Damage to dykes and levees in the Netherlands is extensive and increases with muskrat (*Ondatra zibethicus*) density

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Abstract: The muskrat (*Ondatra zibethicus*) is an invasive species in the Netherlands. Its burrowing habits are alleged to threaten the integrity of the extensive water control infrastructure, posing a public safety hazard in this densely populated, low-lying country. A national control program currently traps and kills tens of thousands of muskrats each year. The costs (annually about € 35M) as well as concerns raised by animal welfare groups have raised questions about whether the control program could be improved, and even whether it is necessary at all. To better quantify the extent of putative damage, 2634 km of dykes, levees and banks were inspected annually (2013-2016) for 'major', and 220 km for 'minor' damage. The study was co-organised with a large-scale experiment (reported elsewhere) manipulating muskrat control effort in 117 randomly-selected 5x5 km squares on the national reference grid. We estimated the mean density of major damage at 0.50 ± 0.05 s.e. and that of minor damage at 17.6 ± 3.8 s.e. per kilometer of bank/levee. For both major and minor damage, there is a significant and positive relationship with the average size of the muskrat catch in the same 5-km square over the previous six years. We also found that various types of standard bank protection structures were not effective as preventive measures against burrowing.

Keywords: Invasive Alien Species (IAS), pest-species, burrowing, dyke-failure.

Introduction

Due to the many waterways bordered by luxuriant vegetation, the presence of few predators and a mild climate, the Netherlands provides ideal habitat for the muskrat (*Ondatra zibethicus*), an invasive species in Europe. Muskrat numbers and distribution grew rapidly after its arrival in the Netherlands in 1941. A control programme was immediately started, because it was feared that muskrat burrows could compromise the integrity of

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Figure 1. Typical muskrat burrows. Above, left: projections of three typical forms. Adapted *from: COW 1984*. Above, right: burrow excavated from a bank, after filling with styrofoam. *Photo courtesy: M. Akkermans, STOWA*. Below, left: cross section. *From: COW 1984*. Below, right: excavated burrow in a levee. *Photo: H. van Hemert*.

dykes, and hence pose a serious public safety threat (Verkaik 1990, Barends 2002). The dike system in the Netherlands is extensive and essential to safety from flooding. There was also concern about other effects such as the occurence of sink holes in roads along waterways, as well as economic damage (Gaaff et al. 2007).

Muskrats burrow to create shelter and sites for reproduction. Burrows vary in form from short, single tunnels to a network of lengthy tunnels interspersed with chambers. The entrance is usually submerged, presumably to reduce detection by predators. The outline and dimensions of typical burrows are presented in figure 1. Based on measures of five complete burrow systems (made by injecting liquid styrofoam and excavating the cast), burrow systems measure 2-6 m in width, extend 1.5-6 m into banks with nest chambers of 50 cm diameter, and entrances of 15-25 cm diameter (Akkermans 2014). The muskrats dig throughout the whole year as existing burrows are expanded to accommodate successive litters, and dispersing young animals establish their own burrow systems. Furthermore, muskrats may abandon established burrows and move to a new site if they are disturbed by predators, if the burrow is damaged by livestock or tillage, or if the water level changes and exposes or floods a burrow and upward digging is restricted.

The tunnels and displacement of soil that result from burrowing affect the hydraulic characteristics of dykes and levees. Even burrows that partially penetrate a levee can cause or contribute to an increase of seepage, internal erosion of embankment materials that may lead to 'piping' (due to shortening of seepage paths), perforation of impermeable components (revetments, clay covers), decreased dyke height due to collapsed burrows, direct seepage (by 'through-embankment' burrows), and decreased stability due to saturation of the levee. Over time, erosion may exacerbate the damage, eventually leading to a breach. Examples of levee breaches caused by animal burrowing can be found in Bayoumi & Meguid (2011) and in the International Levee Handbook (CIRIA 2013).

The need for muskrat control in the Netherlands to avoid such damage and risks has long been advocated (Ritzema-Bos 1917, Kluyver 1937, Thijsse 1937, van Koersveld 1953, Doude van Troostwijk 1976, Barends 2002), but systematically collected data on the extent of damage are lacking. This study aimed to quantify the damage attributable to muskrats, and to assess whether and how this is related to the number of muskrats in an area. To do so we measured the number of muskrat excavations found in randomly selected transects along waterways, and related it to the muskrat catch made in the same area over preceding years.

Animal welfare and some other organisations advocate the use of various bank protection measures (i.e. cladding or other hardened surfaces) as alternatives to muskrat control. These measures aim to make burrowing impossible or irrelevant (Spoorenberg 2007, Zandberg et al. 2011) and thus eliminate the need to capture and kill animals. We assessed the extent to which standard types of bank protection are effective in lowering structural damage by muskrat burrowing. Our main hypotheses are that the damage attributable to muskrat increases with the number of muskrats in an area (as estimated by the recent catch), and that some types of bank protection may be effective in preventing muskrat from burrowing.

Methods

Study area

The Netherlands (50°-54°N, 3°-8°E) is characterised by flat topography, with most of the country at an elevation between -10 and + 20 m Dutch Ordnance Level. Large areas are below sea level and about two-thirds of the country is protected by dikes against flooding. The low-lying western and northern parts of the country are characterised by peat and clay soils, while sandy soils predominate in the east and south. Most areas below sea level are anthropogenic, caused by peat extraction or achieved through land reclamation. Since the late 16th century, large polder areas have been created through elaborate drainage systems that include dikes, canals and pumping stations. The Netherlands has a dense human population of over 17 million on roughly 33,700 km^2. It has a mild maritime climate with average monthly temperatures ranging from 6°C in winter to 23°C in summer. Average annual precipitation is about 800 mm. Intensive agriculture dominates land use, occupying more than 55% of the country. Muskrats are found throughout the country, but over the past decades the catches have been especially high in low-lying peat and clay areas.

