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Alternative control strategies against ASF in wild boar populations

PG EcoEpi

Helmholtz Centre for Environmental Research Leipzig/Halle Department Ecological Modelling

M. Lange

Abstract

ASF is a devastating infectious disease of domestic pigs and wild boar, usually fatal. No vaccine exists to combat this virus. It does not affect humans nor does it affect any animal species other than members of the Suidae family. From the beginning of 2014 ASF has spread in Estonia, Latvia, Lithuania and Poland, mainly in the wild boar, causing very serious concerns. The European Commission requested EFSA to assess different wild boar management options taking into consideration its ecology in the Baltic States and Poland. Therefore, a simulation study was performed comparing control strategy alternatives using a spatio-temporally explicit individual-based model. The model was developed based on literature regarding wild boar ecology; ethology of the ASF virus recently circulating in Eastern Europe; wild boar density maps from the ASF affected regions and an expert consultation meeting. The model results did not reveal one single immediately effective control measure based on accepted wild boar management tools. Strategies using conventional wild boar management approaches - ban of feeding and targeted hunting of reproductive females - were found to become effective slowly over multiple generations of reproduction. Therefore, when applying the strategies, a width of 100-200km is required as buffer zone surrounding the area with ASF detections in order to compensate the forward spread till measures become effective. Massive population destruction (i.e. about 80% of the population in the control area within 4 months with any available technique) or instantaneous removal of infectious carcasses could stop ASF spread already by limited buffer width of below 50km. The equal outcome is reasoned by the avoidance of infectious carcasses when the population was destroyed. Centred on the effective and immediate exclusion of wild boar contacts with infectious carcasses, hybrid strategies including reasonably intensified conventional hunting may suffice to stop ASF spread using a practical buffer width (about 50km) resp. time horizon (less than 3 years) for control while avoiding destructive measures.

Keywords: African swine fever, wild boar, wildlife disease control, depopulation, feeding ban, targeted hunting, simulation model

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Correspondence: AHAW@efsa.europa.eu

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Summary

On the first of December 2014, the European Commission requested scientific advice from EFSA on African swine fever. One of the requests made by the commission required EFSA to assess different wild boar management options taking into consideration its ecology in the Baltic States and Poland. To achieve this, published and unpublished information, together with the data described in EFSA, (2015) were used to parameterise the wild boar ecology and ASFV components of an epidemiological simulation model, with the aim to evaluate the effect of the different management options on the behaviour of ASF in the wild boar populations.

The wild boar ecology model was derived from existing applications to study the spread and control of other infectious diseases of wild boar. The wild boar model represents the host population as individuals and follows each individual's life cycle including birth, sub-adult dispersal in females and males, annual reproduction, litter sizes and mortality. All processes are driven by parameter distributions from literature or gathered from expert knowledge. Mortality varies annually due to good or bad years for wild boar. Female wild boar groups are assigned spatially to core areas of their home-range which is represented by 2km x 2km patches in the model landscape thus it is reflected that actual home-ranges may overlap substantially between neighbouring female groups. Male wild boars explicitly roam over multiple female groups. The habitat quality is expressed as breeding capacity for each single core home-range. The breeding capacity determines the maximum number of breeding sows in a group and subsequently drives the local population density. Cell-wise breeding capacity was derived from existing wild boar density distribution maps or alternatively from mapped landscape vegetation data. The wild boar ecology model was validated with different experts for the Central European situation on several occasions.

The modelled population of wild boar was superimposed by an individual-based fully stochastic SEIR sub-model of ASF to simulate disease transmission and the disease course in all affected individuals. The course of ASF lasts around 1 week per infected individual and the infection will end by the death of the animal. ASF transmission is simulated by nose-to-nose transmission within social groups, between group contacts through infected males joining a female group, infected sub-adult females when they establish a new group during dispersal and contact to carcasses of infectious animals. Carcass distribution is driven by the probability that an ASF-moribund animal will retreat into the shelter of its core home-range and the time till disappearance or non-infectiousness of carcass material. If a carcass did not fall in the core home-range it was assumed to die in the overlapping area to neighbouring groups enabling carcass contact transmission to adjacent animals. Additionally, in special scenarios a moribund animal may be forced to leave its core home-range by intensive drive hunts. This could cause the animal to move further away and their carcass finally will be in contact with more distant wild boar groups.

The alternative strategy scenarios were developed with experts during an expert consultation meeting held at EFSA premises. Proposed strategies were either rapid and drastic control measures aiming at prevention or removal of infectious carcasses in the environment (i.e. short-term population destruction or fast carcass removal) or long-term conventional measures aiming at the reduction of the population turn-over (i.e. feeding ban and targeted hunting of reproductive females).

In general, the model results indicate that any control strategy aiming to combat ASF in wild boar populations has to foresee simultaneous control measures inside the area with ASF detections and in a surrounding buffer zone. The critical extent of the buffer zone and the required time till control success depended on which strategy was applied.

Short-term massive depopulation (e.g. 90% of the present population within 4 months) is capable of controlling ASF, since the future generation of infected carcasses will be limited. The same control success was met in simulations that assumed the immediate removal of infectious carcasses from the control area. However, the required effort for short-term massive depopulation would necessitate drastic measures that are not conventional wildlife management practises (e.g. poisoning or shooting

with night vision). The systematic prevention of wild boar contact with infected carcasses was equally effective and required large efforts are not yet practically approved.

The strategies based on conventional wild boar management options (i.e. feeding ban or targeted hunting of reproductive females) had to be implemented over a long period of time to be efficient (above 2-3 years). Reducing population numbers by influencing reproduction naturally requires multiple generations to become effective. During this time forward spread of the infection in wild boar cannot be avoided. Thus, huge buffer zones and time horizons were necessary for these control strategies (e.g. model simulations indicate more than 200 km buffer and several consecutive years of control before ASF was slowed or stopped). Additionally, no assumptions were made regarding adaptability of reproductive ecology of the treated wild boar population in response to the long-term measure.

Summarizing the observations from the modelling study, ASF control in wild boar may require strategic measures applied over areas of several hundreds of kilometres, for at least 2 to 5 years. In theory, the following combination of alternative strategies was useful in halting the spread of ASF in wild boar: treating a buffer zone with more than 50km of width (by immediate removal of or exclusion of contacts with carcasses) and the intensification of conventional hunting which would reduce reproduction the following year by 30-40%. The quantitative prediction of the effort-outcome relation is not yet supported by acknowledged resource data for intensified hunting or carcass exclusion activities.

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1. Introduction

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

This contract/grant was awarded by EFSA to:

Helmholtz Centre for Environmental Research - UFZ

Contract/Grant title: Modelling the efficacy of wild boar management options in view of controlling African swine fever

Contract/Grant number: NP/EFSA/AHAW/2015/15

ASF is a devastating infectious disease of domestic pigs and of the wild boar, usually fatal. No vaccine exists to combat this virus. It does not affect humans nor does it affect any animal species other than members of the *Suidae* family.

From the beginning of 2014 up to 31/10/2014, ASF has spread in Estonia, Latvia, Lithuania and Poland, mainly in the wild boar, causing very serious concerns. The information available suggests that the disease originated from Russia via Belarus from where there have been several introductions of the virus with the creation of a number of clusters of disease in those Member States.

There is knowledge, legislation, technical and financial tools in the EU to properly face ASF. EU legislation primarily targets domestic pig and addresses, when needed, lays down specific aspects related to wild boar. The main pieces of the EU legislation relevant for ASF are:

1. Council Directive 2002/60/EC2of 27 June 2002 laying down specific provisions for the control of African swine fever and amending Directive 92/119/EEC as regards Teschen disease and African swine fever: it mainly covers prevention and control measures to be applied where ASF is suspected or confirmed either in holdings or in wild boars to control and eradicate the disease.

2. Commission Implementing Decision 2014/709/EU of 9 October 2014 concerning animal health control measures relating to African swine fever in certain Member States and repealing Implementing Decision 2014/178/EU: it provides the animal health control measures relating to ASF in certain Member States by setting up a regionalisation mechanism in the EU. These measures involve mainly pigs, pig products and wild boar products. A map summarising the current regionalisation applied is available online3.

The current epidemiological situation requires risk managers to take into account several aspects related to pig production, encompassing both industrial pig production as well as backyard. While these are obviously crucial aspects when addressing ASF, another aspect that needs to be addressed is the management of wild boar populations, both in areas affected by ASF and in bordering areas.

Several aspects related to wild boar were already addressed in the EFSA opinion on ASF of 2010 and in the EFSA scientific report of March 2014; these are proving quite useful in supporting risk managers in defining the EU approach to ASF. Nevertheless there are several aspects of wild boar ecology and management that need to be addressed in the light of the latest scientific information and of the evolution of ASF in the eastern part of the EU.

In view of controlling ASF, assess the best management options for wild boar both in infected areas and in the bordering risk areas, taking into account the local climatic conditions and wild boar ecology. Assess in particular the suitability, effectiveness and the practical aspects of implementation of the main measures, in particular different tailor-made feed ban(s) for wild boar, selective well-described hunting practices, taking into account the local situations and giving quantitative baseline indications on these measures as well as spatial and temporal parameters.

