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Effects of physical barriers and eradication on recolonization of rodents in poultry farms

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ABSTRACT

Mus musculus, *Rattus rattus* and *Rattus norvegicus* are pests in poultry farms, causing economic losses and transmitting diseases. Control is commonly conducted through anticoagulant rodenticides, but this control is not effective through time. We aimed to assess the effect of rodent exclosure on long-term success of rodent control in poultry farms of the pampean region, Argentina, and to evaluate indirect estimators of rodent abundance. In both exclosure and non-exclosure sheds rodent abundance decreased significantly after eradication but mice populations showed a recovery, suggesting that the eradication was not complete. Rats did not recover, but the low abundance found at the beginning of the experiment does not allow an accurate conclusion.

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1. Introduction

Because of their high reproductive potential and adaptable behavior, many rodent species are major pests in agricultural or urban habitats. Abundant food, mild environmental conditions and the absence of predators allow commensal rodents to reach high densities (Brown et al. 2002; Zhang et al. 2003), causing significant losses in grain production and damages to stored food and buildings. Some rodent species are also involved in the epidemiology of several diseases of humans and domestic animals and may carry diseases among wild, domestic and peridomestic habitats (Elias 1988; Meerburg et al. 2004; Singleton et al. 2005).

In rural habitats of central Argentina, most native rodent species do not reach plague densities, whereas commensal *Mus musculus* (House mouse, Linnaeus 1758), *Rattus rattus* (Black rat, Linnaeus 1758) and *R. norvegicus* (Norway rat, Berkenhaut 1769) often reach high densities. These commensal species are common in animal production farms, particularly in poultry farms on which they are primarily found inside or around chicken sheds and do not show strong seasonal variations in abundance because of reproduction throughout the year (Gómez Villafañe et al. 2001; Miño et al. 2007). In these farms, these rodents cause economic losses by consumption of chicken food, contamination, disease transmission, and by killing small chickens.

Some native species are also found on farms but are less abundant, particularly the small vesper mouse (*Calomys laucha*, Fischer 1814) in chicken sheds and the pampean grassland rodent (*Akodon azarae*, Fischer 1829) along weedy fences that surround the perimeters of farms (Miño et al. 2007). Even less common are the vesper mouse (*Calomys musculinus*, Thomas 1913), the reservoir of the Junín virus, the etiological agent of Argentine Hemorrhagic Fever (Parodi et al. 1959; Sabattini et al. 1977), and the rice rat (*Oligoryzomys flavescens*, Waterhouse 1837), the reservoir of orthohantavirus, the etiological agent of Hantavirus Pulmonary Syndrome (López et al. 1996; Levis et al. 1998). In spite of their low abundance, these two last species involve a serious risk to farm workers, who enter sheds without protection and can be exposed to the inhalation of viral particles scattered among the sunflower or wheat husks that usually cover the floor of sheds. In these habitats, rodents also pose a serious sanitary risk as transmitters of several other diseases to humans and domestic animals, including leptospirosis, salmonellosis and trichinosis (Acha and Szyfres 1986; Calderón et al. 1999; Seijo et al. 2002; Lovera et al. 2017), and they act as reservoirs for reinfection by diseases after cleansing and disinfection of chicken sheds (Rose et al. 2000; Pocock et al. 2001).

Although chemical control is a common practice in central Argentina, previous surveys found 97% and 70% of farms infested by house mice and rats, respectively (Gómez Villafañe et al. 2001; León et al. 2007). The source of infestation of poultry farms by

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M. musculus is not clear, because farms are dispersed within a matrix of crop fields in which this species is rare (León et al. 2010), and genetic studies suggest low genetic exchange among populations, particularly between those that are separated by more than 0.5 km (León et al. 2010). An alternative hypothesis to active dispersal is that humans introduce *M. musculus* individuals during the transport of chickens or their food (Ryan et al. 1993). Rats, by contrast, move more extensively, and infestation of a new farm most likely occurs from other farms (Gómez Villafañe and Busch 2007). The mean distance between nearest neighbor farms in the area is 0.58 km (range: 0–1.7 km), and according to Taylor (1978) and Hardy and Taylor (1979), normal daily movements of rats are between 0.2 and 1.26 km and can reach 3.3 km/day when looking for food.