Data collection

This study formed part of an extensive investigation by the Dutch Water Authorities

('Waterschappen') into muskrats in the Netherlands. This study was integrated into a large-scale manipulative experiment (described in full by Bos et al. 2016) testing the effectiveness of trapping in reducing muskrat numbers. Briefly, the experiment took place nationwide from 2013-2016 in 117 5x5 km squares (of which the national reference grid contains a total of 2202), randomly selected from three 'strata' representing regions of historically high, medium and low muskrat catch. The experiment either increased or decreased trapping effort by 30%, or in control 5-km squares kept trapping effort at the level during the reference year preceding the start of the experiment. Effort is measured as hours of trapping time per kilometre of waterway per year. The experiment offered the opportunity to combine assessments of damage with a large set of other measures.

Burrow density and the incidence of damage was measured during the experiment with a program of inspection of banks and levees. Inspections took place annually during February and March, 2013 - 2016, and were carried out by two persons, one an experienced, professional muskrat trapper and the second a water infrastructure expert, both employed by the Dutch Water Authorities. Burrows are usually invisible from the surface, and have underwater entrances, and hence expertise and experience are required to be able to detect and score the extent of damage and to establish the cause.

Muskrat burrow entrances, eroded banks, slides of a slope/bank, depressions in the bank or levee, and bars in the waterway created by excavated soil were all classed as 'damage'. Each instance was judged by the inspectors as (a) certainly caused by muskrats, (b) possibly caused by muskrats, or (c) not due to muskrats, and further classified as 'major' or 'minor'. Damage was defined as 'major' if any of the following criteria were met: the volume of displaced soil exceeded 0.5 m^3, a depression in the bank or levee exceeded a surface area of 2 m^2 or a depth of 0.2 m, the length of the damaged or eroded bank exceeded 2 m, or the cost for repair exceeded € 2500. Damage not meeting any of the 'major' criteria was classified as 'minor'.

All instances of major damage were described, photographed, exact location noted, and given a unique identifier. The age at observation of the damage was judged (<3 months, 3-12 months, 1–2 years, >2 years) based on knowledge of the historical trapping record at that location, the morphology of the damage and the vegetation. For each instance of major damage the number of burrow entrances (*n*), the estimated cost of repair (euros), the surface area of settlements/sinks, and the volume of displaced soil were classified in three to five categories. In addition, the status (inhabited by muskrats or abandoned) and type of bank protection and soil type, was noted. The description was updated at each subsequent inspection. All these data were registered in a standardised way with a custom-designed application installed on a handheld device. Information from the previous year(s) was available to the observers.

Teams searched for major damage by walking along dikes and levees. The length of the banks and levees present in a 5-km square ranges from 0 up to 1560 km and 75 km, respectively, of which a portion (up to 44 km of banks and up to 20 km of levees, or 5-100%, depending on the total length in each 5-km square) was inspected. The inspected sections were chosen to be representative for each 5-km square with respect to vegetation, land use and water depth. To avoid edge effects the sections were located in the interior (middle 3 km x 3 km portion) of a 5-km square. The same sections, totalling 2634 km, were inspected annually.

Minor damages were located by carefully searching along the shoreline, including detailed examination by probing below the waterline. This was much more time-consuming than the search for major damage, because minor damage occurs more frequently and the inspection often required for an observer to proceed in the water. Therefore, we selected 10 representative sub-sections for inspection and measurement of minor damage. Sub-sections averaged (mean ± se) 263 m ± 1.7 in length, were homogenous in bank type, and were positioned in the interior (middle 3 km x 3 km portion) of a 5-km square to avoid edge effects. Minor damages in each 5-km square were categorised into burrow entrances, eroded banks, slides of a slope/bank, depressions in the bank or levee (= settlements/sinks), and shallow bars in the waterway. Minor damages were counted per category per sub-section. The annual number of sub-sections inspected rose from 624 in 2013, to 853 in 2016 (average 774). A summary of the total length inspected of banks and levees is given in table 1.

The datasets generated during and/or analysed during the current study are available in the University of Groningen repository, DataverseNL https://hdl.handle.net/10411/EFR9TN

Table 1. Summary of the total length (km) of banks and levees present in the 117 experimental 5-km squares (divided into those assigned to the 39 control, 39 increased effort and 39 decreased effort treatments), and of the lengths inspected for major and minor damage. The same 2634 km of banks and levees were inspected annually for major damage over the years 2013-2016. The total length of sub-sections inspected for minor damage has varied somewhat between these years and the values for year 2016 are given in the table.

Object		Control	Decreased effort	Increased effort	Total
Banks	Present	16,406	14,142	15,084	45,632
	Major	685	719	701	2,105
	Minor	51	49	50	150
Levees	Present	595	412	526	1,544
	Major	150	164	215	529
	Minor	23	20	28	71
Total	Present	17,001	14,556	15,620	47,177
	Major	835	883	916	2,634
	Minor	73	70	77	220

Analysis

We summed for each 5-km square the number of major and minor damages that had been categorised as (possibly) caused by muskrats, including those repaired in previous years. The density (n km^{-1}) was obtained by dividing the number of major damages counted (n) by the total length inspected (km) per 5-km square. The density of minor damage was calculated by averaging the density (number of burrow entrances (n) divided by transect length in km) over all the transects in each 5-km square. The number of burrow entrances is the aspect of minor damage that was most prominent, least subjective, and easiest to interpret. We removed very short (<10 m) and long transects (>800 m) from the analysis, to increase consistency and robustness.