1.2. Interpretation of the Terms of Reference

The mandate addresses the control of ASF spread in wild boar populations i.e. dominantly on larger spatial scales and longer spatial scales. The mandate requires the explicit consideration of wild boar ecology, habitat models, spatially heterogeneous movements and contacts, temporally heterogeneous contacts and seasonality, as well as individual age and sex difference of targeted animals. Therefore, the mandate specifies a tactic approach to the problem using a rather detailed modelling frame-work. Published and unpublished information, together with the data described by experts were used to parameterise the wild boar ecology and ASFV components of an epidemiological simulation model, when the effect of the different management options was evaluated on the dynamics of ASF infections in the wild boar populations.

The EFSA requested to assess a list of suggested ASF management options for wild boar specific to the ecology of the Baltic States and Poland. The suitability, effectiveness and the practical aspects of implementation of the main measures was elaborated elsewhere (see EFSA AHAW Panel, 2015). The results presented here require bearing in mind the uncertainty around quantitative aspects related to the implementation needs and resource requirements of these ASF management options themselves, and knowledge gaps regarding ASF ethology as it affects behaviour of wild boar with clinical disease and the contact transmission between non-socialising individuals.

The mandate refers to legal terminology when asking for comparative assessment of management options. The ambiguity of the legal terms when it comes to the analysis of strategic or epidemiologically relevant regions, areas or zones required the local mapping between the conceptual frame-works (see 2.2.1 in Methodologies).

2. Data and Methodologies

2.1. Data

The model input consisted of the most recent experimental data on ASF, the wild boar habitat models and the ASF notifications from the affected countries, all as provided by EFSA (see EFSA AHAW Panel, 2015).

2.2. Methodologies

2.2.1. Definitions and conceptual framework

Disease monitoring in wildlife has to cope with the limited access to the possibly infected hosts. Therefore, data collected on the distribution of infected hosts are per se an imperfect approximation of the precise situation. Management measures usually are applied to a spatial zone defined based on detections and extended by extra safety margin using administrative demarcation lines (e.g. "Infected area").

When alternative control strategies are evaluated the area defined for management ("infected area") is not sufficient to determine necessary spatial details in the landscape. More useful concepts are defined in the following and applied during the assessment:

- Infected area = the area subjected to ASF measures, according to legal terminology.
- **Affected area** = the area containing the ASF detections stipulating a dedicated control effort. The area would be identified by a convex polygon around all ASF detections. The wild boar population within the area is deemed to be affected by ASF and case detections have occurred all over the area. In the model proposed control measures will be applied also to the affected area without subjecting a non-affected buffer zone into the control zone.

- **Buffer zone** = the uniform extension of the affected area into the unaffected part applying a certain width. The width of the buffer zone is uncertain and needed systematic consideration for the comparative assessment of control strategies.
- **Control area** = area assigned for the application of control measures in the model scenarios constituted by the affected area and/or the buffer zone.
- **Control measures** = the strategic alternatives subjected to the comparative assessment (here the focus was on alternatives discussed in an expert consultation meeting:
  - **Feeding ban** = immediate offset of feeding wild boar i.e. providing energy to the animals that changes the ecological capacity of a habitat (e.g. winter feeding to sustain the animals). Feeding ban does reduce the fertility of a wild boar group or the survival of piglets;
  - **Intensified conventional hunting** = conventional contact hunting using bait attraction and tower. The hunting techniques rely on conventional methods and no activity is performed that chases the animals out of their ecological habitat. The intensified conventional hunting assumes these soft methods applied more often or for longer time so that the weekly/monthly hunting bag was increased
  - **Targeted hunting** = the conventional hunting practice that does not alter the hunting bag size but replaces young wild boar by females in the reproductive age. Targeted hunting does reduce the annual turnover of a wild boar population.
  - **Short-term massive depopulation** = non-conventional hunting method applying every possible approach to depopulate a wild boar area e.g. by 80% of the acute density within short time of e.g. 4 months. The method explicitly refers to any method to kill as much as possible wild boars including night vision, poisoning, drive hunt, automatic arms, etc.
  - **Carcass removal** = the exclusion of contacts of live wild boar to carcasses lying in the habitat environment. The removal thus does not imply the physical transportation out of the forest but could also include buries, burning or other ways of shelter. In implies effective ways to detect dead wild boar including commercial search dogs (Leichenhunde).

2.2.2. ODD-Protocol

2.2.2.1 Overview

The ASF wild boar model is a compilation of a spatially explicit, stochastic, individual based demographic model for wild boars (Sus scrofa) in a structured landscape of habitat area. Superimposed is a transmission and disease course model for the ASFV. The model is documented following the ODD protocol (Overview, Design, Details; Grimm et al., 2006; Grimm et al., 2010).

<u>Wild boar ecology model:</u> The model represents the wild boar population as individuals and follows each individual's life cycle including birth, sub-adult dispersal in females and males, annual reproduction, litter sizes and mortality. All processes are driven by parameter distributions from literature or gathered from expert knowledge. Mortality varies annually due to good or bad years for wild boar. Female wild boar groups are assigned spatially to core areas of their home-range which is represented by 2km x 2km patches in the model landscape thus it is reflected that actual home-ranges may overlap substantially between neighbouring female groups. Male wild boars explicitly roam over multiple female groups. The habitat quality is expressed as breeding capacity for each single core home-range. The breeding capacity determines the maximum number of breeding sows in a group and subsequently drives the local population density. Cell-wise breeding capacity can be derived from available wild boar density distribution maps or alternatively from real landscape vegetation mapping. The wild boar ecology model was validated with different experts for the Central

European situation on several occasions (Dhollander et al. 2015; Lange et al. 2015, 2012; EFSA 2012, 2009; Kramer-Schadt S et al. 2009; Fernandez et al. 2006; Alban et al. 2005).

ASF transmission model: The modelled population of wild boar was superimposed by an individual-based SEIR sub-model of ASF to simulate disease transmission and the disease course in all affected individuals. The course of ASF lasts around 1 week per infected individual ($t_{\inf}$) and the infection will end by the death of the animal with probability p_L. ASF transmission is simulated by nose-to-nose transmission within social groups $P_{\inf}^{(i)}$, between group contacts through infected males joining a female group, infected sub-adult females when they establish a new group during dispersal and contact to carcasses of infectious animals $P_{\inf}^{(c)}$. Carcass distribution is driven by the probability that an ASF-moribund animal will retreat into the shelter of its core home-range p_{core} or not $\hat{p}_{core} = 1 - p_{core}$ and the time till disappearance or non-infectiousness of carcass material t_{carc}. If a carcass did not fall in the core home-range (i.e. $\hat{p}_{core} = 1 - p_{core}$) it was assumed to die in the overlapping area direct to neighbouring groups enabling carcass contact transmission to adjacent animals. Additionally, in special scenarios a moribund animal may be forced to leave its core home-range by by intensive drive hunts (expert scenario). This could cause the animal to move further away (Sodeikat and Pohlmeyer, 2003). Thus their carcass finally will be in contact with more distant wild boar groups.

2.2.2.1.1 Purpose

The model aims to assess the performance of temporary erecting mobile barriers as contingency measures against wild-boar mediated spread of ASF, compared to local depopulation in the vicinity of detected infected animals. Transmission of ASF infection is operated by direct contacts within groups of socialising wild boar hosts and through carcass scavenging within and between groups.

2.2.2.1.2 State variables and scales

The model comprises three major components: spatial habitat units, connecting edges between these units and wild boar individuals.

All processes take place on a raster map of spatial habitat units. Each cell represents a functional classification of a landscape denoting habitat quality. The cells of the model landscape represent about 4 km² (2 × 2 km), encompassing a boar group's core home range (Leaper et al., 1999). State variables comprise wild boar habitat quality of the grid cells. At run time, habitat quality is interpreted as breeding capacity, i.e. the number of female boars that are allowed to have offspring (explicit density regulation; Jedrzejewska et al., 1997).

Habitat cells are connected by edges to the neighbouring eight cells. Connecting edges represent space between core habitat areas that is shared among neighbouring herds. Each habitat cell and each connecting edge handles a list of infectious wild boar carcasses.

The third model entities are the individual wild boars. State variables of host individuals are the age in weeks (where one week represents the approximate ASF infectious period in wild boar (Blome et al., 2012), resulting in age-classes: piglet (< 8 months ± 6 weeks), sub-adult (< 2 years ± 6 weeks) and adult. Each host individual has a location, which denotes its home range cell on the raster grid as well as its family group. Further, the individual host animal comprises an epidemiological status (susceptible, non-lethally infected, lethally infected, or immune after recovery or due to transient maternal antibodies). Sub-adult wild boar may disperse during the dispersal period (i.e. early summer) dependent on their demographic status (disperser or non-disperser).

2.2.2.1.3 Process overview and scheduling

The model proceeds in weekly time steps. Processes of each time step are performed as applicable: virus release, infection, dispersal of sub-adults, reproduction, ageing, mortality, hunting (for surveillance and depopulation), and erection of barriers. Submodels are executed in the given order. In the first week of each year, mortality probabilities are assigned stochastically to represent annual fluctuations in boar living conditions, and boars are assigned to breed or not, according to the carrying capacity of their home range cell.