Many efforts to prevent rodent infestations in farms include removing food and shelter or minimizing potential food sources, but in sheds in which domestic animals are kept and fed, rodent proofing is the most important preventive measure. When rodents have invaded and settled in farm buildings, efficient control can usually only be achieved by the application of rodenticides (Pelz and Klemann 2004), but the effect of this control is frequently temporary because of the recolonization from the surroundings (Singleton et al. 1999; Pelz 2003; Brown and Tuan 2005), which depends on the mobility of the species and the characteristics of the surrounding habitat. Failure in rodent control may also be associated with the existence of resistance to anticoagulants (Guidobono et al. 2010). Therefore, eradication and the prevention of reinvasion are crucial to the effectiveness of control measures over time. One method to reduce the effects of rodents in post-harvest stores and intensive animal production units is the use of physical barriers and fences (Singleton et al. 1999), which may be used in combination with traps (Singleton et al. 2005). To improve rodent control in these systems, knowledge of whether reinfestation comes from outside or from resident individuals who are not affected by control measures is crucial, in addition to reliable abundance estimates both before and after control is applied. Abundance assessment in this case must not require much time or money investment and may not involve direct contact of personnel with rodents. In this context, the use of infestation indices based on signs of presence or footprint records over different type of materials may be useful (Ahmad et al 1995; Coto 1997; Aplin et al. 2003; Shahwar et al. 2015, 2016), but these indices must be calibrated through removal trapping experiments coupled with routine rodent monitoring by tracking tunnels (Brown et al. 1996).

To contribute to more effective management of rodent control in farms, the goals of this work were the following: 1- To assess the effect of physical barriers on rodent population recovery through time after intensive eradication; 2- To obtain relations between direct (through captures) and indirect (based on footprints) estimates of rodent abundance. The hypothesis tested was that population recovery after control measures was by recolonization from the surroundings, and the prediction was that after intensive eradication of rodents, chicken sheds surrounded by physical barriers would not be colonized or be colonized later than non-exclosure sheds.

2. Materials and methods

2.1. Ethics statement

Trapping, handling and euthanasia were performed according to the procedures and protocols of the Argentine National Law for Animal Care 14346 and the Ethics Committee for Research on Animals of Laboratory, Farm and obtained from Nature of the National Council for Scientific and Technological Research (CONICET, resolution 1047, section 2, annex II). This work is part of the projects approved by the National Council for Scientific and Technological Research (PIP 1410), the Universidad de Buenos Aires (UBACYT 20020100100512) and the National Agency of Scientific and Technological Promotion (ANPCYT, PICT 33513), which were evaluated by an ethics committee. We did not conduct experiments with humans or laboratory animals.

2.2. Study area and characteristics of the farms

The study was conducted in poultry farms located in Buenos Aires Province, Argentina (34°17′ S, 59°14′ W), between April and December 2008. This area is located in the pampean region, characterized by a temperate climate (mean annual temperature of 16 °C and mean annual rainfall of 1000 mm) and grassland-type vegetation that is currently replaced by crops. Poultry farms are surrounded by a matrix of crop fields and pastures (Miño et al. 2007; León et al. 2010).

The study was conducted in two poultry farms that were representative of the farms of the area and whose owners gave the consent to conduct the work. These farms were devoted to breeding broiler chickens, occupied approximately 1 ha and were surrounded by wire fences under which a well-developed weed community occurred. Neighboring fields were devoted to agriculture or livestock breeding. In both farms, large, integrated breeding companies provided the farmers five-day-old chicks, medicines