We obtained from the Dutch Muskrat Control Program (which has maintained accurate records; see van Loon et al. 2017) and from Bos et al. (2016) the annual catch and effort expended in each 5-km square, and from these we calculated the cumulative catch (number of muskrats trapped per kilometer of waterway per year) for periods of 1-10 preceding years. The values for cumulative catch were log-transformed in order to meet assumptions of normality and homogeneity of variance. We also obtained for each experimental 5-km square the dominant soil type (clay, sandy-clay, peat and sand), and the type of treatment in the contemporaneous large-scale experiment.

To test whether the density of damage depended on experimental treatment and the history of the catch we competed linear mixed effect models using the package lme4 (Bates et al. 2015), in the R programming environment (R Core Team 2017). The model set (table 2) comprised a null model with only 5-km square as a random intercept, a model with year of measurement (2013-2016, coded from 1-4 and termed 'year') as predictor in addition to the random effect of 5-km square, mod-

Table 2. Ranking of the top 8 models competed to assess the density of major damages (n km^{-1}).
Year = year of measurement (2013-2016); catch = the (log_transformed) cumulative catch (log (n km^{-1})) in the 5-km square over the five or six years preceding each year; soil = dominant soiltype in the 5-km square; treatment = type of treatment in the contemporaneous large-scale experiment. The models are ranked according to AICc values. The first model (bold) is best supported by the data. K = number of free parameters; AICc = Aikake Information Criterion; delta AICc = difference in AICc value with best model; weight = AICc weight.

Model *	K	AICc	delta_ AICc	Weight
Year*(6y catch)	6	-26	0	0.90
Year*(6y catch) + soil	9	-22	5	0.08
Year*(5y catch)	6	-18	8	0.02
Year + (6y catch)	5	51	77	0
Year	4	102	128	0
Year * treatment	8	102	128	0
Year + treatment	6	105	131	0
null	2	210	237	0

* The null model contains only 5-km square as a random intercept. Each of the other models includes this random effect of 5-km square. The other models includeYear as predictor; Year + treatment as additive predictors; Year + treatment and the Year* treatment interaction; Year + cumulative catch over 1, 2, 3, 4, 5, 6, 7 and 10 preceding years as additive predictors; Year + cumulative catch over 1, 2, 3, 4, 5, 6, 7 and 10 preceding years as additive predictors and the year*catch interaction, either with or without soil class as a fixed factor.

els with year and treatment as predictors in addition to the random effect of 5-km square (additive: year + treatment and in interaction: year * treatment), and models with year and the (log-transformed) cumulative catch per km over 1, 2, 3, 4, 5, 6, 7 and 10 years respectively (additive: year + cum. catch and in interaction: year * cum. catch), with and without dominant soil type as additional fixed factor. The response variables 'density of major damage (n km^{-1})' and 'density of minor damage' (n km^{-1}), were log-transformed. The influence of individual data points on the final model predictions was assessed by calculating Cook's distance using the package Influence. ME (Nieuwenhuis et al. 2015).

The numbers of major damages (i.e. burrow systems) still inhabited by muskrats were tabulated in a contingency table with regard to age at observation and volume, hypothesising that the severity of damage would increase with age. Using a Chi-square test we tested the null hypothesis of independence of rows and columns.

The proportion of the number of entrances observed in different types of bank protection was compared to the proportion of length of sections inspected for these sections using a Chi-square test, to quantify the extent to which these types of bank protection could function as 'preventive measures'. To do so, the number of burrow entrances observed and the lengths of waterway inspected were averaged over the four years of study, and the expected number of burrow entrances was calculated by multiplying the overall mean density by the inspected length.

Results

A total of 1924 major damages classified as Muskrat-caused were detected during annual inspections of 2634 km of dikes and levees. Each year the total number of major damages attributable to muskrats increased by several hundred (mean 434 ± 44 s.e.) Most of these were new, but some had gone undetected in previous inspections. In 2016 (the last of the four annual inspections), the mean incidence of major damage was 0.50 km^{-1} ± 0.05 s.e. The majority of cases reflected major damages that were judged to be abandoned (83%), while 17% were still inhabited. About 10% of the cases were repaired annually. Most of the major damage was found in the low-lying 5-km squares in the north-east (province of Groningen), the delta of the river IJssel (province of Overijssel), and Zuid-Holland (fig-