2.2.2.2 Design concepts

Wild boar population dynamics emerge from individual behaviour, defined by age-dependent seasonal reproduction and mortality probabilities and age- and density-dependent dispersal behaviour, all including stochasticity. The epidemic course emerges stochastically from within group transmission of the infection, individual disease courses, spatial distribution and decay of infectious carcasses, contact to carcasses as well as wild boar dispersal. Stochasticity is included by representing demographic and behavioural parameters as probabilities or probability distributions. Annual fluctuations of living conditions are realised by annually varying mortality rates. Stochastic realisation of individual infection and disease courses are modelled explicitly.

2.2.2.3 Details

2.2.2.3.1 Initialisation

The model landscape represents 200 km × 100 km of connected wildlife habitat without landscape barriers. The local breeding capacity of each of the 5,000 grid cells is initialised randomly with uniformly distributed integer values that result in locally specified population density (see map in Data section). Each cell is connected to eight neighbouring units (Moore neighbourhood). One boar group is released to each habitat cell, where group size is six times breeding capacity. Initial age distributions were taken from the results of a 100 years model run (see Table 1).

Table 1: Initial age distribution (Kramer-Schadt et al., 2009).

Upper age bound (years)	1	2	3	4	5	6	7	8	9	10	11
Proportion	0.38	0.24	0.15	0.09	0.06	0.03	0.02	0.01	0.01	0.01	0.00

2.2.2.3.2 Input

The applied model setup does not include any external inputs or driving variables.

2.2.2.3.3 Submodels

Submodels are described in the order of their execution. Parameters and their values are listed in Table 2 in section “Parameters”.

2.2.2.3.4 Virus release

The virus is released to 25 hosts, randomly selected from the right-most 10 columns of habitat cells of the model landscape (see **Error! Reference source not found.**). Release is scheduled in the 26th week (i.e. June 1st) of the 5th year of each simulation in order to allow population dynamics to establish.

2.2.2.3.5 Virus transmission

Direct transmission: Direct within-herd transmission is modelled stochastically. Parameter $P_{inf}^{(i)}$ determines the probability of contracting the infection from an infectious group mate during one week. For each susceptible animal, the probability of becoming infected accumulates over all infectious animals within the group:

$$\Pi_i^{(i)} = 1 - \left(1 - P_{inf}^{(i)}\right)^{\lambda_i} \tag{1}$$

where λi is the number of infectious individuals in the herd.

Carcass transmission: Transmission through carcasses is modelled stochastically. Parameter $P_{inf}^{(c)}$ determines the probability of contracting the infection from an infectious carcass during one week. For each susceptible animal, the probability of becoming infected accumulates over accessible carcasses

$$\Pi_i^{(c,s)} = 1 - \left(1 - P_{inf}^{(c)}\right)^{\omega_i} \cdot \left(1 - P_{inf}^{(c)}\right)^{\Sigma_j \omega_{ij}} \tag{2}$$

where ωi is the number of carcasses in the respective core home range, ωij is the number of carcasses in the connecting edges (i.e. shared areas).

Total transmission: Total transmission probability is accumulated from direct and carcass transmission probabilities

$$\Pi_i^{(t,s)} = 1 - \left(1 - \Pi_i^{(i)}\right) \cdot \left(1 - \Pi_i^{(c,s)}\right) \tag{3}$$

The model iterates over all individuals and stochastically sets each susceptible individual to infected if a uniformly distributed random number r drawn from U(0, 1) is smaller than $\Pi_i^{(t,s)}$ of its home cell.

2.2.2.3.6 Disease course

The disease course following infection is modelled for each infected individual. The probability of lethal infection is given by parameter pL. Each host is infectious for tinf weeks and thereafter either turns immune lifelong (probability 1-pL) or dies (probability pL). For the processing of the carcasses after virus-induced death, see submodel 'Carcass distribution and persistence'.

2.2.2.3.7 Group splitting

Group splitting is performed in specified weeks of the year only. All groups containing more females than the cells breeding capacity and at least a minimum number of subadults to move N_{disp}, are processed. The model then collects subadult female yearlings without offspring of these groups. Groups are iterated randomly for the splitting submodel. For each of them, an empty habitat cell is selected randomly among all accessible cells. All migrating individuals out of the considered source group establish the new group on the target habitat cell. If no empty habitat is available, disperser females do not move. Accessible habitat cells are all cells within Euclidean distance D_{disp} that can be reached accounting for between-cell barriers and blocked cells (i.e. water bodies). Accessible cells are determined using breadth-first search on the cells (nodes of a graph) and connecting edges in radius Ddisp. Thus, the distance travelled to the target cell can be larger than D_{disp}, but the linear distance from the home cell does not exceed D_{disp} during search.

2.2.2.3.8 Male dispersal

Male dispersal is performed in weeks 25 to 30 of the year only (i.e. mid-June to end of July). Uniformly distributed over the weeks of the dispersal period subadult males start to disperse. During dispersal, a male moves from cell to cell along connecting edges. Each week, S_w steps are performed, until a total of S_t steps of dispersal are made. Each dispersal step can be either oriented (probability p_{ori}) or straight ahead (probability $1 - p_{ori}$). For oriented movement, the boar moves to the cell with the highest habitat value among the accessible neighbouring cells. For straight movement, the previous direction is just continued. If the boar encounters a barrier edge or a blocked cell during straight movement, a random direction is taken as previous direction and movement continued with the next iteration.

2.2.2.3.9 Reproduction

Females reproduce only once a year if at least in subadult age. Individual females reproduce depending on the season with a peak in March (EFSA, 2012). In the first week of the year, female individuals are checked whether they are able to breed. Starting with the oldest individuals and up to the breeding capacity CC_{ij} of the habitat cell, females are allowed to breed. The week of breeding is individually assigned by drawing of weekly probabilities, rooted of the data-based monthly probability distribution (Bieber & Ruf, 2005; EFSA, 2012; Figure 1a). Litter size is drawn from data-based truncated normal distribution (Bieber & Ruf, 2005; EFSA, 2012; Figure 1b). Litter size is reduced to a constant fraction for infected individuals. Litter size of transient shedders and lethally infected hosts is multiplied with the reduction factor α_f.

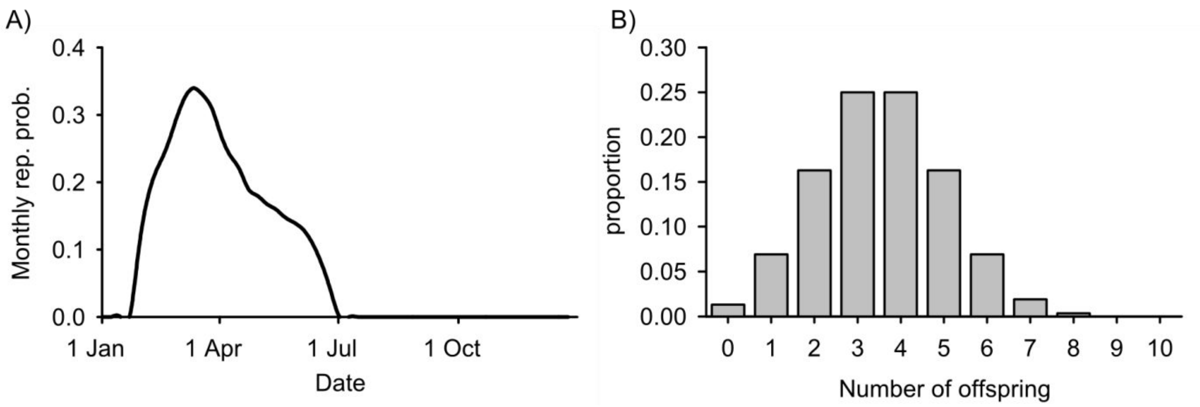


Figure 1: A) Monthly reproduction probabilities for wild boar. B) Breed count distributions for wild boar (Bieber & Ruf, 2005; EFSA, 2012).

Depending on the disease state of the breeding individual, its piglet's disease states have to be adjusted. The epidemiological data are not yet available for ASF in wild boar. Therefore the process was parameterised in accordance with existing evidence for Classical Swine Fever (CSF) in wild boar. However, at time of the study lethality due to virus infections (p_L) was maximum hence the uncertainty does rather not conflict with the simulations: If assigned for reproduction, susceptible and infected but not yet infectious individuals produce susceptible offspring, immune individuals produce offspring temporarily immune by maternal antibodies. Reproduction of transient ($1\text{-}p_L$) and lethally infected (p_L) individuals yields lethally infected offspring, each new-born with probability of prenatal infection PPI.

2.2.2.3.10 Mortality

Iterating over the entire population, each individual either stochastically dies with age class dependent mortality rates or after reaching a certain maximum age (T_{max}). Stochastic age class dependent mortality rates are adjusted to annual survival estimates from literature. Survival estimates and reported variability (see Table 2) determine a Gaussian distribution which is used in the model to draw the random annual survival (SP_{Year}). This stochastic effect resembles 'good' or 'bad' years for the host species, i.e. environmental noise. In the application the Gaussian distributions are truncated symmetrically around the mean. Per time step, the adjusted age-dependent mortality (PM_{Week}) was applied to the individual:

$$PM_{Week} = 1-(SP_{Year})^{1/52} \tag{4}$$

Virus-induced mortality is independently treated by the disease course submodel.

2.2.2.3.11 Carcass distribution and persistence

Virus-induced death can occur either in the core area of the herd (probability p_{core}), or in the shared space between neighbouring herds (edges, probability $p_{shared} = 1 - p_{core}$). After death in the core area, the carcass is only accessible for the individuals living in the respective cell. For death in the shared area, the carcass is randomly assigned to one of the connecting edges of the habitat cell, so it is accessible for the individuals in the cell of its origin as well as to the individuals from one of the neighbouring cells.

