i.e. core area (red), the WZ (orange) with the distance between CA and WZ reflected by the green region. A) Scenario "Reactive WZ next to ALC" where every new introduction is responded by an individual radial WZ. B) Scenario "Proactive WZ" where in the moment that the infection approaches the green rectangle a WZ is implemented as block from top to bottom and maintained till the end of the simulation. C) scenario "Reactive WZ focal" as in A but after the first WZ was triggered further transmission in the adjacent limited control part is supressed. D) scenario "Proactive WZ roll-back" as in B but when there is no more infection in the upper segments of the block-wise WZ then these segments are released from measures.

Figure 3: Snapshot of the model output for the different scenarios

The simulation considers four scenarios (Figure 3). The **first scenario** (A: "Reactive WZ next to ALC") mimics measures for every introduction of ASF into the left part due to continued spread in the right part. **Scenario two** (C: "Reactive WZ focal") disables transmission in the right part of the simulation landscape (i.e. the limited control part) right after the fifth wild boar in the other, the left part of the landscape, got infected. The purpose is to mimic a focal introduction into the left part. Comparing the Scenario "Reactive WZ next to ALC" to the "Reactive WZ focal" scenario facilitates the assessment of the extent to which the two epidemiological situations (neighbouring to limited control vs standard focal) differ by their outcome e.g. overall success rate. The **third and fourth scenario** immediately place a block-like WZ along the complete demarcation line once the infection approaches to a trigger distance. The block-like WZ (instead of the successively build WZ in A) was simulated either as such till the end of the simulation (B: "Proactive WZ") or the WZ was rolled-back segment-wise dependent on the current case distribution in the limited control part (D: "Proactive WZ roll-back"). To operationalise the latter scenario the landscape was compartmentalised into horizontal segments and the WZ segment-wisely released of the measures, where there is no more infection observed in the same segment of the adjacent limited control area (ALC).

The number of repetitions per simulation scenario was for the randomised landscape 1.000 runs on different landscapes.

2.2.2. Analysis of model output

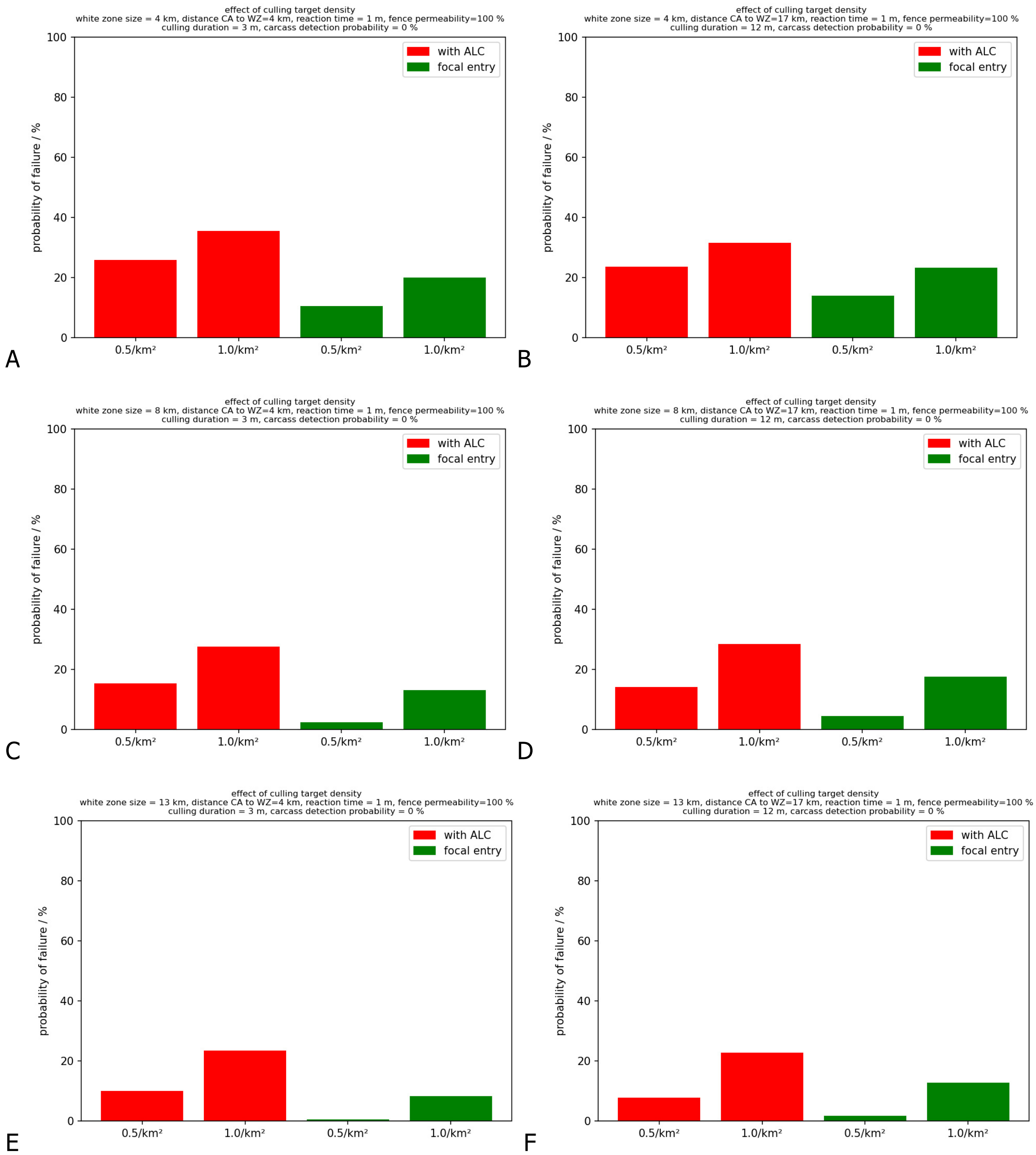
The output measure per simulation was the **number of failed runs**, the **number of animals culled for population reduction during WZ implementation and maintenance**. The interaction between control parameters was investigated in systematic cross-combination of parameter variations in the knowledge-based parameter range. Unexpected dependencies were analysed using pivotal experimentations to understand the respective model characteristics.

3. Results

3.1. Reactive white zone

3.1.1. Comparing reactive white zone adjacent to area with limited control and focal introduction

Simulation outcome reveals substantial difference between the two epidemiological situations (Figure 4, red vs green bars). The red bars reflect the outcome of the control effort required adjacent to a ALC with expansive spread in parallel to the border between the two parts (see Figure 1, ALC scenario). The green bars show the failure rate if further transmission in the ALC was switched off after the infection had entered the standard control part (mimicking the focal introduction, focal scenario). The sequential need for new WZs in response to consecutive introductions from the limited control part (Figure 3A) makes the overall strategy more vulnerable to failure compared to the isolated single introduction (Figure 3C). As illustrated by Figure 3A and C, the repeated introduction along the spatial expansion of the infection in the ALC repeatedly also results in breakouts from (one of) the sequentially WZs (red in Figure 4) – while the WZ was more successful if applied only to the focal introduction (green in Figure 4).