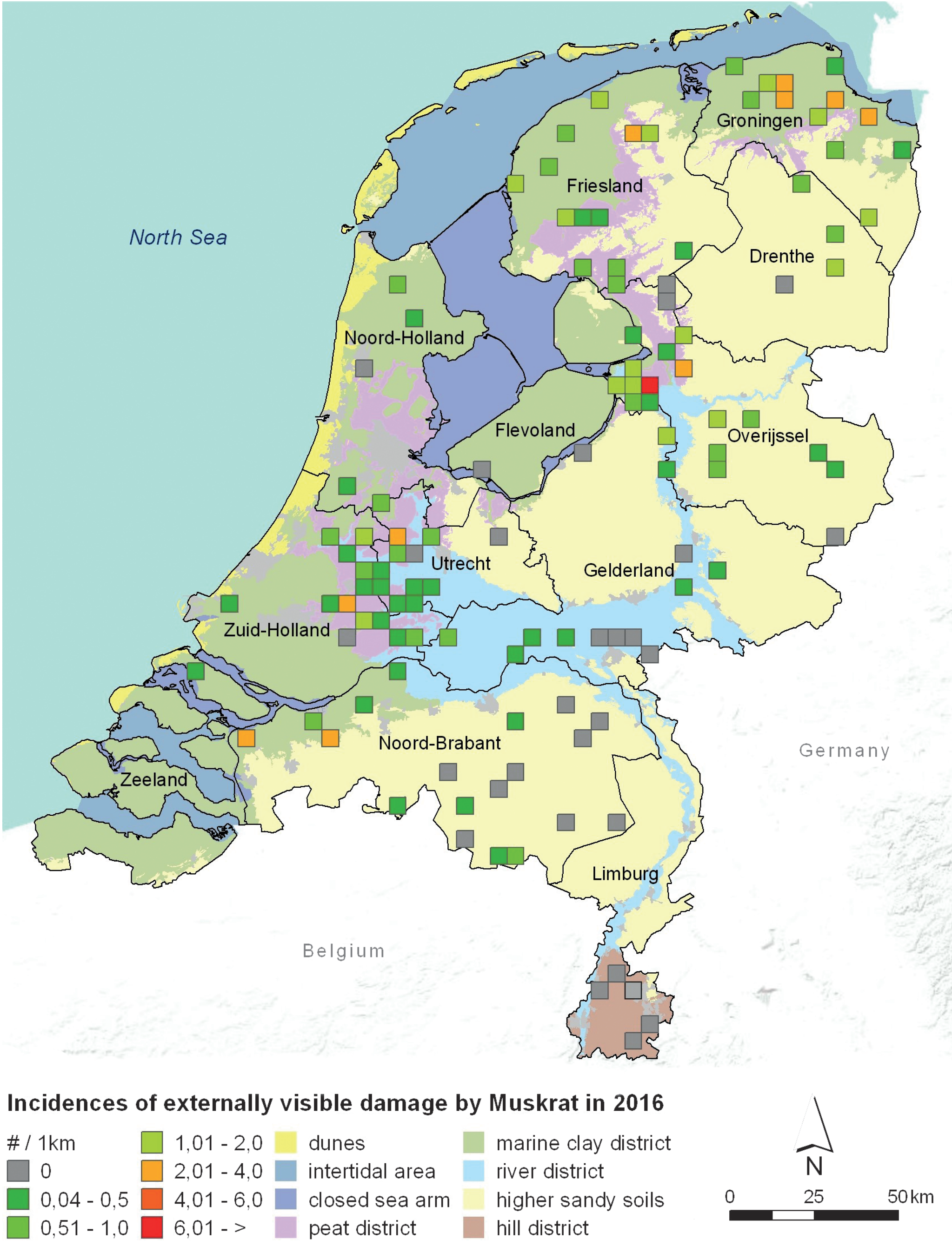

Figure 2. Map of the 117 experimental 5-km squares, soil classes, and the density of major damage (n km^{-1}) observed in 2016.

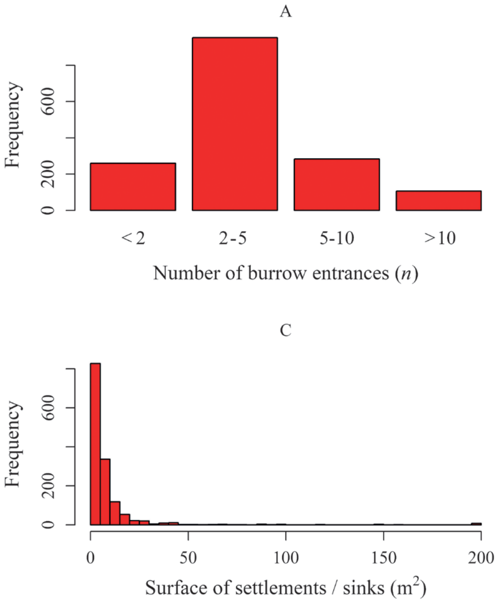

Figure 3. Histograms of the size of the major damages recorded. Panel A: number of entrances; Panel B: estimated costs of repair; Panel C: surface area of settlements and sinks; Panel D: estimated volume of soil displaced.

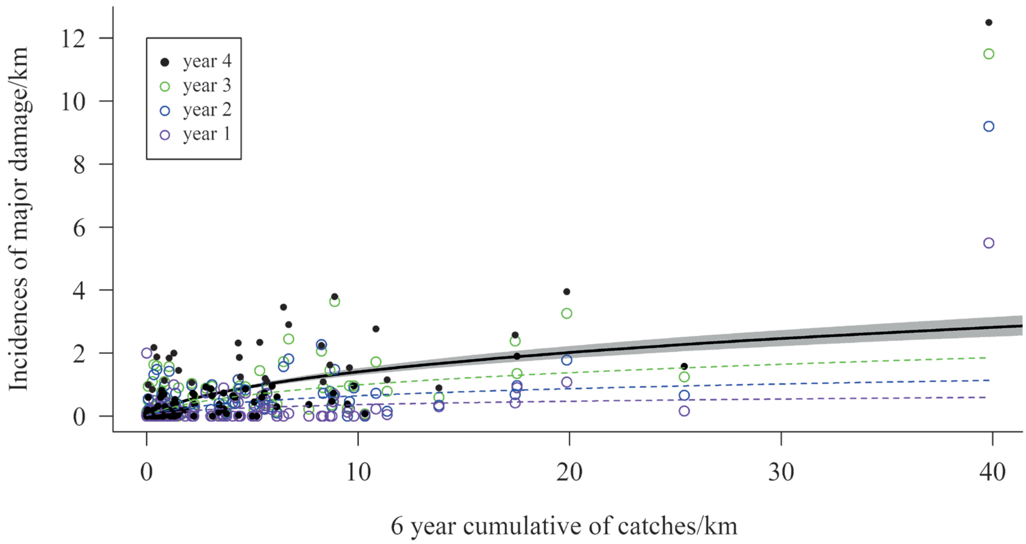

Figure 4. The relation between the density of muskrat-caused major damage in 2013-2016 (years 1-4, respectively) and the cumulative catch in the corresponding 5-km square during the preceding six years. Average inspected length per 5-km square was 22.5 km ± 0.89 s.e. The black line, log(y+1) = 0.035 + 0.35*log(x+1), represents the linear mixed regression model fitted for year 4 (2016), based on repeated observations (n=464) in 116 5-km squares. The grey shading is the 95% confidence interval for that year. Marginal R^2=0.38, conditional R^2=0.81.