Carcasses are present in the cell or edge for a given number of weeks tcarc.

Disturbances due to depopulation activity are assumed to cause virus-induced death in neighbouring cells with probability p_{neigh}. The remaining share of virus-induced deaths $(1 - p_{neigh})$ is distributed according parameters p_{core} and p_{neigh} (see Carcass distribution and persistence). Disturbances are applied for $t_{disturb}$ weeks to all cells where depopulation is performed starting in the week of the depopulation campaign.

2.2.2.3.12 Ageing

The ageing process iterates over all individuals. For each individual k, age Tk is incremented one week. Consequent disease state transitions are performed following evidence from CSF: Transient shedders recover from the infection and are converted to immune after their individual infectious period tinf. An offspring individual protected by maternal antibodies turns susceptible after reaching the maximum age of maternal immunity Timmune. Seropositivity due to maternal antibodies vanishes on reaching a maximum age of maternal antibody presence Tanti. After finalising disease state transitions the age of the infection is incremented one week for all infected individuals.

2.2.2.3.13 Management

A: Massive depopulation subsequently addressing either one quarter or one sixteenth of all female group cells of the control area (i.e. buffer+affected area). Thus the depopulation campaign was performed within 4 weeks or 4 months. Depopulation was assigned starting from the buffer towards right until the affected area was treated completely. Based on the density in the non-affected area at start of measures, the scenario-specific target density is determined. Animals are then randomly removed to achieve that target density. Maximum disturbance was assumed resulting in about half of the infected animals dying out of their natural home-range.

B-FB: "Feeding ban": Fertility reduction = reproduction capacity reduced + extra mortality of piglets in bad years (those with already high mortality). It was necessary to adapt the reproduction parameters to the situation in Estonia Central Europe by assuming 80% mortality from hunting.

B-TH: "Targeted hunting": The total size of the hunting bag is meant unchanged. However, in accordance with the efficiency parameter all adult (adult+subadult) females were removed that would have survived in the current year (extra mortality to target group). The corresponding proportion of "normally" dying piglets was simulated as surviving in order to maintain the size of the hunting bag.

If one assumes 20-30% natural mortality as included in literature estimates or equivalently that nearly 80% annual mortality comes from hunting efforts (Guberti pers. Comm.) the respective size of the age classes in the hunting bag can be approximated from the simulated dead animals unrelated to ASF.

C-CR: "Carcase removal" implied the exclusion of carcasses immediately (C-CR-0) or after one week (C-CR-1) with the respective efficiency randomly across the control area (i.e. buffer + affected area). A schematic diagram of the spatial layout of the management strategies is shown in Figure 2.

C-CR+CH: "Carcass removal" combined with "increased soft hunting" implied the application of C-CR, i.e. the exclusion of carcasses immediately with the respective efficiency randomly across the control area, plus B-CH, the intensity of the conventional hunting was assumed to be increased on all age classes proportional to the hunting bag structure. Parameters studied for both options are less extreme and did not show success if used in isolation.

Features of landscape structure were not mimicked because the suggested strategy options did not consider the exploitation of certain landscape effects for control planning due to uncertain relevance in future ASF occurrences elsewhere.

2.2.2.4 Parameters, simulation experiments, analysis

2.2.2.4.1 Parameters

Model parameters of the indirect transmission model are shown in Table 2.

Table 2: Model parameters

Name	Description	Value	Source / details
$T_{\max}$	Maximum age of boar	572 weeks	(Jezierski 1977; 11 years)
$SP^{(a)}_{mean}$ / $SP^{(a)}_{\min}$	Mean / minimum annual survival rate (natural mortality + conventional hunting)	0.65 / 0.4	(Focardi et al. 1996)
$SP^{(y)}_{mean}$ / $SP^{(y)}_{\min}$	Mean / minimum annual survival rate (natural mortality + conventional hunting)	0.65 / 0.4	(Gaillard et al. 1987)
$SP^{(p)}_{mean}$ / $SP^{(p)}_{\min}$	Mean / minimum annual survival rate (natural mortality + conventional hunting)	0.5 / 0.1	(Focardi et al. 1996)
p_L	probability of lethal infection	0.95	(Blome et al. 2012)
$t_{\inf}$	Average period between infection and dead	1 week	(Blome et al. 2012)
$P^{(i)}_{\inf}$	Infection probability by direct transmission within social groups	0.05	ad hoc, reflecting the limited contact transmission but permanent "nose-to-nose" contact (see Blome et al. 2012)

Name	Description	Value	Source / details
$P_{\text{inf}}^{(c)}$	Infection probability per carcass (including contact and transmission)	0.2	According to best fitting model explaining observed spatial spread
t_{carc}	Time of carcass persistence	6 weeks	According to best fitting model explaining observed spatial
p_{core}	Probability of virus-induced death in core area	0.2	according to best fitting model explaining observed spatial spread
p_{shared}	$1-p_{core}$; Probability of virus-induced death outside core area	0.8	dependent on p_{core}
p_{neigh}	Probability of virus-induced death in neighbouring cell if infected animals are chased off their home-range under large-scale disturbance	0.5	(Sodeikat & Pohlmeyer 2003)
$t_{disturb}$	Duration of disturbances after a depopulation campaign	4 weeks	(Sodeikat & Pohlmeyer 2003)
α_f	Fertility reduction if ill	0.625	
P_{PI}	Probability of prenatal infection	0.5	
T_{anti}	Maximum persistence of maternal antibodies	15 weeks	(Depner et al., 2000)
T_{immune}	Maximum duration of immunity by maternal antibodies	12 weeks	(Depner et al., 2000)
N_{disp}	Minimum number of subadult females for dispersal	2	
D_{disp}	Maximum dispersal distance for subadult females	6 km	(Sodeikat & Pohlmeyer, 2003)
S_t	Male dispersal steps	24 (48 km)	
S_w	Male dispersal steps per week	12 (24 km)	
p_{ori}	Probability of oriented movement during male dispersal	0.5	

2.2.2.4.1.1 Independent variables

The primary independent variables are the management strategy (population reduction, targeted hunting, feeding ban, carcass removal; see Simulation experiments), the radius of the buffer zone rB and the efficiency parameter of the strategy.

2.2.2.4.2 Simulation experiments

Spatial distribution of local habitat quality was randomly assigned in each simulation run while repeating the overall population density in January. Each variation or control scenario was repeated 120 times (i.e. fixing the minimum precision for percentage estimates) including a control without any measure applied. The latter provided the reference regarding ASF occurrence and mortality details assuming combined mortality due to conventional hunting and natural mortality (i.e. framework of the majority of data available; see e.g. Annex 1 except for Toigo et al. 2010 who estimated both separately using drive hunts).

The infection was seeded towards the right of the affected area (dotted segment in **Error! Reference source not found.**). ASF spread was awaited till infected animals initially hit the trigger zone (dark shaded segment). Following the trigger event measures were activated in the subsequent time-step all across the affected area and the buffer (light grey control area) as prescribed by the scenario (i.e. buffer width db and selected control options). All scenarios regarding buffer width and control strategy start at exactly the same epidemiological situation i.e. after the trigger event was recorded the model situation freeze and is reused as input for all other scenarios. Thus, 120 input conditions (independent repetitions) were equally subjected to all control strategies, times five efficiency levels of the applied measures (30%, 50%, 70%, 90%), times alternative buffer widths (0, 6, 12, 18, 24 grid cells or approximately 0, 12, 24, 36, 48km). The 120 input conditions were further run on an extended landscape assuming continuously increasing buffer up to 200km.

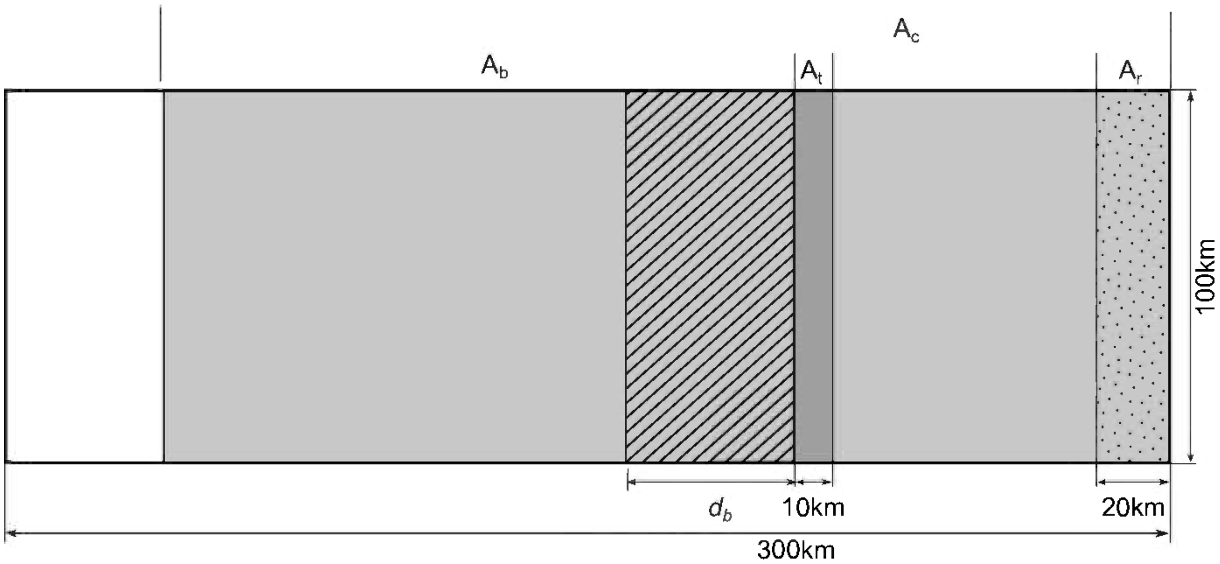


Figure 2: Schematic diagram of the simulation landscape. From right to left, areas are: A_r: Virus release area (dotted), A_c: Control area (complete shaded area), A_t: Trigger zone (dark shade), A_b: Buffer area (hatched) with width d_b.