The outcome is shown for the three main parameters of the WZ: width in km (row; 4, 8, 13); distance CA to WZ in km (column; 4, 17), and population reduction target density (0.5 left bar vs 1.0 wild boar per km² right bar). The outcome is compared between the scenario "Reactive WZ next to ALC" (red) and the scenario "Reactive WZ focal" (green). Parameterisation is listed on top of the diagrams.

Figure 4: Model output of the probability of overall failure of the simulated strategy for the different scenarios and randomised landscape

3.1.2. Design parameters of the reactive white zone

Figure 4 illustrates the importance of different design parameters of the reactive WZ. These parameters are the WZ width (4, 8, 13 km); distance CA to WZ (4, 17 km), and population reduction target density (0.5, 1.0 wild boar per km²).

The model output revealed the **target density is an important determinant of the success** both for the focal and the ALC scenario. The importance of target density for the WZ strategy is reasonable as less animals lead to less carcasses and therefore transmission chains that are more vulnerable to stochastic fade out. The effect is visible across all 12 parameter scenarios (Figure 4A-F) and the two epidemiological scenarios (Figure 4: red vs green). For the reactive WZ with ALC (red bars) the failure rate is lowered between 25 to 50% when reducing the target density of the culling measures from 1 to 0.5/km². While for the reactive WZ in the focal setting (green bars) the improvement can be close to 0% failure (Figure 4E).

The **wider WZ further improve the success**. The reduction of the width of the WZ with ALC by two thirds (form 13 km to 4 km) increased the failure rate by about one third for the 1.0/km² target density (Figure 4: E vs A) and by nearly doubled failures for the lower target density of 0.5/km² (Figure 4: F vs B). Nevertheless, failure of the reactive WZ with ALC remains more frequent than that of the reactive WZ in focal setting.

Interestingly, the **increased distance between the CA and the WZ** (and therewith the prolonged time to reach the target density inside the WZs), did not lead to systematic changes in the overall failure rate neither for the WZ with ALC nor the focal setting (Figure 4: A vs B; C vs D, E vs F). This is important as the distance between the left and right diagram per row varies by fourfold size and fourfold time to achieve target density level.

When setting-up a WZ the distance to the CA is critical. The purpose of adequate choice of the distance between CA and WZ is to assure that the infection enters the WZ if the zone is best prepared. The adequate distance must integrate the speed of propagation of ASF in wild boar of the control region (population size/density) and the time horizon over which the population reduction within the WZ should be accomplished (resource implication). The effective estimation of the speed of propagation using parsimonious case network analysis was demonstrated in e.g. in EFSA (2018a). The procedure increased reliability the longer the real wild boar cases are recorded in an area which is less suitable for early determination of the speed of propagation to set-up WZ parameterisation. A promising method to swift estimation is proposed using early case network as basis for diffusion constant estimation (Lentz et al 2022).

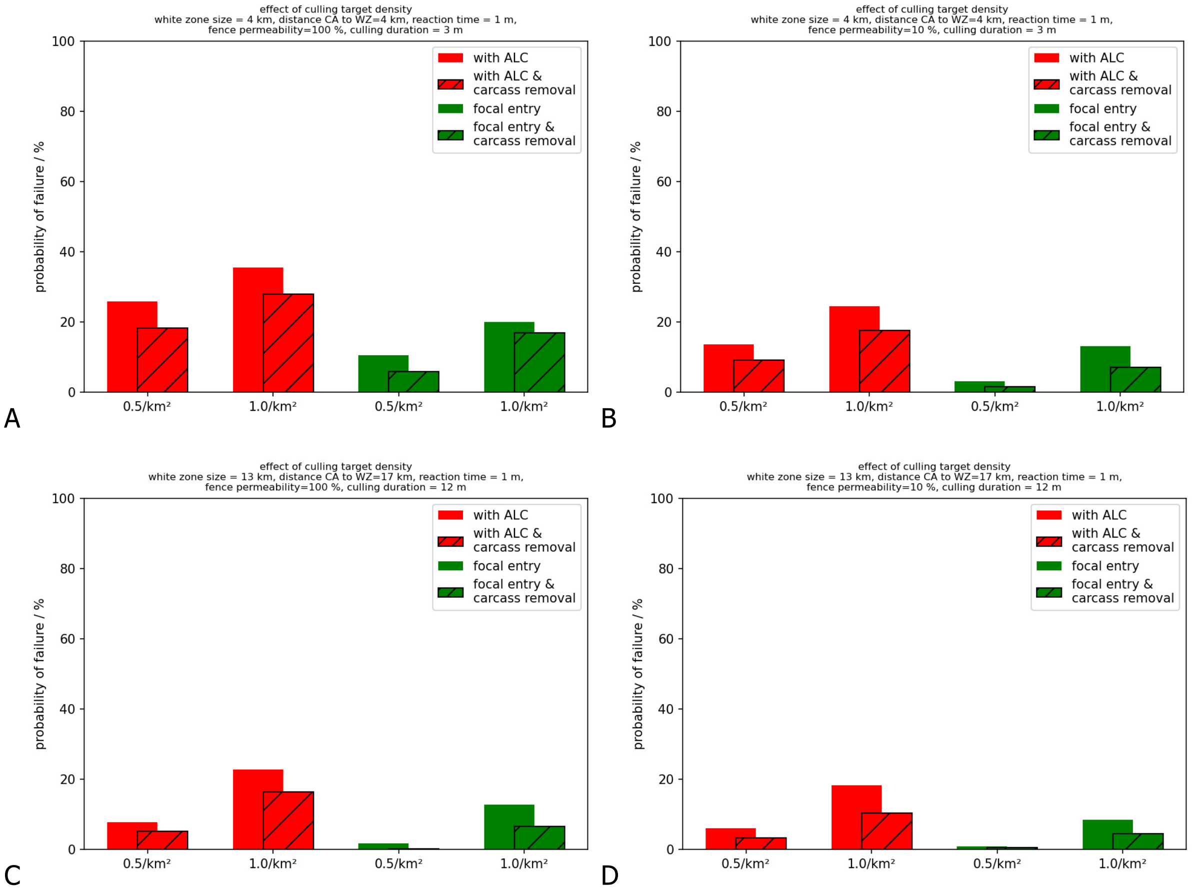
For the following argumentation the data is limited to the adjusted choice of the distance between CA and WZ (i.e. distance CA to WZ = 4, 8, 17 km with 3, 6, 12 months duration to achieve the set the target density by culling measures).

3.1.2.1. Carcass removal and fences

The next aspect of the WZ design relates to the additional inclusion of fencing and carcass removal in support of the WZ efficiency. The interest, therefore, is whether the addition of fences, carcass removal or both further reduces the failure probability. To illustrate the effect, Figure 4 was combined with the same output but after adding fences (Figure 5 row-wise) or/and carcass removal (Figure 5 solid vs striped bars).

The **inclusion of fences around the CA and the WZ improved the overall outcome** of the strategy (left column in Figure 5 vs right). The better the WZ is parameterised (width, distance CA to WZ, target density) and equipped (carcass removal) the lower is the effect of fencing.

The inclusion of **carcass removal of 40% reduced the overall failure**. However, from the complementary simulation experiments, either without carcass removal, or in the CA, between CA and WZ as well as inside the WZ, did not allow to disentangle the effect that carcass removal in WZ itself adds. The value of 40% refers to optimistic observations from structured carcass search but not mimicking focused intensified search for confirmatory purpose after case detection. The better the WZ is parameterised (width, distance CA to WZ, target density) and equipped (fences) the lower is the effect of carcass removal.