Table 3. Fixed effect sizes in the top model of the density of major damages (see table 2). The model includes a random effect of 5-km square. Marginal R^2=0.38, conditional R^2=0.81. Significance levels: *** =0.001, ** =0.01, * =0.05.

Fixed effects	Estimate	Std. Error	df	*t* value	Pr(>|*t*|)	Significance
Intercept	0.017	0.051	226	0.33	0.74	
Year	0.005	0.012	246	0.38	0.70	
Catch	0.042	0.035	226	1.22	0.22	
Year*catch	0.077	0.008	246	9.44	<2e-16	***

ure 2). These are the regions responsible for the majority of catches prior to and during the study period. Many 5-km squares in the Netherlands have little damage and regions without damage overlap to a large extent with areas where muskrat catches have been low or non-existent.

A summary description of major damage is provided in figure 3. The majority of major damages are characterised by multiple entrances (figure 3A), and had a repair cost less than € 2500 (figure 3B). The area of depressions or slumps associated with burrowing was in the majority of cases less than 10 m^2, but was occasionally estimated at 50 m^2 or even larger (figure 3C), while the volume of excavated soil was smaller than 1 m^3 in 58% of the cases (figure 3D).

The statistical model for the density of major damages best supported by the data includes the cumulative catch made over the preceding six years, the year of study, and a year by catch interaction (table 2). This model captures the great majority (0.90) of the model weight, and is 5 AIC units lower than the next best model. The top model is depicted graphically in figure 4, showing the cumulative muskrat catch (n km^{-1}, summed 2010-2015) in each 5-km square in relation to the density of major damage recorded in 2013 (year 1), 2014 (year 2), 2015 (year 3) and 2016 (year 4). Effect sizes are given in table 3.

The lines depicted in figure 4 are based on a linear mixed regression model with repeated observations in 116 5-km squares over four years (n=464). With regard to influential data, the Cook's distance for all datapoints was always lower than 0.2, but one 5-km square (identified as 2144 DEC) contributed three influential data points. Excluding it from the analysis did not alter the model ranking.

Table 4. The number of minor damages of all types distinguished recorded during the four years of inspections.

Type of damage	2013	2014	2015	2016
Burrow entrances	1729	2213	2595	3085
Eroded banks	288	548	468	870
Minor slides	354	370	351	442
Settlements/sinks	492	753	739	1084
Shallow bars	26	81	143	127
Inspected length (km)	161	203	217	218

Major damages estimated to be three months or more in age were larger than those found soon after presumed initiation (Chi-square test, P<0.001, n=274). Of damages younger than three months, 24% were in the smallest category (<0.1 m^2), and 22% in the largest (>1 m^2), while of those older than three months more than 60% are found in the largest category.

A total of approximately 16,750 minor damages were registered during the experiment, and are summarised in table 4. The majority of minor damage was in the form of burrow entrances (61%), followed by settlements/sink and eroded banks. The mean incidence of burrow entrances in 2016 was 17.6 km^{-1} ± 3.8 se, but in several 5-km squares densities >100 km^{-1} were observed. The cumulative number of minor damages recorded increased over the four-year period.

The model results for minor damage (density of burrow entrances) was very similar to that for major damage. The model involving year in interaction with the cumulative number of catches made over the past six years, was best supported by the data (see figure 5). The observed number of entrances per km increased with historical catch rate and over the course of the years.

Table 5 summarises the incidence of minor damage, as measured by the incidence of burrow entrances, in different types of standard bank protection. The density of entrances is not evenly distributed based on the length inspected (Chi-square=73.1, df=4, P<0.001), which means that there is an effect of the type of bank protection. Burrow entrances were found in each of the major types of bank protection inspected, except for 'sheet pile', where none were found at all.

Table 5. The number of burrow entrances (one aspect of minor damage) per type of standard bank protection recorded in subsections along waterways in the Netherlands. Data refer to the average numbers observed and average lengths of waterway inspected (with known type of bank protection*) over the four years of study. The number of burrow entrances expected (last column) was calculated by multiplying the overall mean density by the inspected length.

Bank protection	Mean inspected length (m)	Mean no burrow entrances observed	Burrow entrances expected
Sheet pile	3000	0	35
Rip-rap	5032	12	58
Hard revetment	2220	22	26
Braided tree branches or wood	9708	83	112
Natural bank/ slope (vegetated)	168,604	2064	1950
Total	188,563	2180	2180

* sheet piles are sections of sheet materials with interlocking edges; rip-rap refers to rock or other material used to armor the bank or slope against wave attack; hard revetments are sloping structures constructed with asphalt or concrete blocks to protect a bank or slope against erosion by waves.