Parameters of control strategies are listed in Table 3.

Table 3: Parameters of control strategies

Name	Description	Value
bw	Width of the buffer zone in km	0, 12, 24, 36, 48, 200km
rMD	Efficiency of massive depopulation in reducing animal density	90%, 70%, 50%, 30%
rFB	Efficiency of feeding ban in reducing reproductive capacity	90%, 70%, 50%, 30%
rTH	Efficiency to target adult (adult+subadult) female cohort	90%, 70%, 50%, 30%
rCR	Efficiency to remove carcasses from the control area	90%, 70%, 50%, 30%
tMD	Time frame for the massive depopulation campaign	4, 16 weeks
tCR	Time frame for carcase removal	0, 1 weeks

2.2.2.4.2.1 Dependent variables

The following independent variables were recorded from all simulations: Time-series of number of animals removed other than by disease, time-series of number of animals infected or dead by ASF, distance spread into the buffer area, duration of virus circulation.

2.2.2.4.3 Analysis

The outcome of the dependent variables of individual simulation was aggregated by management scenario, radius of the buffer zone and management efficiency parameter.

The main ASF model parameters were calibrated against the spatio-temporal dynamics of the available confirmed ASFV detections in wild boar from the Eastern European outbreaks. Model quality was assessed against the observed spatio-temporal distribution of ASF detections i.e. spatial and temporal likelihood of detections given the simulation output; agreement regarding area coverage, annual velocity; and secondary field data-driven patterns e.g. seasonal abundance of infected animals, limited/absent regional fade-out etc. For the other parameters results will be reported with their values systematically varied.

3. Assessment

3.1. Simulations using a fixed buffer of 50km

There are two general observations that will be highlighted in the following diagrams. First, massive depopulation with high efficiency and across large spatial scales will eliminate the infection from the population. Second, any other strategy proposed as less disturbing i.e. reduced reproductive capacity through feed ban or targeted but conventional hunting did not have a measurable impact on the spread of the infection because the envisaged effect will become effective too late to halt the forward spread of the infection. It is important to notice, however, that only those massive depopulation scenarios provided certain success in halting spread and eradicating the infection from the control area that require reduction effort beyond acknowledged limits achievable by intensive hunting measure i.e. large scale drive hunts with beaters, dogs and helicopters. In the common sense such levels of massive depopulation are not feasible to be implemented with accepted destruction methods (see also EFSA report).

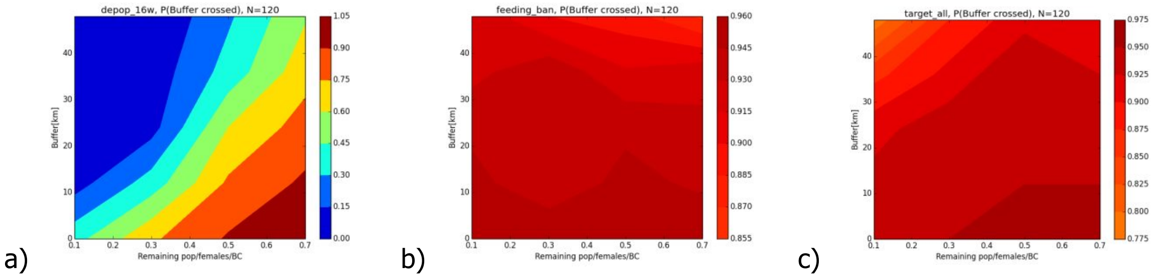


Figure 3: Example summary plots of the proportion of 120 repetitions where the simulated ASF infections spread beyond the buffer area (i.e. beyond the left edge of the stripped area in Figure 2 = failure of measures) depending on increasing buffer width (y-axis from 0km to 48km) and the assumed efficiency (x-axis from left 0.1 = 90% to right 0.7 = 30% efficiency). Red = highest probability to fail to blue = lowest probability to fail. a) Massive depopulation of the buffer area and affected area (= control area) within 4 months; b) “feeding ban” in the control area; c) “targeted hunting” of adult and sub-adult females across the control area.

Figure 3 reveals that the infection could be halted in or eradicated from the control area neither by the strategy “feeding ban” (b) nor the “targeted hunting” (c). Massive depopulation within 4 month (a) achieved the goal when 70%-90% percent of the current animal density was removed from the affected area and the surrounding buffer of at least 25km width (or 12 female groups).

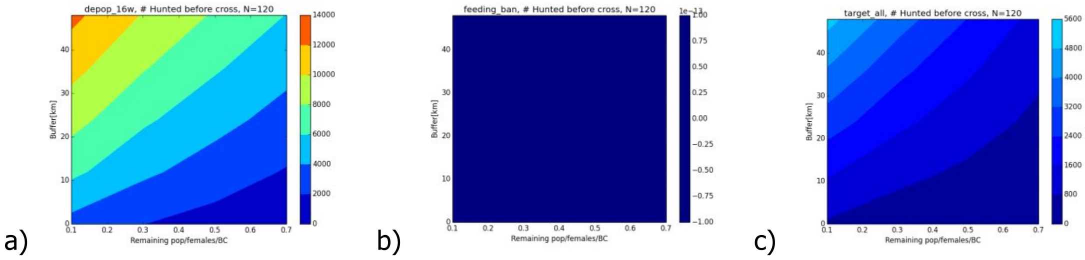
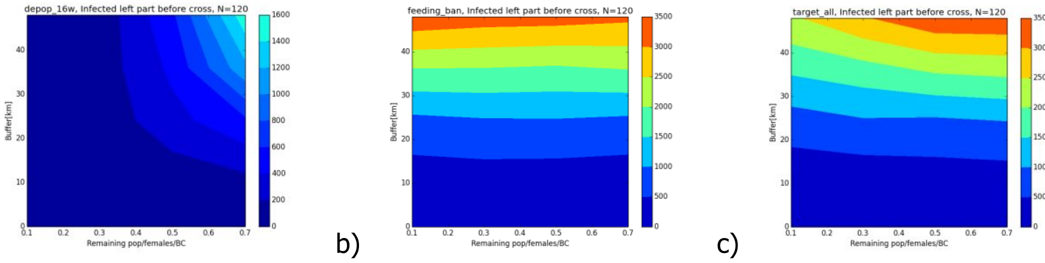


Figure 4: Example summary plots of the average number of incurred shootings of animals (other than through conventional hunting) of 120 repetitions before the simulated ASF infections spread beyond the buffer area (i.e. beyond the left edge of the stripped area in Figure 2 = failure of measures) depending on increasing buffer width (y-axis from 0km to 48km) and the assumed efficiency (x-axis from left 0.1 = 90% to right 0.7 = 30% efficiency). Red = highest number to blue = lowest number. a) Massive depopulation of the buffer area and affected area (= control area) within 4 months; b) “feeding ban” in the control area; c) “targeted hunting” of adult and sub-adult females across the control area.

Figure 4 reveals the intended hunting activities other than those required by regular conventional hunting. Obviously, the numbers of additionally killed animals during “massive depopulation” increase both with buffer width and increasing efficiency (a: right bottom to left top corner). “Feeding ban” does not incur special hunting (b: all zero). The targeting of adult and sub-adult female cohort as primary source of the hunting bag again increase the numbers of assigned hunts but these are balanced by less piglets hunted so that the effective number of hunts is unchanged. The quotes are less than half the number of animals randomly killed during mass destruction. But the latter two strategies do not achieve the control aim.

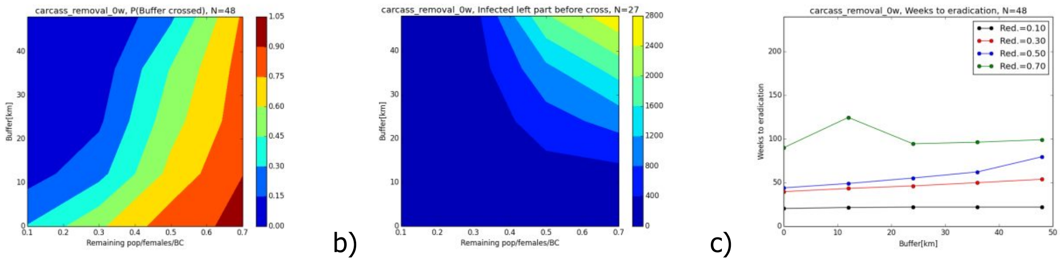


a) b) c)

Figure 5: Example summary plots of the average number of infected animals in the buffer area of 120 repetitions before the simulated ASF infections spread beyond the buffer (i.e. beyond the left edge of the stripped area in Figure 2 = failure of measures) depending on increasing buffer width (y-axis from 0km to 48km) and the assumed efficiency (x-axis from left 0.1 = 90% to right 0.7 = 30% efficiency). Red = highest number to blue = lowest number. a) Massive depopulation of the buffer area and affected area (= control area) within 4 months; b) "feeding ban" in the control area; c) "targeted hunting" of adult and sub-adult females across the control area.