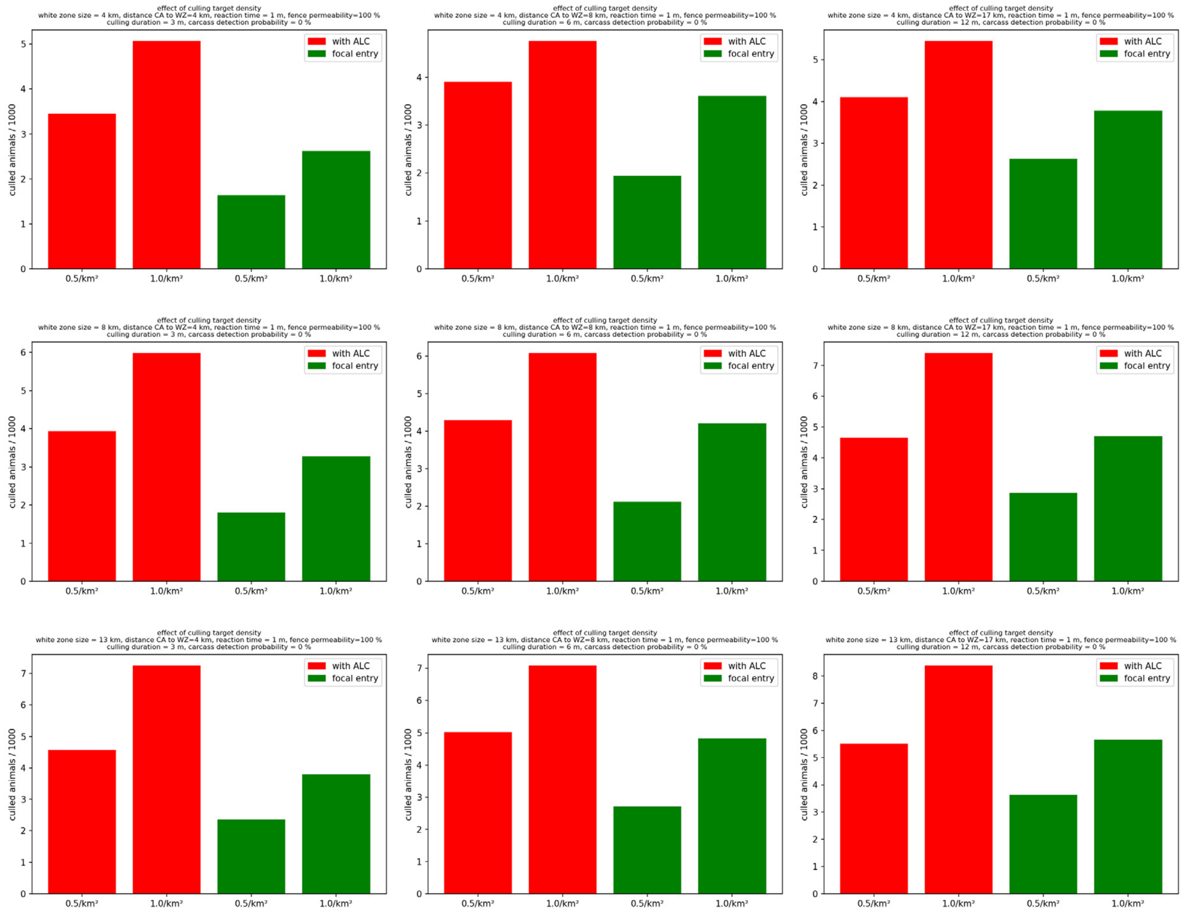
The influence of fencing (A+C no fence; B+D with fence of 10% permeability) and carcass removal (solid bars: no carcass removal; striped bars: Carcass removal in the CA, the area between CA & WZ, and the WZ). The outcome is shown for alternative width of the WZ (A,B 4 km; C,D 13 km), distance between CA and WZ (A,B 4 km and 3 months culling duration; C,D 17 km and 12 months), and different target densities (0.5 vs 1.0 wild boar per km², x-axis) comparing the reactive WZ scenario (red) with the focal WZ scenario (green). Parameterisation is listed on top of the diagram.

Figure 5: Model output of the probability of overall failure for different combinations of carcass removal and fencing

3.1.2.2. Less overall culling effort

The intuitive expectation would argue that with lower target density in the WZ there is an extra effort needed to initially cull the animals accordingly. While this can be confirmed from the model analysis another aspect was found. The total culling effort, i.e. over the period the WZ was sustained, was always lower by up to 35% culled animals when addressing a more stringent target density (Figure 6).

Given the WZ must be sustained for longer than the time foreseen for implementation then an originally lower target for the population density pays back, because less animals did survive the recovery between subsequent population reduction campaigns is lower and therefore the subsequent culling volume smaller than for the same WZ but addressing a higher target density (Figure 6, 0.5/km² instead of 1.0/km²).

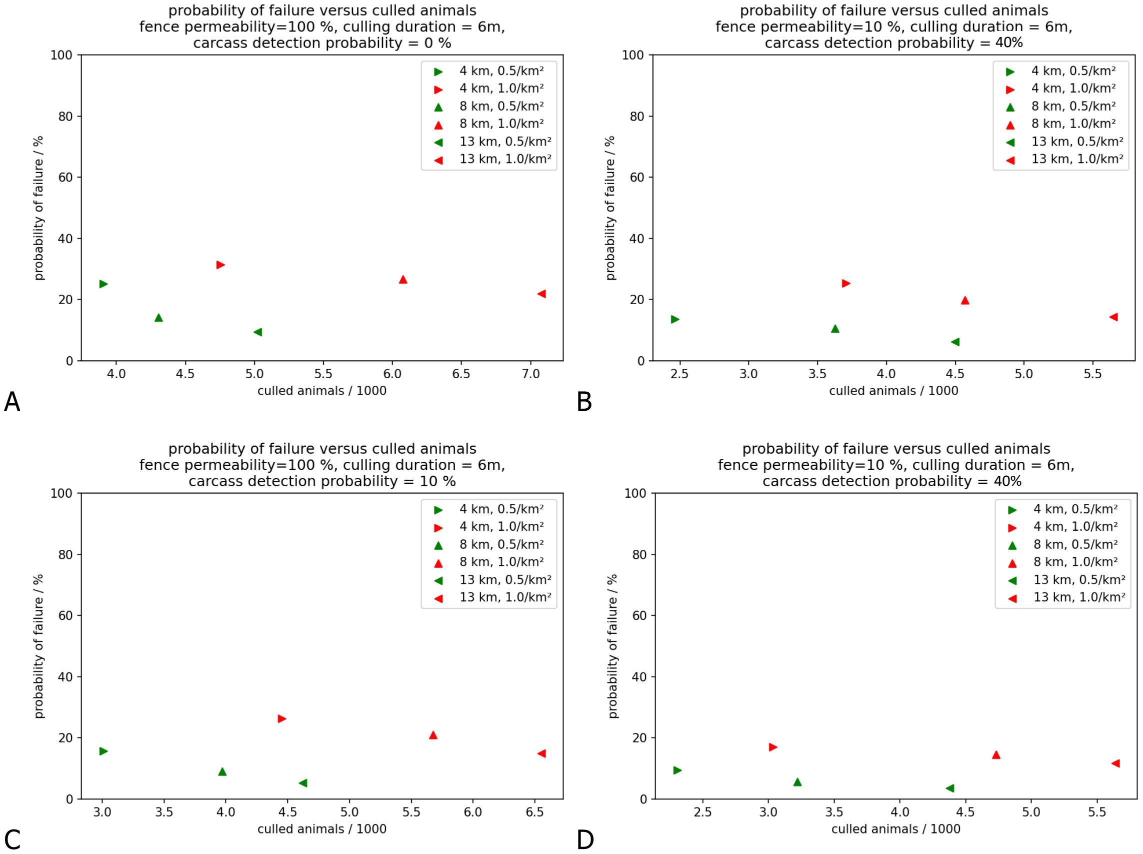


The data is shown across increasing width of the WZ (top to bottom) and increasing distance between CA and WZ (left to right). Parameterisation is listed on top of the diagram.