Discussion

Assertions that muskrats would by their burrowing habits threaten the integrity of dikes and levees were made even before the 1941 arrival of this invasive species in the Netherlands (Ritzema-Bos 1917, Kluyver 1937, Thijsse 1937). The consequent apprehension for public safety was and remains the main reason for the ongoing extensive control program (van Koersveld 1953, Doude van Troostwijk 1976, Barends 2002), which currently costs about € 35 million annually. For the same reason, muskrats are subject to control in Flanders (Belgium) (Stuyck 2008, Vlaamse Milieumaatschappij 2010) and Lower Saxony (Germany) (Fritz & Röver 2015). This study provides the first systematically collected data on the extent of this damage, and supports these assertions. The information is highly relevant in relation to recent European legislation (EU regulation no 1143/2014) on the management of invasive alien species.

The overall average measured incidence of major damage is 0.50 km^{-1} ± 0.05 s.e., and of minor damage 17.6 km^{-1} ± 3.8 s.e. in year 4 of the study. This constitutes a substantial hazard in the Netherlands, given that more than 17,500 km of dikes and levees are present, and much of the country lies below sea level. The density measured in year 4 of the study likely provides the best estimate of the amount of damage present at any time, since it is a combination of the new damage from that year, older damage undiscovered in preceding years, and the known damage from the previous years. It is likely that the densities measured are underestimates. Muskrat burrows are difficult to detect because they are (by definition!) underground and have underwater entrances. Circumstances such as temporary water drawdowns (see figure 6) occasionally make more thorough inspections possible, and reveal burrow densities higher than the averages reported above.

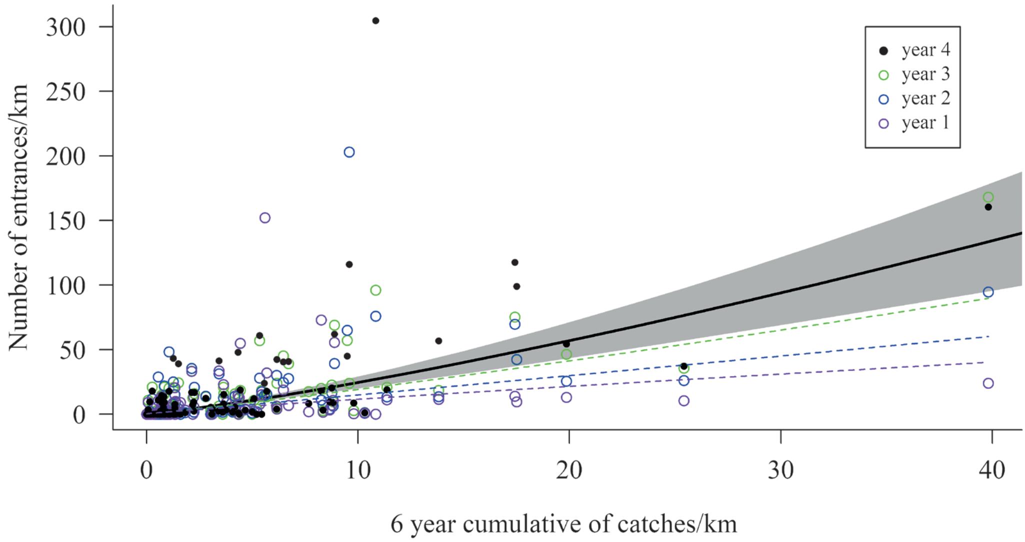

Figure 5. The relation between the density of muskrat burrow entrances (the most frequent type of minor damage) in 2013-2016 (years 1-4, respectively) and the cumulative catch in the corresponding 5-km square during the preceding six years. The black line, log(y+1) = 0.20 + 1.27*log (x+1), represents the linear mixed regression model fitted for year 4 (2016), based on repeated measures in 111 5-km squares. The grey shading is the 95% confidence interval for that year. Marginal R^2=0.45, conditional R^2=0.81. Average annual transect length was 263 m ± 1.7 s.e.

A second important finding of this study is the positive relation established between the muskrat catch and the extent of damage measured (Figures 4 and 5). Although the relationships differ in detail, the density of both major and minor damages rises with the muskrat catch recorded in preceding years, with a period of six years being most informative. Catches are interpreted as a proxy for population numbers, and population modelling by van Loon et al. (2017) corroborates that these measures are positively related. Van Loon et al. (2017) estimated the numbers of muskrat in exactly the same study plots - a posteriori - using a spatially explicit population dynamic model, while Bos & Gronouwe (2018) showed that the relation between damage and cumulative catch presented here also holds using the thus estimated population sizes of muskrat as an explanatory variable.

The study detected no effect of the experimental treatments on the level of damage, though the experimental treatments did alter the catch as predicted (Bos et al. unpublished data, 2016). Presumably this can be attributed to a time lag before the effects on damage are seen, because several years are required until burrows collapse and cause major damage that is visible on the surface. Historical and experimental data (Bos et al. 2019, van Loon et al. 2017) show that the muskrat catch increases strongly in the absence of control, which in combination with the catch-damage relationship quantified here shows that the incidence of damage would also rise.

Our conclusions about the effectiveness of standard bank protection measures are based on hundreds of sub-sections distributed throughout the country. The majority of these were visited repeatedly. Two types of standard bank protection measures, 'sheet pile' and 'rip-rap' clearly had lower incidence of minor damages than expected based on the overall incidence, but frequent burrowing was nonetheless observed in almost all types of bank protection structures. The data thus indicate

Figure 6. Outer slope of the levee along the Veendiep canal, during a drawdown of the water level to facilitate inspection. Several burrow entrances can be seen. March 2012. *Photo: M. Rothengatter*.

these are not effective measures against burrowing, perhaps unsurprising as these measures were designed to protect against erosion rather than against burrowing. In fact, such measures may even complicate matters by camouflaging developing burrow systems. Better knowledge of muskrat burrowing habits might help in this regard. In particular, the maximum depth below the water surface where burrowing takes place, is not yet sufficiently known to design bank protection measures properly. We therefore recommend a study of the burrowing capacity of muskrats.