Figure 5 reveals the total number of infected animals inside the buffer area associated with alternative strategies. As before "feeding ban" did not alter the number of infected animals in the buffer area (the increase parallels the widened buffer; horizontal isoclines in b). The targeting of adult and sub-adult female cohort as primary source of the hunting bag led to a small reduction of infected animals if efficiency in targeting the adult+subadult cohort was above 50%. The numbers of infected animals associated with "massive depopulation" were substantially lower with all buffer widths particularly for efficiency assumed beyond 70%.

The potential cause of effectiveness of mass destruction is two-fold: First animal numbers are reduced (density/frequency related approach) and second, shot animals cannot become infectious carcasses (carcass removal approach). In order to understand the role played by both approaches an ad hoc strategy was tested (C-CR) assuming removal of carcasses with different efficiency during one week or instantaneously while no other measure was applied. The probability to fail with the strategy (comp. to Fig. 3) was zero with 90% efficient instantaneous carcass removal (left in Fig. 6a) and already minimum buffer of 12km. But failure rate was already near to 90% if under same conditions carcass removal was scheduled with delay of one week (data not shown). Therefore, the success found with the massive depopulation strategy is contributed completely by the implicit assumption of simultaneous removal of all destroyed animals (compare Fig. 6a to 3a; Fig, 6b to 5a). Nevertheless, efficient and instantaneous carcass removal across the control zone is as difficult to implement in the field as massive depopulation with maximal efficiency.

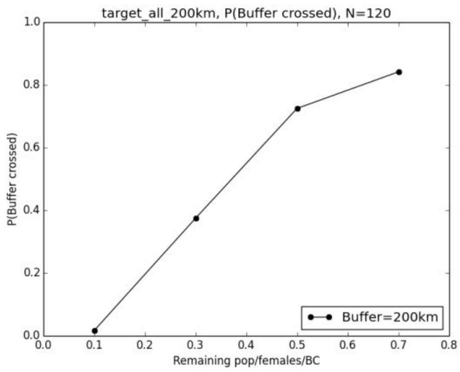


a) b) c)

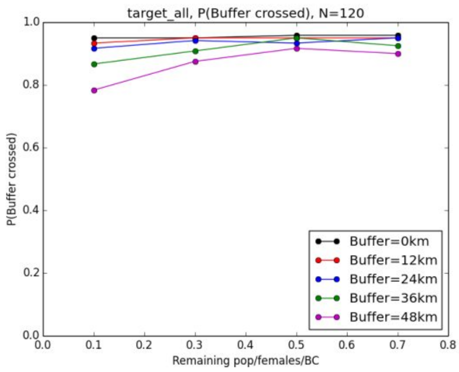
Figure 6: Example summary plots of different results of 120 repetitions of the scenario assuming instantaneous carcass removal. a) proportion of repetitions with simulated ASF infections spread beyond the buffer area (i.e. beyond the left edge of the stripped area in Figure 2 = failure of measures) depending on increasing buffer width (y-axis from 0km to 48km) and the assumed efficiency (x-axis from left 0.1 = 90% to right 0.7 = 30% efficiency). Red =

highest probability to fail to blue = lowest probability to fail; b) average number of infected animals in the buffer area before the simulated ASF infections spread beyond the buffer (i.e. beyond the left edge of the stripped area in Figure 2 = failure of measures) depending on increasing buffer width (y-axis from 0km to 48km) and the assumed efficiency (x-axis from left 0.1 = 90% to right 0.7 = 30% efficiency). Yellow = highest number to blue = lowest number; c) the time in weeks between start of measures and eradication if successful (y-axis from 0weeks to 200weeks) dependent on the different buffer widths (x-axis from left 0km to right 48km) and the assumed efficiency of carcass removal (line colour).

It was reasoned that the strategic alternatives "feeding ban" and "targeted hunting" did not unfold any effect because the time that the infection required to spread through the buffer was shorter than the delay between the onset of the strategy measures and an effect on the population level. To assure the proposed causality further ad hoc simulation of the strategy alternative were performed applying a much larger 4 fold buffer of 200km width representing about 100 wild boar groups distance from the affected area (Fig. 7). Indeed, the proportion of simulations that failed ASF eradication, decreased sharply with the efficiency of the targeted hunting on adult and sub-adult females (Fig. 7a) compared to the outcome with smaller buffers (i.e. less than 50km; Fig. 7b). The time needed to cross the buffer was more than 200 weeks in the former simulation but only between 10km and 60km weeks in the runs applying smaller buffer.



a)



b) d)

Figure 7: Example summary graphs of 120 repetitions of the "targeted hunting" scenario compared for different buffer size a) 200km and b) 0, 12, 24, 36, 48km; dependent on assumed efficiency to target the adult+sub-adult female cohort (x-axis from left 0.1 = 90% very efficient to right 0.7 = 30% limited efficiency; different colour represent different buffer widths).

3.1.1. Simulations using a variable buffer between 0 and 200km

Table 3 and Fig. 8 summarize the performance of the control strategies is compared for an increasing buffer width between 0 and about 200km. The simulation results are expressed as the percentage of runs in which the infection did not spread beyond the buffer (i.e. once the 100% success was achieved that translate up to larger buffers). Table 4 provides the simulation outputs for the most plausible parameterisation (density 1.5/km²; carcass infectivity 0.9 i.e. $P_{\text{inf}}^{(c)}$) as well as the same outputs including uncertainty ranges for the parameters (density between 1 and 2/km²; $P_{\text{inf}}^{(c)}$ between 0.3 and 0.9). The uncertainty did not affect the general insights from the simulation data.

Table 4: Simulation output (elimination success rate) for alternative control strategies and different buffer sizes added to the affected area and continuously treated together with the affected area. The values are given for the most plausible parameterisation (i.e. average population

density 1.5 animals per km² and carcass infectivity of 0.9). The right value given in italics is the average outcome including uncertainty regarding population density (i.e. 1.0 to 2.0 animals per km²) and carcass infectivity (i.e. between 0.1 and 0.9) is shown.

Strategy	%runs ASF halted inside the buffer assuming 90% effective strategy and applying the respective buffer width									
	0km		40km		100km		140km		200km	
No Measures	12%	*3%*	22%	*6%*	27%	*12%*	29%	*15%*	35%	*17%*
Feeding ban	15%	*3%*	19%	*15%*	50%	*48%*	73%	*72%*	95%	*91%*
Targeted hunting	16%	*5%*	29%	*19%*	60%	*54%*	85%	*74%*	99%	*91%*
Massive depop. 16w	22%	*17%*	97%	*97%*	100%	*100%*	100%	*100%*	100%	*100%*
Carcass removal 0w	62%	*66%*	100%	*100%*	100%	*100%*	100%	*100%*	100%	*100%*
Carcass removal 1w	17%	*5%*	22%	*23%*	27%	*21%*	29%	*24%*	32%	*29%*

There are two general observations from the simulation output that will be highlighted in the following diagrams (Fig. 8). For medium and high densities (1.5-2.0/km²) only those strategies that prevented targeted release of infectious carcasses were successful (i.e. massive depopulation and carcass removal) if the efficiency to implement the measures was high (i.e. here 70% and more).