Figure 6: Model output of the total culling effort for the WZ with ALC (red) and the WZ at focal entry (green) but assuming either a target density of 0.5 or 1.0 wild boar per km²

3.1.2.3. Summary

The data of the probability of failure and the number of culled animals allow crossing over the main efforts and the expected results when applying the reactive WZ.



The influence of fencing (A+C no fence; B+D with fence of 10% permeability) and carcass removal (A+B: no carcass removal; C+D: carcass removal 40% in the CA, the area between CA & WZ, and the WZ). The outcome is shown for alternative width of the WZ (orientation of symbols right 4 km, up 8 km, down 13 km), and different target densities (green 0.5 and red 1.0 wild boar per km²). The distance between CA and WZ was 8 km i.e. 6 months culling duration. Parameterisation is listed on top of the diagram.

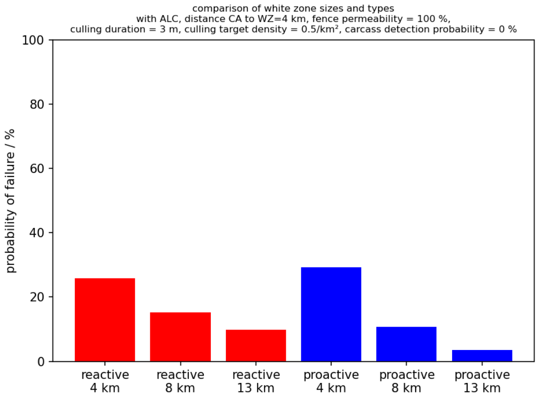
Figure 7: Model output of the probability of failure (y-axis) and the number of culled animals (in 1000, x-axis) for different parameterizations of the reactive WZ adjacent to an ALC

The crossing of efforts and outcome when applying the reactive WZ adjacent to an ALC reveals the advantages of the lower target density both regarding effort and success (Figure 7). But it is highlighted that in general the deliberate increase of the width of the WZ does not necessarily payback adequately. Indeed, a threefold increase in width (4 km to 13 km) may add up to 100% more animals to hunt while the reduction in failure rate is small as soon as supportive measures were in place (fences and/or carcass removal).

3.2. Proactive white zone

3.2.1. Comparing reactive and proactive white zone adjacent to area with limited control

The discussion of the outcome in Chapter 3.1. revealed the intrinsic difficulties due to the application of the WZ approach adjacent to limited control regions. Therefore, the question arises whether the immediate implementation of a block-like WZ parallel to the border of the limited control region would be more useful. The approach will be called proactive WZ.



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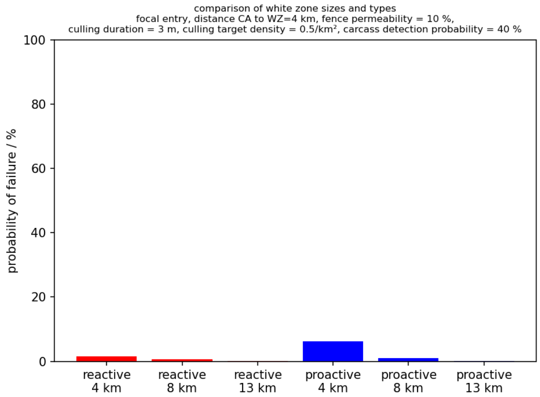

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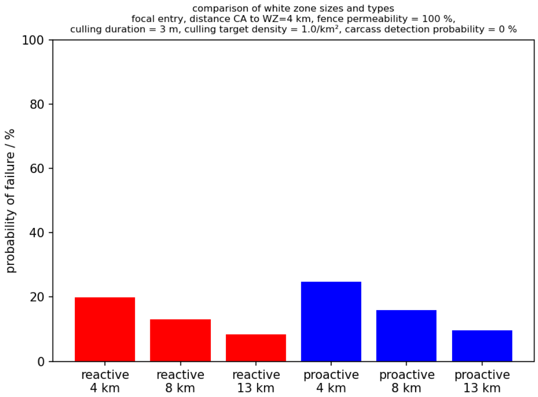

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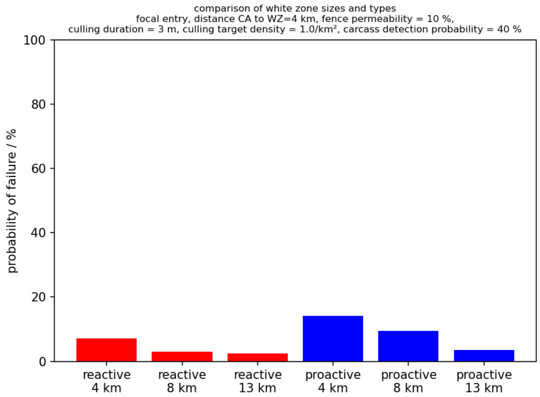