When evaluating the need for and usefulness of muskrat control, knowledge on the relation between numbers and serious damage is one of the criteria that needs to be considered (Lammertsma & Niewold 2005). Other criteria include the evidence that muskrat density is causally related to control (Bos et al. 2019, van Loon et al. 2017), ethical considerations (Warren 2007, Zandberg et al. 2011) and a lack of feasible alternative methods to maintain safety from flooding. It is recommended to carefully study the feasibility of alternative methods to prevent damage for any given landscape, and provide a cost-benefit analysis (Bos & Gronouwe 2018, Reyns et al. 2018). The relationships between trapping effort and catch, and between catch and damage (this study) underlie such analysis of the most economical long-term management strategy. The options for muskrat control range from 'no control' to 'eradication'. The costs include those of the control program, and of the ongoing inspection and repair of banks and levees. Both are proportional to the numbers of muskrat present. Ceasing control eliminates the cost of the trapping program, but would require substantial investment in bank protection, and would require inspection, as well as repair and maintenance costs. The complete removal (sensu Robertson et al.

2017) of muskrats would require sustained up-front investment in the trapping program, but would lower the costs of control and repair later. The quantitative relationships established here and in van Loon et al. (2017), and Bos et al. (unpublished data), will allow the best course of action to be decided.

Conclusions

There is a significant and positive relation between the burrowing damage observed and historical catches of muskrat. This is valid for minor and major damages distinguished in this study.

Many 5-km squares in the Netherlands have little damage, but on average 0.50 ± 0.05 s.e. incidences of major damage (above the tresholds defined by us) were found per km in 2016. Minor damage occured much more often, with 17.6 burrow entrances / km ± 3.8 s.e. on average.

The average size of major damages is in the order of 1 m^3 of displaced soil, habitations with 2 to 5 entrances and an average surface of 10 m^2.

Muskrat do not avoid banks that are characterised by standard protection measures, such as hard revetments and rip-rap, which have not especially been designed as preventive measures against burrowing.

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References

Akkermans, M. 2014. Muskrat Digging Capacity. Stowa, Amersfoort, The Netherlands.

Barends, F. 2002. The muskrat (*Ondatra zibethicus*): Expansion and control in the Netherlands. Lutra 45 (2): 97-104.

Bates, D., M. Maechler, M. Bolker & S. Walker 2015. Lme4: Linear Mixed-Effects Models using 'Eigen' and S4. R Package Version 1.1-9. URL: https://CRAN.R-project.org/package=lme4; viewed June 2016.

Bayoumi, A. & M.A. Meguid 2011. Wildlife and safety of earthen structures: A review. Journal of Failure Analysis and Prevention 11 (4): 295-319.

Bos, D. & J. Gronouwe 2018. Toekomst van het muskusrattenbeheer in Nederland. Deel A: De mogelijkheden onderzocht. Rapport 2461. Altenburg & Wymenga ecologisch onderzoek, Feanwâlden, The Netherlands.

Bos, D., E. Klop, H. van Hemert, M. LaHaye, H. Hollander, E. van Loon, and R.C. Ydenberg 2016. Beheer van Muskusratten in Nederland. Effectiviteit van bestrijding op grond van historie en een grootschalige veldproef. Deel 2. Achtergrond Studies. Rapport 2191. Altenburg & Wymenga ecologisch onderzoek, Veenwouden, The Netherlands.

Bos, D., R. Kentie, M. La Haye & R.C. Ydenberg 2019. Evidence for the effectiveness of controlling muskrat (*Ondatra zibethicus* L.) populations by trapping. European Journal of Wildlife Research 65: 45.

Bos, D., E.E. van Loon, E. Klop & R.C. Ydenberg, unpublished data. A large-scale experiment to evaluate the effects of trapping to control muskrats (*Ondatra zibethicus*) in the Netherlands.

Centrum voor Onderzoek Waterkeringen 1984. Inventarisatie muskusrattenschade in waterkeringen. Rapport S-72.029-II. Centrum voor Onderzoek Waterkeringen, 's Gravenhage, The Netherlands.

CIRIA 2013. The International Levee Handbook. Publication no. C731. CIRIA, London, UK.

Doude van Troostwijk, W.J. 1976. The musk-rat (*Ondatra zibethicus* L.) in the Netherlands, its ecological aspects and their consequences for man. Verhandeling 7. Rijksinstituut voor Natuurbeheer, Arnhem, The Netherlands.

Fritz, H. & E. Röver 2015. Jahresbericht 2014 über das Auftreten und die Bekämpfung des Bisams in Niedersachsen. Landwirtschaftskammer Niedersachsen, Oldenburg, Germany.