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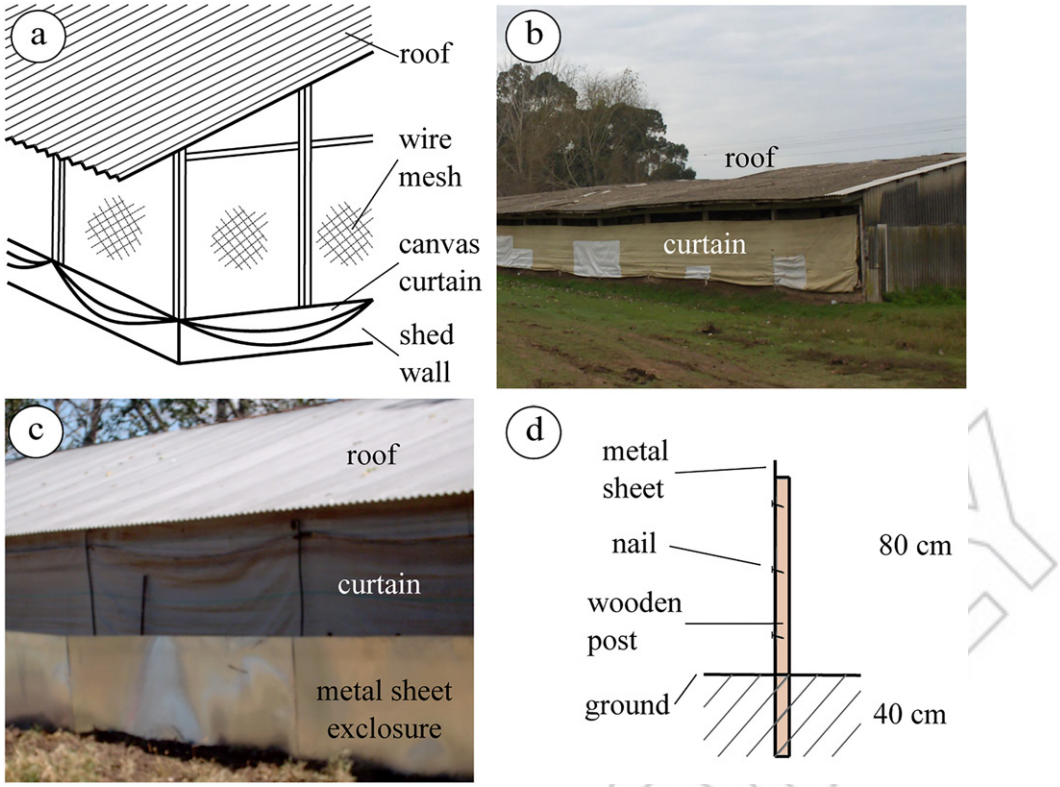

Figure 1. Schematic representation of a farm shed (a) and photos of the external aspect of a farm shed without (b) and with exclosure (c). (d) Diagram of the position of a sheet attached to a wooden post.

and food. Chickens were maintained in breeding sheds at a comfortable temperature using either heat or cooling and received food and water *ad libitum*; food was offered in feeders that hung from the ceiling, and an automatic device provided water. After 45–50 days, chickens were removed for sale. During the next 15–20 days, sheds were prepared for the arrival of new chickens, including the application of rodenticides in some cases (Gómez Villafañe et al. 2001).

In the studied farms, sheds were constructed with galvanized steel sheet walls of approximately 40 cm in height, extended to the ceiling by a non-rodent proof wire mesh (more than 0.5 cm wide). The ceiling consisted of expanded polystyrene sheets or hanging canvas, and the roof was made of galvanized sheets. The floor of the sheds was covered by sunflower or rice husks. On the outside walls of sheds, canvas curtains were left hanging from the roof to the floor or were rolled up depending on the outside temperature (Figure 1). Rodents could enter sheds through the wire mesh but also through spaces between galvanized sheets or by burrowing below them.

One of the studied farms (Farm 1) had two breeding sheds, one 101 m × 12 m (Shed 1) and the other 78 m × 12 m (Shed 2), separated by an approximately 10 m area covered with grasses and weeds that grew spontaneously. The distance to the perimeter of the farm was approximately 2 m for Shed 1 and 10 m for Shed 2. The other farm (Farm 2) had 4 sheds of similar construction and width that ranged from 50 to 100 m in length and were 12 m in width. Only two sheds were located near the boundary of the farm, Sheds 1 and 4; whereas internal paths surrounded the others. Weedy areas also separated the sheds.

2.3. Sampling design and experimental methods

Relative abundances of mice and rats were estimated in all sheds of each farm using a Footprint Index (FI) before eradication and exclosure. Footprint indices have been previously and extensively used to assess densities of different rodent species (Brown et al. 1996; Ahmed and Fiedler 2002) and are generally obtained using tiles coated with ink or talcum powder (Shell Guide to Rodent Control, 1987; Promkerd et al. 2008). In a previous work, we tested different coatings and selected chalk powder (Gómez Villafañe et al. 2001), which was also used to assess rodent abundance in poultry farms in Pakistan (Shahwar et al. 2015, 2016).