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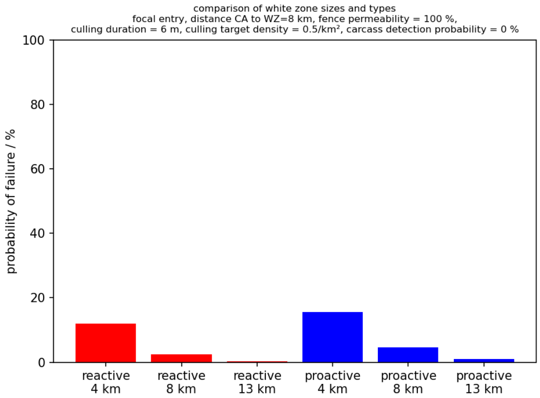
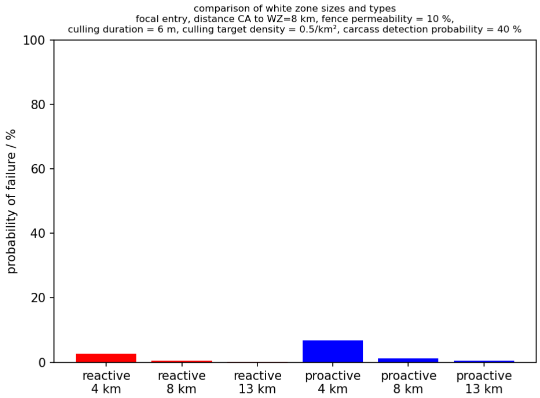
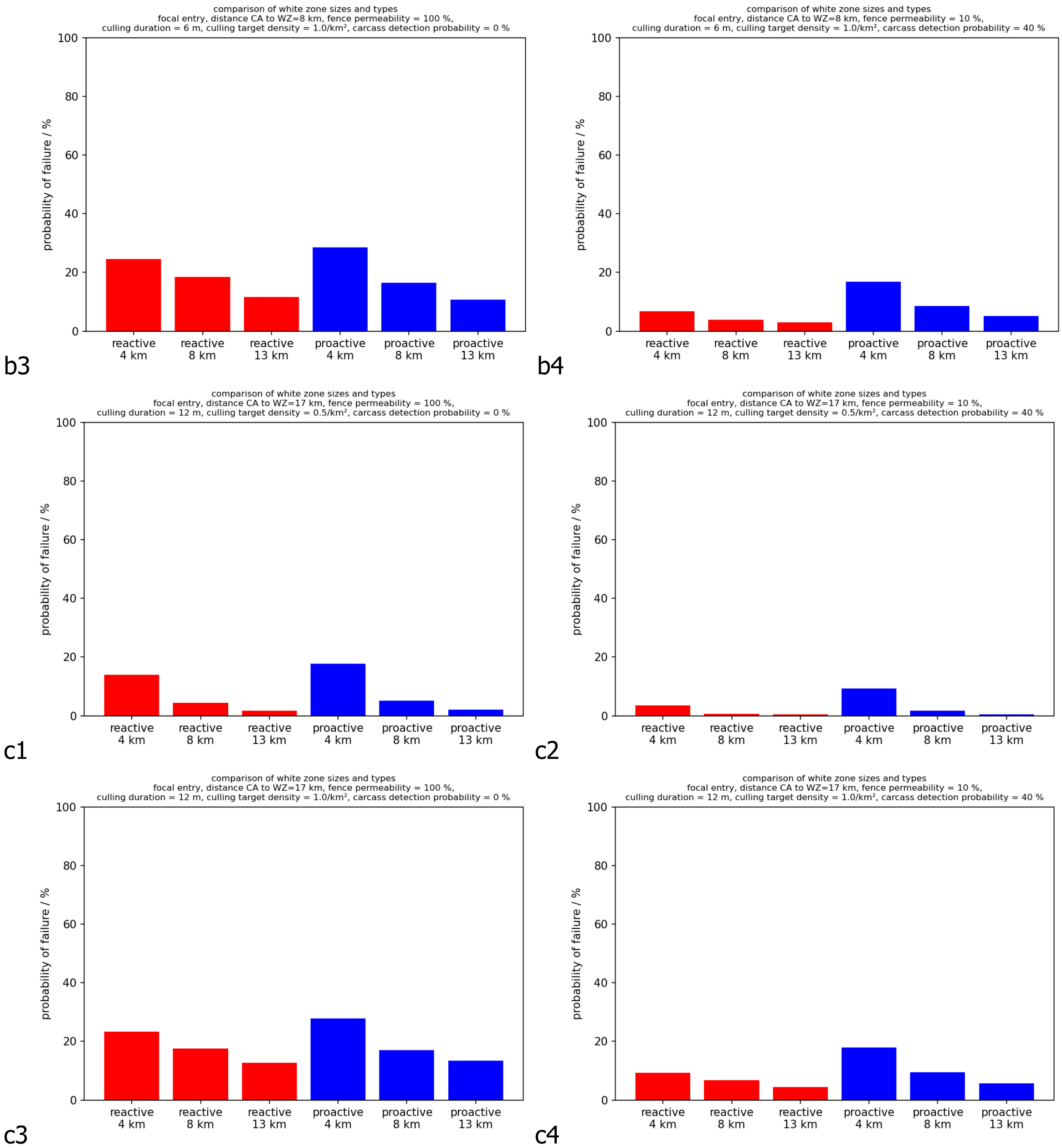


b1



b2



The reactive WZ (red bars) adds WZ-ensembles responding to the continued entry of the infection along the borderline. The proactive WZ (blue bars) is immediately installed along all the borderline and low population density continuously maintained. Every quadruple of diagrams relates to one distance between CA and WZ (a1-a4 4 km; b1-b4 8 km; c1-c4 17 km). Details see text. Parameters are listed on top of the diagrams.

Figure 8: Comparative model output for the reactive (red) and the proactive WZ (blue) with alternative width of the WZ

Figure 8 shows the model outcome for different width of the WZ and different distance between CA and WZ (a1-a4 4 km; b1-b4 8 km; c1-c4 17 km). The four subfigures ressemble the intense target density (0.5/km²) in the first (subpannel 1 & 2) and the lower (1.0/km²) in the second row (3 & 4). Left (1 & 3) is without fences and no carcass removal while right (2 & 4) compiles standard fenses (10% permeable) and perfect carcass removal (40%).

The overall strategy outcome may improve when replacing the reactive and the proactive WZ if all other parameters were kept unchanged (e.g. Figure 8 a1). Comparing the bars with the same value on the x-axis addresses the difference in success when replacing the reactive WZ (red) by the precautionary proactive WZ (blue). For selected parameter constellations the application of a proactive WZ may support eventual success, however this picture is not unique when the outcome for randomised landscape selection was analysed in common. Whether the proactive WZ can reduce the failure probability of the reactive WZ is dependent on the remaining parameters and the landscape.

The proactive WZ, comes at extra costs. This is due to the need of full area treatment all the time when implementing the target density inside the WZ. Comparing the final output for the reactive and the proactive WZ approach there was an area covered by WZs of 4,000 km² vs 3,400 km² but in total 28,000 vs 68,000 animal had to be shot. The threefold increase in culling effort may render the proactive WZ quickly impractical, particularly when the width of the WZ must be maximised to facilitate lower failure rate.

3.2.2. Proactive white zone and compartmental roll-back

The drawback found with the proactive WZ results from the large culling effort. The proactive WZ is placed proactively along the demarcation line between the standard control area and the ALC. Therefore, it has immediately with the first incursion the full dimension and thereby substantially larger numbers must be culled compared to the successive increase of the reactive WZ. The extended culling efforts remain even then when the infection distribution in the ALC does no longer put all the proactive WZ at risk (see Figure 3B). Earlier infected parts of the ALC may become free of the infection after the epidemic peak passed.

The recognition brought-up the idea of a compartmental "roll-back" to compensate the continued culling efforts. This refers to the sequential release of parts of the WZ which are no longer under direct exposure to ASF infections from the ALC (Figure 3D).

Figure 9 puts together the comparison of the proactive WZ without (blue symbols) and with roll-back (green symbols). The obvious outcome of comparing the tow data series underpins that the **proactive WZ with roll-back will result in similar failure rate as the proactive WZ but involving only about one quarter of the culling effort**.