Gaaff, A., R. de Graaff, R. Michels, S. Reinhard & H. Vrolijk 2007. Economische schade als gevolg van graverij en vraat door muskusratten. LEI, Den Haag, The Netherlands.
Kluyver, H.N. 1937. De Bisamrat. Verslagen en Mededelingen van de Plantenziektekundige Dienst Te Wageningen 85: 1-32.
Lammertsma, D.R. & F.J.J. Niewold 2005. Muskusrattenbestrijding in Nederland: een quick scan naar nut, noodzaak en alternatieven. Rapport 1197. Alterra, Wageningen, The Netherlands.
Nieuwenhuis, R., B. Pelzer & M. te Grotenhuis 2015. Influence.ME: Tools for detecting influential data in mixed effects models. The R Journal 4 (2): 38-47.
R Core Team 2017. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL: http://www.R-project.org/.
Reyns, N., J. Casaer, L. De Smet, K. Devos, F. Huysentruyt, P.A. Robertson, T. Verbeke & T. Adriaens 2018. Cost-benefit analysis for invasive species control: The case of greater Canada goose *Branta canadensis* in Flanders (northern Belgium). PeerJ 6: e4283.
Ritzema-Bos, J. 1917. De Muskusrat, Bisamrat of Ondatra (*Fiber zibethicus* L.). Tijdschrift over Plantenziekten 23: 1-79.
Robertson, P.A., T. Adriaens, X. Lambin, A. Mill, S. Roy, C.M. Shuttleworth & M. Sutton-Croft 2017. The large-scale removal of mammalian invasive alien species in Northern Europe. Pest Management Science 73 (273): 279.
Spoorenberg, C. 2007. Preventieve maatregelen tegen graverij van muskusratten en beverratten. DHV, Amersfoort, The Netherlands.
Stuyck, J. 2008. Muskusrattenbestrijding in Vlaanderen. Bevalt de nieuwe aanpak? Zoogdier 19 (3): 18-19.
Thijsse, J.P. 1937. De muskusrat. De Levende Natuur 41: 348-349.
van Koersveld, E. 1953. De Muskusrat, *Ondatra zibethica* L., in Nederland en zijn bestrijding. In: Jaarboek 1951-1952: 229-249. Plantenziektekundige Dienst, Wageningen, The Netherlands.
van Loon, E.E., D. Bos, C. van Hellenberg Hubar & R.C. Ydenberg 2017. A historical perspective on the effects of trapping and controlling the muskrat (*Ondatra zibethicus*) in the Netherlands. Pest Management Science 73 (2): 305-312.
van Loon, E.E., R.C. Ydenberg & D. Bos 2017. Statistical estimation of muskrat abundance. Rapport 2017-41. STOWA, Amersfoort, The Netherlands.
Verkaik, A.J. 1990. Onderzoek naar de dispersie van muskusratten *Ondatra zibethicus*. Lutra 33: 79-80.
Vlaamse Milieumaatschappij 2010. Ratten op Vlaamse wijze. Vlaamse Milieumaatschappij, Erembodegem, Belgium.
Warren, C.R. 2007. Perspectives on the 'alien' versus 'native' species debate: A critique of concepts, language and practice. Progress in Human Geography 31 (4): 427-446.
Zandberg, F., P. de Jong & F. Kraaijeveld-Smit 2011. Muskusrat. Op allternatieve wijze schade voorkomen.: Nederlandse Vereniging tot Bescherming van Dieren / Bont voor Dieren / De Faunabescherming, Den Haag, The Netherlands.

Samenvatting

Graafschade door muskusratten in oevers en kades

In Nederland worden muskusratten intensief bestreden. De bestrijding is een middel om de (water-) veiligheid te waarborgen, door graverij in dijken, waterkeringen en andere infrastructuur te voorkomen. Tot in het vorige decennium was het echter een onbeantwoorde vraag of de hoeveelheid schade wel gerelateerd is aan de aanwezige aantallen muskusratten. Tussen 2013 en 2016 zijn daarom de omvang en aantallen van schades, die zijn toe te wijzen aan graverij door muskusratten, systematisch gekwantificeerd in 117 representatieve 5 km x 5 km hokken. Voor de registratie zijn in deze 5-km hokken vaste tracés op oevers en waterkeringen geselecteerd en is gedurende vier jaren de schade door graverij geïnventariseerd. Ieder jaar zijn 2634 km oevers en keringen geïnspecteerd om schadegevallen boven een bepaalde drempel van omvang of verwachte reparatiekosten te tellen en te beschrijven (de grote schades). Om ook niet zichtbare en de

wat kleinere schades goed in beeld te brengen zijn systematisch korte transecten (gemiddeld 263 m lang) 'afgetrapt', o.a. op de aanwezigheid van pijpjes die in de oever of de waterkering zijn gegraven. Over een totale lengte van 220 km is aldus op deze transecten het aantal kleine schadegevallen vastgesteld (kleine schades). De schade-inventarisatie werd georganiseerd in samenhang met een grootschalig, landsdekkend veldexperiment, waarbij is gevarieerd met de bestrijdingsintensiteit en waarover elders wordt gerapporteerd. Voor alle 5-km hokken is informatie beschikbaar over een groot aantal parameters, waaronder bodemtype en aantallen vangsten. De van buiten zichtbare omvang van de schades door muskusratten is veelal gering. De geschatte orde van grootte per geval fluctueert rond 1 m^3 vergraven grond, met meestal 2-5 ingangen onder water op het moment van ontdekking. Meerdere schades bij elkaar of op de verkeerde plek kunnen echter een reëel gevaar voor de veiligheid vormen. De grootste aantallen schades worden in laag Nederland aangetroffen. Dichtheden van grote schades variëren tussen 0 en 12 per km, maar liggen gemiddeld op 0,50 ± 0,05 s.e. gevallen per km. Schades beneden de gestelde drempel van omvang of risico komen veel meer voor, gemiddeld ca. 17,6 ± 3,8 holen per km. Voor zowel de grote als de kleine schades is er een relevant en statistisch significant positief verband aangetoond tussen het aantal schades en het aantal muskusratten dat in de voorgaande zes jaren was gevangen. De resultaten voor kleine schades laten zien dat graverij toch optreedt als de oever beschermd is met harde bekleding en stortsteen. Bij een kadeconstructie met een stalen damwand is evenwel geen schade aangetroffen. De in deze studie verzamelde informatie is waardevol, omdat het één van de essentiële bouwstenen is om een goede afweging te kunnen maken over nut en noodzaak van bestrijding van muskusratten.

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