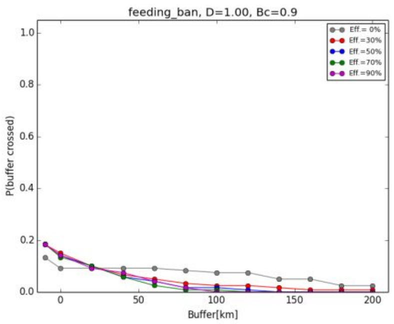
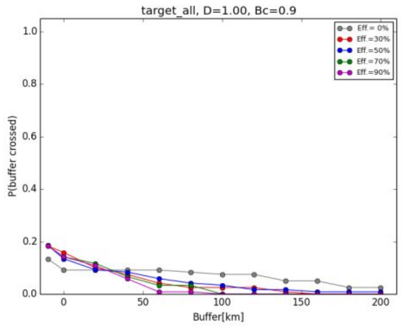
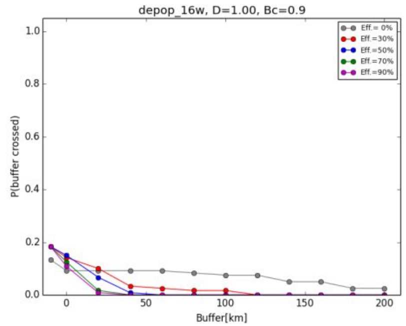
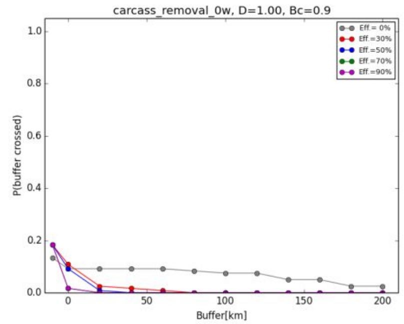
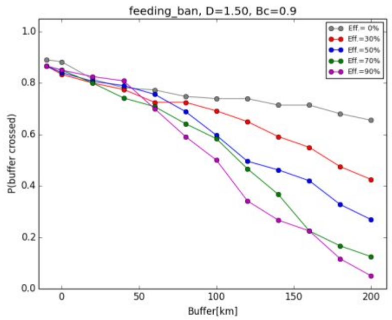
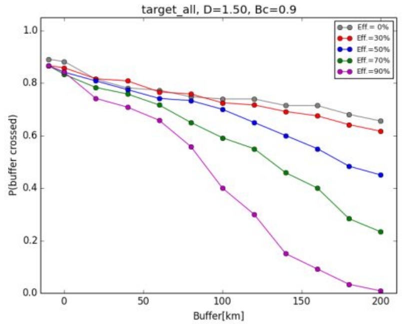
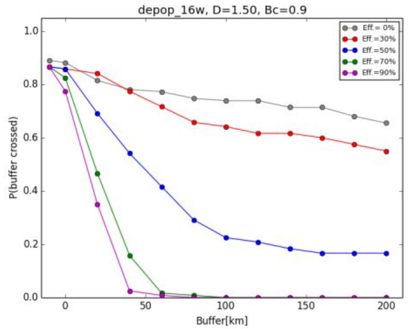
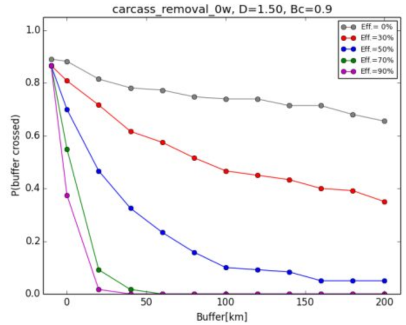
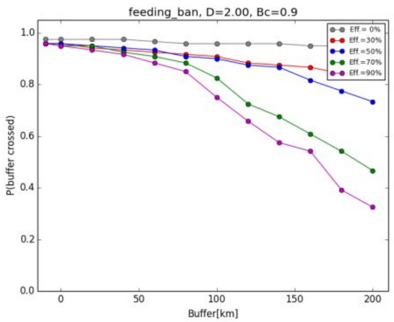
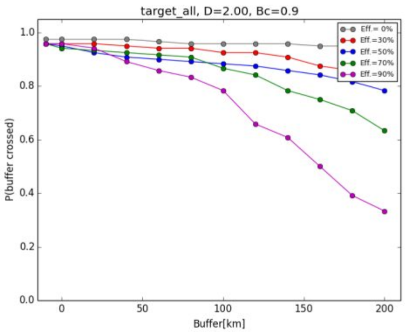
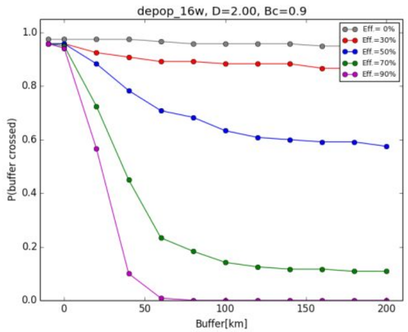
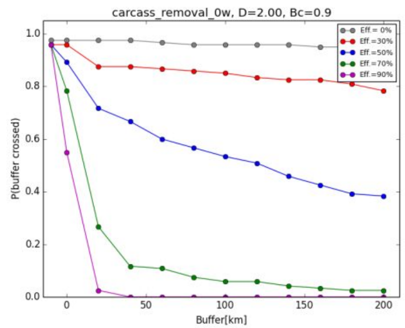
Density	Feeding ban	Targeted hunting	Massive depopulation	Instantaneous carcass removal
1.0				
1.5				
2.0				

Figure 8: Summary graphs of 120 repetitions of simulation scenarios including the buffer width and he size of the affected area at the onset of the measures. The line graphs depict the risk to fail in halting ASF with the respective control area in the model simulations. The results is shown for scenarios applying different alternative strategies (left to right: feeding ban, targeted hunting, massive depopulation, and carcass removal) for different average population densities (top to bottom 1, 1.5 and 2 animals per km² in pre-reproduction) and increasing effectively of the measures (top line to lowest line in the diagram: grey - 0% effective, red – 30% effective, blue - 50% effective, green – 70% effective, pink – 90% effective) different buffer widths between 0km and 200km.

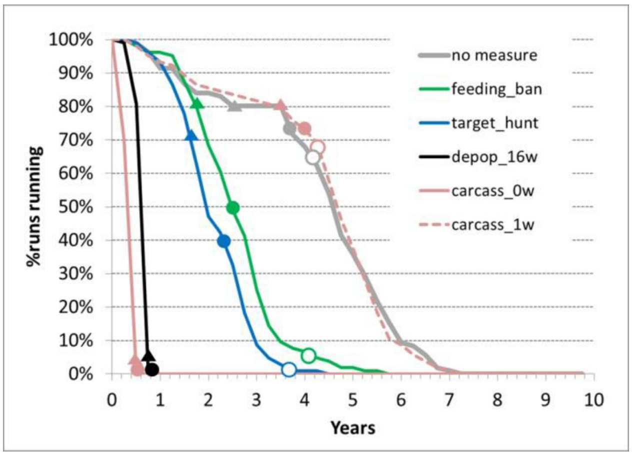


Figure 9: Duration of simulated local ASF epidemics in wildlife for the alternative control strategies. Triangles, points and circles mark the respective proportion of runs that were halted within 50, 100 and 200km (see Table 3). Notice that not all simulated local ASF epidemics were successfully controlled even with the maximum buffer width of 200km. The grey graph representing the ASF spread without any measure, demonstrates the forward spread resulting from most plausible model parameterisation (i.e. average population density 1.5 animals per km² and carcass infectivity of 0.9)

The additional analysis using variable buffer reveals the extended simulations used in the previous chapter to understand the indicative insights regarding limited success using the buffer of less than 50km. Alternative strategies aiming at the reduction of the population by reducing the reproductive performance (i.e. feeding ban and targeted hunting of adult and sub-adult females) require very large buffer zones (of at least 100 to 200km) already for low to medium densities (1-1.5 km²). The 200km buffer was still insufficient with larger numbers of animals per area unit. The underperformance is due to the prolonged build up time of the envisaged effect on the population structure. These strategies can be used only well in advance of an ASF incursion as preventive measure but must then be maintained as long as the possible risk of introduction exists.

In a follow up simulation the measure of carcass removal was combined with slightly increased intensity of conventional hunting (between 10% and 40%; mixing the strategies C-CR-0 with B-CH). The intention of this hypothetical scenario was to achieve an eradication with relaxed assumptions with an efficiency that may be closer to practicality. As expected, the results are more positive than the single measure application (see technical report). Assuming minimum buffer of 30km and carcass removal efficiency beyond 50% in combination with conventional hunting intensity increased to remove at least 30% of the normal survivors in a year, the eradication was very likely with the simulated mixed strategy. The outcome suggests a way of thinking further towards a strategy combining reasonable buffer width, reasonable management effort and sustainable time horizons with ethical reservation of stakeholders in the system (including wild boar).

Experimental data may imply the direct contact with live infectious animals as transmission pathway of ASF. Likely, this would be a density dependent spread. Density thresholds for ASF transmission are not yet established but were suggested to be much greater than for CSF, i.e. about 6 animals per sqkm (Cristian Gortazar, Universidad de Castilla, La Mancha, 2015, personal communication) compared to about 2 animals per sqkm estimated for CSF (Guberti et al. 2000). This is reasonable due to the much reduced effectiveness of the alive animals contact transmission pathway in comparison to CSF in wild boar. However, for ASF the spread through carcasses is expected to play an even more important role. Carcasses of infected animals provide a storage of infectious material until the material is broken up by other predators (Selva et al, 2005) which may be several weeks e.g. in winter. Subsequently, contacts to open carcasses provides direct access to blood related highly infectious material. This spread is suggested to be dependent on the frequency at which naïve animals have contact with infected carcasses within their range of daily movements. Already one infectious carcass within the spatial movement range of certain number of wild boar groups will cause large number of secondary infections no matter what the density of animals is on the spot. Thus, it is still inconclusive whether any threshold may be involved in this process and whether it can be usefully estimated (i.e. Lloyd-Smith et al. 2005).

According to proposed estimates of the overall reproductive ratio of ASF in wild boar of Russian Federation (Iglesias et al. 2015) the required level of wild boar density that would stop spread of ASF in wild boar would be between 0.1 and 0.2 animals per sqkm (see the density map in Fig. 3 in EFSA, 2015). Literally translating these densities and assuming the same transmission dynamics as in the Russian Federation would require to cull 80 -90% of the wild boar population in the affected member states (see scenario massive short-term population destruction). The difficulties to implement such destructive strategies were already well acknowledged before and demonstrated already for other infectious disease of wild boar (EFSA, 2014).

Alternative strategies proposed for the model based assessment were either rapid control measures aiming at prevention or removal of infectious carcasses in the environment (i.e. through drastic depopulation (80%) or fast carcass removal) or long-term preventive measures through a sustainable reduction of the population size (i.e. feeding ban and targeted hunting of reproductive females).