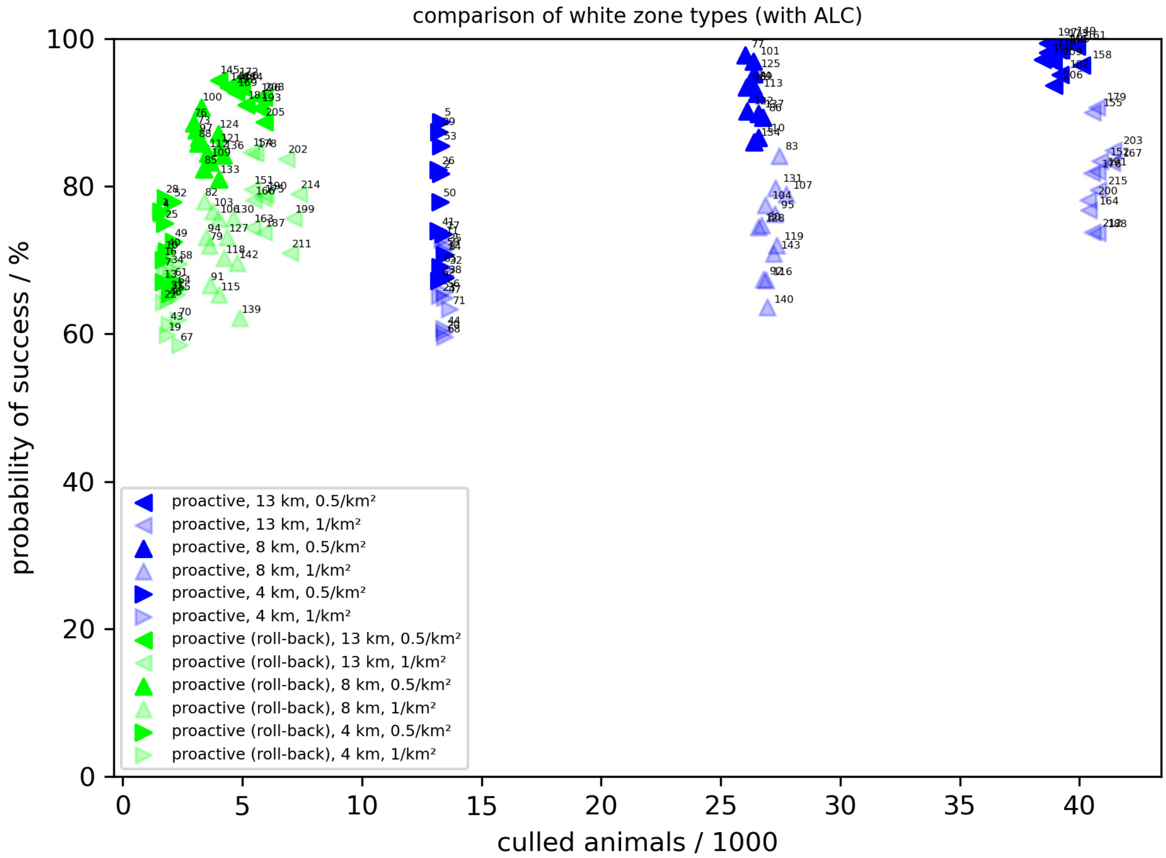


Figure 9: Overview of model output comparing the proactive WZ (blue triangles) and the proactive WZ with additional compartmental roll-back (green triangles). Triangle orientation represents the width of the WZ (i.e. 13, 8, and 4 km). Colour intensity is used to represent target population density in the WZ (0.5 strong, 1/km² transparent). Numbers refer to different parameter combinations (Appendix A)

4. Discussion

The study referred to the epidemiological scenario of a WZ application in adjacency to an area with continued ASF spread due to limited control measures implemented. The peculiarity of the scenario is that ASF spread expands along the area controlled with a WZ. Hence, further incursions after first WZ set-up must be expected. The main insight of the study confirmed that ASF control under such circumstances is substantially complicated. Although the same measures were applied in model simulations the outcome of WZs in adjacency to a limited control area was less optimistic than for the application in the focal context.

Due to the continued risk of further incursions from the ALC the resulting multiple WZs create an enlarging control area. Therefore, quantitative aspects of the WZ implementation become more and more dominant when understanding the practical implications. Resources increasingly must be opposed with potential success improvements to decide for best combination of management plans.

4.1. Parameters of the WZ

The aligned **distance between WZ and CA** is an important prerequisite of the useful WZ implementation. Aligning distance means integrating the approximate speed of propagation in an area (or reasonable upper bounds) with the time planned for culling efforts inside the WZ to reach the set target density. The results underpin that once the distance is adjusted such that the infection will not enter the WZ before the population reduction is accomplished, longer distances are possible. However, logically, the wider the distance between WZ and CA greater the effort to manage carcasses in the resulting zone. On the other hand, shortening the distance between CA and WZ eventually shortens the time to reach the target population level inside the WZ. If distance between WZ and CA and time to reach the target population density match, then there is room for practically driven decisions, which pair of distance and culling time is preferred.

The lower the **target density** of population reduction inside the WZ is chosen the low the resulting risk to fail with the control approach. This tendency was found for all parameter combinations although the effect size differed dependent on the other WZ parameters. The model simulations considered stringent target densities of 0.5 and 1.0 animals per km². However, the importance of target density for the final success of measures, and the feasible effective and fast population reduction demonstrated with a WZ in France (EFSA, 2021a), motivated the consideration of such optimistic depopulation targets.

We have presented impact analysis for the randomised landscape approach. Hence, the absolute improvement by lowering the target density from 1.0 to 0.5/km² is an average value. There would be landscapes where the difference between ALC and focal scenario is more drastic dependent on the real geography. Most important, however, is the principal trend of increased strategy success with intensified culling. This was seen in the average already and therefore independent of the individual scenery.

The **width of the WZ** is deemed a flexible strategy parameter. The results support this understanding as wider WZ correspond with less failure of the measures. Additionally, the parameter is simply to decide on the crisis map. However, the implications of wider WZ are on the side of resources for implementation.

The model simulation results adding **fences** and **carcass removal** led to a reduction of failure rate. The more the better is not an unexpected insight. Interestingly, the improvement by either tool is not proportionate between different WZ setting (Figure 5: A, B most limited WZ design simulated vs C, D most optimistic WZ). Dependent of the original failure rate fences did contribute more than carcass removal (A, B small WZ) or equally to the overall failure rate (C, D widest WZ). With the latter and a target density of 0.5% the differences in simulation output are already near the stochastic uncertainty and thus need not to reflect a causal disadvantage of either tool.

Carcass removal is critical for reactive ASF control (and early detection surveillance) and does reduce incidence in the CA and in the region between CA and WZ. However, the removal of 40% (infectious) carcases has led to limited improvement of WZ management. The finding is reasonable because carcass removal in the WZ (after potential entry of the infection) may determine success in halting/eliminating the infection inside the WZ falls short as ASF perpetuation is planned to stop due to the reduced numbers/density of susceptible wild boar in the WZ. Hence, the effect of carcass removal seen in the model outcome is rather associated with the effort addressing the CA and the zone between CA and WZ, and not the effort inside the WZ. Moreover, to make carcass removal inside the WZ useful ASF must enter the WZ first. Then, however, the zone is ASF positive and standstill requirements may be advised – hence the WZ is successful or not based on its preventive and timely implementation.

4.2. Proactive white zone

The approach to proactively build a WZ corridor between the ALC and the area to protect from ASF incursion (green in Figure 1) did improve the final success in few parameter simulations compared to the repeated reactive extension of the WZ according to the standard WZ protocol. Interestingly the improvement was not general for all landscapes or all WZ parameterisations. The reasons for the inconsistent outcome may be related to the less structured proactive WZ. Indeed, the reactive version must deploy several sub-compartments of the final WZ always culling animals within a closed half-ring. This special structure might break the expanding wave of ASF often better than the unstructured outcome of the proactive WZ. However, the considerations require more situation-dependent analysis to aggregate conditions of the infection, the habitat geography and the WZ parameterisation that would favour proactive vs reactive WZ set-up.

As usual, such proactive management comes as substantial extra cost, here the increased number of animals to cull. The addition of roll-back suggests a solution to this drawback of the proactive WZ. However, the uncertain element of this refined strategy is the undoubted clarification of infection free status in compartments of the ALC. In practise a developed exit criteria must be derived (e.g. based on EFSA, 2021b). Unfortunately, the most adequate surveillance might not be possible in the ALC for various reasons.

4.3. Pertinent queries extending the results

Based on data and modelling output, this document addresses principal aspects of WZ effectiveness if applied adjacent to a limited control region. The evaluation of the specific epidemiological situation, 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: What are tangible units of increase to explore the trade-off between the options and costs of WZ parameterisations integrating WZ width, distance between CA and WZ as options and culled animals, carcasses to remove as costs with the strategy success? What does another km in width of the WZ mean per hundreds of carcasses removed?

Q2: Does the proactive but compartmentalized set-up of WZ generate situation independent benefits compared to the reactive application and which determines support the decision to apply either or approach?

Q3: Estimators of speed of propagation of ASF in wild boar are available after the epidemic entered a landscape. How can the speed of propagation be a-priori determined from ecological and landscape features to set-up the adequate distance between CA and WZ given the culling duration planned?

5. Conclusions

Is there a difference between the low-control neighbourhood scenario and the standard EU concept of WZ application?

- The WZ approach is developed to address entry or incursion of ASF infections in ASF-naïve wild boar populations.
- The application of the standard WZ approach is substantially complicated in adjacency to areas where ASF infections spread in wild boar and low-control efforts are applied.
- For the same set of measures the overall success rate is greatly reduced if adjacent to low-control zones compared to WZ-based combat of ASF infections in homogeneously managed areas.

How the WZ approach may be strengthened in the low-control neighbourhood context?

- Effective population reduction measures are the key to useful application of the WZ approach.
- Targeting higher population reduction in declared WZ cause larger numbers of wild boars to cull. However, targeting greater population reduction (for example less than < 0.5/km² instead of 1/km² within 6 months) results eventually in less overall culling effort and "additionally" maximises control success.
- The second determinant of success rate is the width of the WZ. Thus, the wider a WZ is established for a given target of population reduction, the better the expected control outcome.

- Wider WZ cause inherently larger numbers of animals to cull.
- Reducing WZ width but implement unchanged culling effort to reach lowered target density levels is more efficient to reduce strategy failure.
- The distance between CA and WZ must respect the spread velocity of ASF infections (landscape dependent) and the time planned to establish and finalise the population reduction measures in the WZ (management decision).
- Inappropriately short distance between CA and WZ does reduce the overall success rate of the measures because the infection will enter the WZ too early.
- Carcass retrieval is important for early detection of expansive spread and to reduce incidence in affected zones – however, carcass removal has limited capacity to improve usefulness of WZ management because carcasses fall later after the infection already did spread inside the WZ.
- The region between the (fenced) core area and the (fenced) WZ can also be treated by population reduction but must not if resources are short.

Trade-offs in applying reactive sequential WZ per entry of the infection or ad-hoc WZ all along the demarcation line (e.g. administrative border) to the region with low-control efforts?

- For the WZ-approach adjacent to an area with limited control there is clear benefit if the WZ was established a-priori in parallel to all the low-control area rather than sequentially build focal WZs in response new incursions of the infection from the limited control area.
- The excess culling effort required to maintain ad-hoc WZ along the border to limited control areas can be compensated with successive release of segments of the WZ put at ASF infection risk early after the infection moved on (roll-back).
- Roll-back should start not too early. The uncertainty with rolling-back are possible translocations of ASF infection e.g. by humans, backward to the already cleared region.

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Appendix A – Scenario legend Figure 9

The results presented in Figure 9 are labelled by a scenario code. The parameter combination per code is given below:

id	width_of_WZ in km	distance_CA_WZ in km	fence_permeability %	target_density per km²	carcass_removal %	Success %	mean_culled	type
1	4	4	1	5	0	76,6	1602	proac. WZ roll-back
2	4	4	1	5	0	81,7	13283	proactive WZ
4	4	4	1	5	4	76,4	1622	proac. WZ roll-back
5	4	4	1	5	4	88,7	13306	proactive WZ
7	4	4	1	10	0	68,6	1723	proac. WZ roll-back
8	4	4	1	10	0	70,7	13503	proactive WZ
10	4	4	1	10	4	70,9	1733	proac. WZ roll-back
11	4	4	1	10	4	72,8	13338	proactive WZ
13	4	4	10	5	0	96,7	1697	proac. WZ roll-back
14	4	4	10	5	0	70,7	13454	proactive WZ
16	4	4	10	5	4	99,7	1690	proac. WZ roll-back
17	4	4	10	5	4	73,5	13390	proactive WZ
19	4	4	10	10	0	59,9	1861	proac. WZ roll-back
20	4	4	10	10	0	60,2	13423	proactive WZ
22	4	4	10	10	4	64,3	1697	proac. WZ roll-back
23	4	4	10	10	4	65,2	13246	proactive WZ
25	4	8	1	5	0	97,5	1756	proac. WZ roll-back
26	4	8	1	5	0	82,2	13197	proactive WZ
28	4	8	1	5	4	78,4	1775	proac. WZ roll-back
29	4	8	1	5	4	87,4	13227	proactive WZ
31	4	8	1	10	0	65,5	199	proac. WZ roll-back
32	4	8	1	10	0	68,8	13509	proactive WZ
34	4	8	1	10	4	68,9	1995	proac. WZ roll-back
35	4	8	1	10	4	71,8	13505	proactive WZ
37	4	8	10	5	0	65,4	1973	proac. WZ roll-back
38	4	8	10	5	0	67,6	13484	proactive WZ
40	4	8	10	5	4	71,2	1841	proac. WZ roll-back
41	4	8	10	5	4	97,4	13202	proactive WZ
43	4	8	10	10	0	61,3	1938	proac. WZ roll-back
44	4	8	10	10	0	60,7	13439	proactive WZ
46	4	8	10	10	4	64,6	1884	proac. WZ roll-back
47	4	8	10	10	4	64,9	13465	proactive WZ
49	4	17	1	5	0	72,5	2124	proac. WZ roll-back
50	4	17	1	5	0	77,9	13267	proactive WZ
52	4	17	1	5	4	77,9	2108	proac. WZ roll-back
53	4	17	1	5	4	85,5	13292	proactive WZ
55	4	17	1	10	0	65,3	2290	proac. WZ roll-back
56	4	17	1	10	0	65,7	13422	proactive WZ
58	4	17	1	10	4	69,5	2347	proac. WZ roll-back
59	4	17	1	10	4	71,3	13422	proactive WZ
61	4	17	10	5	0	67,2	2154	proac. WZ roll-back
62	4	17	10	5	0	67,2	13216	proactive WZ
64	4	17	10	5	4	66,2	2272	proac. WZ roll-back
65	4	17	10	5	4	69,1	13281	proactive WZ
67	4	17	10	10	0	58,5	2385	proac. WZ roll-back
68	4	17	10	10	0	59,6	13441	proactive WZ
70	4	17	10	10	4	61,9	2302	proac. WZ roll-back
71	4	17	10	10	4	63,4	13660	proactive WZ
73	8	4	1	5	0	87,6	3075	proac. WZ roll-back
74	8	4	1	5	0	93,6	26306	proactive WZ
76	8	4	1	5	4	88,6	2953	proac. WZ roll-back
77	8	4	1	5	4	97,8	26029	proactive WZ
79	8	4	1	10	0	97,2	3616	proac. WZ roll-back
80	8	4	1	10	0	74,7	26710	proactive WZ
82	8	4	1	10	4	97,8	3414	proac. WZ roll-back
83	8	4	1	10	4	84,1	27433	proactive WZ
85	8	4	10	5	0	82,3	3385	proac. WZ roll-back
86	8	4	10	5	0	89,3	26755	proactive WZ
88	8	4	10	5	4	85,8	3137	proac. WZ roll-back
89	8	4	10	5	4	93,5	26357	proactive WZ
91	8	4	10	10	0	66,6	3644	proac. WZ roll-back
92	8	4	10	10	0	67,4	2678	proactive WZ
94	8	4	10	10	4	73,1	3502	proac. WZ roll-back
95	8	4	10	10	4	76,3	27264	proactive WZ
97	8	8	1	5	0	86,6	3168	proac. WZ roll-back
98	8	8	1	5	0	93,4	2607	proactive WZ
100	8	8	1	5	4	90,7	3286	proac. WZ roll-back
101	8	8	1	5	4	96,9	26358	proactive WZ
103	8	8	1	10	0	76,6	3759	proac. WZ roll-back
104	8	8	1	10	0	77,5	26860	proactive WZ
106	8	8	1	10	4	75,7	4004	proac. WZ roll-back
107	8	8	1	10	4	78,9	27723	proactive WZ
109	8	8	10	5	0	83,3	3654	proac. WZ roll-back
110	8	8	10	5	0	86,6	26581	proactive WZ