In general, any wild boar management strategy aiming to control ASF in wild boar populations has to foresee measures inside the area with ASF detections and in a buffer zone surrounding this area. The critical extent of the buffer zone depends on which strategy will be applied and was found. Applying any of the proposed measures only within the area where ASF detections were reported (i.e. see Table 3 buffer width 0km) there would be an 80% chance that the measure fail in halting the spread of the infection.

The two sustainable strategies - ban of feeding and targeted hunting - were found to become effective very slow requiring time of multiple generations of reproduction. This is reasonable because the measures change the number of breeding females or the number of piglets. Thus to take effect, more than one generation cycle is necessary i.e. multiple years of continued measure. However, during that time the disease will have spread forward (in the model about 50km each year of control), overwhelming great parts of the control area. Thus, when these strategies are started in and around the area with ASF detections, a buffer width of 100-200km should be treated to compensate this forward spread by size of the control area to maximise the chance of final success. If a smaller buffer width was preferred to be applied, then the reduced chance of success should be anticipated according to Table 3 or Fig. 8.

The rapid response strategy of massive population destruction (i.e. about 80% of the population in the control area within 4 months with any available technique) performed rather well with a reasonable success rate and already limited buffer width of below 50km. The reason for the success found in the simulation was not the massive reduction of population density but the implicit exclusion of infectious carcasses. This was demonstrated by the scenarios of instantaneous exclusion of contacts to infectious carcasses throughout the control area (within one week) which showed the same outcome as the depopulation scenario. Again, this is reasonable as depopulation destroys all animals that later could become infectious carcasses. Hence, in the model, the depopulation strategy worked equally well as instantaneous carcass removal because the depopulation strategy "implicitly" prevents/removes most carcasses.

In the model, however, the carcass removal must happen very quickly (within a week) and everywhere in the control area. It was reported that during the period 1 January-15 May, and in one hunting ground of Latvia, 39 carcasses were removed out of 80 wild boar estimated as dying of ASF during the same period and hunting area; which equals to effectively 49% of carcass detection/elimination success. The carcass removal was therefore simulated with limited efficiency (up to 50%) but together with slight increase in the hunting bag of the conventional hunting methods (i.e.

20-30% greater hunting bag) for about 1 year. These results indicated that there might be a way to find out a least practical + minimum effective combined strategy. This was not further developed.

In agreement with recent observations from the ASF infected MS, the infection as defined by the model assumptions was found in all simulations spreading unambiguously as long as certain wild boar habitat remained connected, although the direct contact infection between alive animals is reported very low (Blome et al. 2012, Gallardo et al. 2015) compared to other infectious diseases in wild boar that spread via direct contacts (e.g. FMD, CSF). The spatio-temporal ASF detection history suggests for the vast majority of plausible wild boar mediated spreading events a velocity below 50km in a year as replicated by the model calibration.

Despite the high lethality of individual infections (i.e. greater than 90%), the ASF does not spontaneously fade off neither in the model nor in the field. As suggested already, there are other mechanisms involved in the transmission of the infection that drive the slow but forward spread of the infection on the landscape scale. Virus can survive with the carcass in the environment. Although there is a low probability of a wild boar to contact an infectious carcass, there is a high probability that the contact will lead to infection. This scenario was found in the model calibration exercise using field data on ASF detections which resulted in indifferent carcass persistence time but always minimal contact/transmission rate.

The importance of carcasses for the modelled epidemiological systems was demonstrated by the comparison of the effect of massive depopulation and instantaneous carcass removal which showed similar results. The outcome indicates that the avoidance of infected carcass deposition implicit in the depopulation scenario was driving the success rather than the density reduction. If theoretically carcasses could be removed instantaneously, and similar to the massive depopulation scenario, the infection came to halt and was eradicated from the control area.

The relevance of carcasses in the epidemiology of ASF is different from that for other diseases such as FMD. in the wildlife species.. With FMD all transmission contacts are already performed either nose-to-nose or environmentally before any carcass would be of importance. If carcasses are deemed as relevant as discussed here (i.e. contact transmission prior to clinical disease is limited, Blome et al. 2012; Gallardo et al. 2015) then the effect on the control measures found with the simulations is plausible. There will be no immediately effective measure if carcasses are not excluded from the systems. Therefore all other alternatives (i.e. feeding ban, targeted hunting) must require substantial build-up time before these can affect ASF spread, seen as large buffer zones in the simulation outcome.

The problem arises with measures aiming at reduction of reproductive capacity (i.e. feeding ban) or reversed age structure in conventional hunting (i.e. targeting reproductive females). To become effective, these measures require more time than the forward spread of the "non-enclosed" infection to breakout from the control area. Therefore, e.g. the measure meant to reduce annual reproduction may become effective first a year after their onset. Hence, the strategy applying this measure needs to compensate for the delayed effectiveness by a larger width of the buffer area. Whether it is feasible to implement measures like targeted hunting of the female reproductive pool across buffer dimensions of up to 200 km around affected areas and to comply with for about 5 years cannot be answered trough model analysis.

It appeared worthwhile to assess combined strategies that maximise population reduction by conventional hunting and barrier-like zones of carcass removal. The corresponding theoretical simulation varying the possible carcass removal rate and increase in efficiency of conventional hunting methods across ad hoc values, showed promising results. However, for the moment the lack of quantitative suggestions regarding feasibility of coordinated carcass removal plus maximum plausible increase of conventional hunting effort limits the precision of such simulations regarding detailed predictions of success or failure.

The general result of the model implies that single measure strategies are insufficient for control because the necessary dimensions are either impractical (size or speed or precision) or unethical (population destruction or extinction). Nevertheless, a strategy concept is needed that combines reasonable buffer area, reasonable management effort and sustainable time horizons with ethical reservation of experts in the system (including wild boar – in German: "eierlegende Wollmilchsau"). Model simulations have suggested that the critical mechanism of the ASF wild boar system is the infectious carcass. Maybe it is a purposeful approach to combine carcass freed buffers or at least carcass thinning with any supportive approach that further reduces the abundance of infectious carcasses without disturbing the population.

The ad hoc simulation of a mixed strategy reflects this way of thinking further. However, very practical parameters of the strategy assumed for the simulations still need commitment by the involved practitioners. Examples are the reasonably possible increase in conventional hunting intensity (non-disturbing) or useful efforts to ban carcasses from being accessed by other wild boar throughout the buffer and ideally the affected area. Quantitative suggestions for these parameters are not yet accessible from literature or expert discussion (i.e. can conventional hunting actually harvest additionally one third of the animals surviving so far and maintain the effort over 1-2 years). Moreover, and once these commitments are available, still the set of the unknown parameters of ASF in wild boar (e.g. carcass accessibility to wild boar, infectiousness "period" of carcasses in the field) needs to be explored to determine quantitative baseline indications on the expected performance of the mixed strategies as well as predictive spatial and temporal parameterisations.

Unfortunately, immediate measures like fast massive depopulation or instantaneous carcass removal are already debated for their feasibility (EFSA, 2014). The option not yet assessed in the model simulations was exploiting barriers induced by natural landscape (Sophie Rossi, Unite Sanitaire de la Faune, Office National de la Chasse et de la Faune Sauvage, 2015 personal communication) and start the soft measures precautionary in those regions while awaiting the infection…

The data evaluated here and also the design of the simulation experiments did focus on the situation, ecological and epidemiological, of the member states recently affected by the ASF genotype II. Other areas in the EU may have much greater number of wild boar which may make application of the proposed measures more difficult (i.e. removing even more carcasses or reducing greater reproductive performance). However, in terms of wild boar mediated forward spread of the infection these regions are still equipped with more time to prepare. Therefore, reconsideration of the proposed strategies under this particular time contain might be a worthwhile effort of preparedness for future incursions.

4. Conclusions

- Any strategy aiming to control ASF in wild boar populations should address the area where ASF has been detected and the supplemented buffer zone (in the sense of this document). The width of an effective buffer zone depends on the applied strategy.
- Massive depopulation of wild boar (in the sense of this document) and subsequent disposal of carcasses within a very short time span will limit the production of untreated infected carcasses and should therefore halt the spread of ASF beyond the control area.
- However, the required effort for effective massive depopulations would necessitate measures that are not acceptable or conventional in management of wildlife populations (e.g. poisoning or shooting with night vision).
- The strategies based on conventional wild boar management options (i.e. feeding ban or targeted hunting) would need to be implemented over a very long period of time. This is because they require multiple wild boar generations to become effective while during the same period the forward spread of the infection would remain unaltered.
- A tailor-made ban on feeding animals to reduce the reproductive performance of a population may be deemed effective only in regions of rather unsuitable wild boar habitat where feeding caused artificial population establishment.

- Targeted hunting practices selecting adult and sub-adult females affect the reproductive pool after several wild boar generations. Prior to the measure having become effective the infection will likely continue to spread forward. Buffer zones need to be sized sufficiently to compensate of forward spread. This requires zones greater than 200km in some simulation scenarios.
- Conceptually, alternative strategies should achieve the effective removal of carcasses (i.e. up to 50% of fallen infected wild boar), and intensify conventional hunting approaches avoiding 30-40% of the next year's new borne with buffers extending beyond 50km and foreseeing about 2-3 years of management. The Feasibility of the required efforts is not yet supported by acknowledged resource data.

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