112	8	8	10	5	4	84,5	3554	proac. WZ roll-back	164	13	4	10	10	0	76,8	40397	proactive WZ
113	8	8	10	5	4	92,6	26501	proactive WZ	166	13	4	10	10	4	78,1	5462	proac. WZ roll-back
115	8	8	10	10	0	65,3	4030	proac. WZ roll-back	167	13	4	10	10	4	83,2	4137	proactive WZ
116	8	8	10	10	0	67,3	26899	proactive WZ	169	13	8	1	5	0	92,7	4740	proac. WZ roll-back
118	8	8	10	10	4	70,3	4235	proac. WZ roll-back	170	13	8	1	5	0	98,1	38664	proactive WZ
119	8	8	10	10	4	97,2	27349	proactive WZ	172	13	8	1	5	4	94,1	4797	proac. WZ roll-back
121	8	17	1	5	0	85,2	4047	proac. WZ roll-back	173	13	8	1	5	4	99,3	39137	proactive WZ
122	8	17	1	5	0	90,2	2611	proactive WZ	175	13	8	1	10	0	78,4	587	proac. WZ roll-back
124	8	17	1	5	4	87,1	3990	proac. WZ roll-back	176	13	8	1	10	0	81,8	40509	proactive WZ
125	8	17	1	5	4	95,2	26392	proactive WZ	178	13	8	1	10	4	84,5	5545	proac. WZ roll-back
127	8	17	1	10	0	73,1	4371	proac. WZ roll-back	179	13	8	1	10	4	90,7	40718	proactive WZ
128	8	17	1	10	0	74,5	26567	proactive WZ	181	13	8	10	5	0	99,1	5148	proac. WZ roll-back
130	8	17	1	10	4	75,7	4620	proac. WZ roll-back	182	13	8	10	5	0	95,1	39187	proactive WZ
131	8	17	1	10	4	79,8	27298	proactive WZ	184	13	8	10	5	4	93,4	4974	proac. WZ roll-back
133	8	17	10	5	0	98,1	4015	proac. WZ roll-back	185	13	8	10	5	4	98,5	39218	proactive WZ
134	8	17	10	5	0	98,6	26398	proactive WZ	187	13	8	10	10	0	73,8	5883	proac. WZ roll-back
136	8	17	10	5	4	84,2	4198	proac. WZ roll-back	188	13	8	10	10	0	73,7	40746	proactive WZ
137	8	17	10	5	4	89,8	26564	proactive WZ	190	13	8	10	10	4	78,8	5970	proac. WZ roll-back
139	8	17	10	10	0	62,2	489	proac. WZ roll-back	191	13	8	10	10	4	98,2	40744	proactive WZ
140	8	17	10	10	0	63,6	26936	proactive WZ	193	13	17	1	5	0	90,6	5733	proac. WZ roll-back
142	8	17	10	10	4	69,6	4796	proac. WZ roll-back	194	13	17	1	5	0	97,2	38463	proactive WZ
143	8	17	10	10	4	70,9	27222	proactive WZ	196	13	17	1	5	4	99,2	5695	proac. WZ roll-back
145	13	4	1	5	0	94,4	4016	proac. WZ roll-back	197	13	17	1	5	4	99,4	38676	proactive WZ
146	13	4	1	5	0	98,5	39109	proactive WZ	199	13	17	1	10	0	75,7	7126	proac. WZ roll-back
148	13	4	1	5	4	93,4	4414	proac. WZ roll-back	200	13	17	1	10	0	78,1	40365	proactive WZ
149	13	4	1	5	4	99,6	39456	proactive WZ	202	13	17	1	10	4	83,7	68	proac. WZ roll-back
151	13	4	1	10	0	79,6	5423	proac. WZ roll-back	203	13	17	1	10	4	84,9	41424	proactive WZ
152	13	4	1	10	0	83,4	40846	proactive WZ	205	13	17	10	5	0	88,7	5915	proac. WZ roll-back
154	13	4	1	10	4	84,6	5365	proac. WZ roll-back	206	13	17	10	5	0	93,7	38935	proactive WZ
155	13	4	1	10	4	99,9	40550	proactive WZ	208	13	17	10	5	4	92,1	5878	proac. WZ roll-back
157	13	4	10	5	0	93,1	4655	proac. WZ roll-back	209	13	17	10	5	4	96,8	38904	proactive WZ
158	13	4	10	5	0	96,4	40105	proactive WZ	211	13	17	10	10	0	97,1	7000	proac. WZ roll-back
160	13	4	10	5	4	93,6	4797	proac. WZ roll-back	212	13	17	10	10	0	73,8	40544	proactive WZ
161	13	4	10	5	4	99,9	39896	proactive WZ	214	13	17	10	10	4	97,9	7373	proac. WZ roll-back
163	13	4	10	10	0	74,4	5422	proac. WZ roll-back	215	13	17	10	10	4	79,5	40785	proactive WZ