Footprints were recorded in tracking stations consisting of a 15 cm × 50 cm hardboard coated with a thin layer of chalk, protected by a half plastic tube (10 cm height) to prevent the spoiling of the tracking powder by rain (Figure 2). Tracking stations were placed at 10 m intervals along the external walls of sheds. We did not place tracking stations inside the sheds because access to the interior of sheds was not possible during all stages of

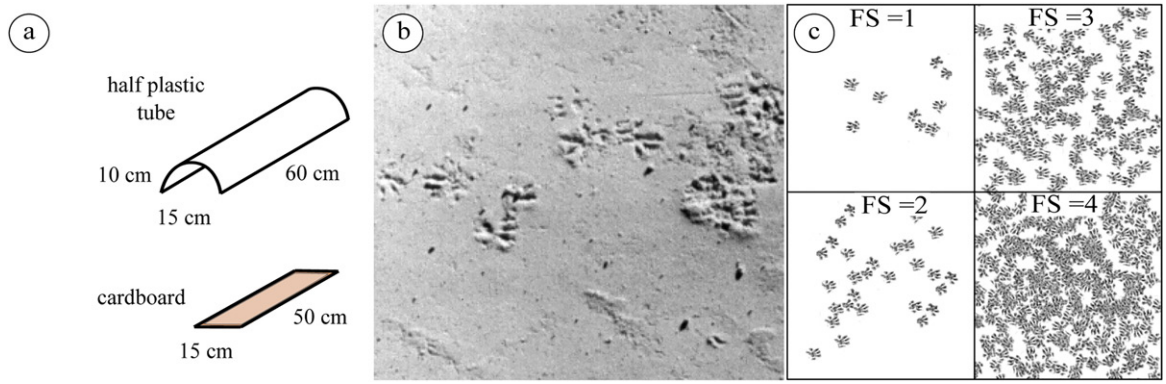

Figure 2. (a) Diagram of the half plastic tube and the cardboard used to register footprints. The half plastic tube was placed over the cardboard. (b) Rodent footprints on chalk powder and (c) Density of footprints for Footprint Scores (FS) = 1 to 4. FS = 0 when no footprints were recorded.

chicken development; however, according to previous works (Gómez Villafañe pers. com.), footprint records outside and inside sheds do not differ because mice and rats construct burrows and tunnels along the walls, with entrances at both sides. We also observed mice running along the outside walls of sheds, between the wall and the curtains. The total number of stations depended on the shed size (from 10 to 18). Rodent footprints were recorded at each tunnel 4 days after the installation. Footprints of rats and mice were discriminated by size (longer than 2 cm for rats and up to 1 cm for mice, Klapdor et al. 1997), but we could not distinguish between rat species (*R. rattus* or *R. norvegicus*) or among mouse species (*M. musculus, A. azarae, Calomys* spp., *O. flavescens*). At each tracking station, we scored footprints on a scale from 0 to 4: 0 = no tracks, 1 = less than 25% of the board covered with tracks, 2 = from 25 to 49% of the board covered with tracks, 3 = from 50 to 74% of the board covered with tracks and 4 = more than 74% of the board covered with tracks (Shell Guide to Rodent Control 1987), Figure 2. Then, we obtained a mean value (FI) for each shed (Gómez Villafañe et al. 2001).

After the first footprint record, one shed at each farm selected at random was surrounded by a physical barrier (exclosure) that consisted of zinc flashing placed at approximately 1 m from the shed wall, with approximately 80 cm projecting aboveground and 40 cm extending belowground. Zinc sheets were 2.40 m long and 1.20 m high and were tightly attached to wooden posts that were placed inside the exclosure, to prevent rodents from climbing (Figure 1). Although they can eventually go deeper, Norway rats generally dig tunnels and burrows up to 30 cm belowground (Smith 1996). These rats can also jump to a height of 75 cm, but their movements are practically restricted to the ground (Montes de Oca et al. 2017). Ship rats are good climbers but were scarce on the studied farms, and even when present, the smooth surface of the zinc sheets prevented climbing. Physical barriers were built between April 23 and May 6 in Farm 1 and between May 14 and June 25 in Farm 2 (autumn). Exclosures surrounded the entire perimeter of each of the experimental sheds but were interrupted by a door, which was also built with zinc sheets closely attached to wooden frames to prevent rodent entry when closed. This door was required to allow normal work of the farm, such as movement of chickens, supplying food and personnel work. Swing doors were installed at the ends of the exclosures to allow drainage of rainwater accumulated in ditches along the sheds. Although farm owners frequently left the doors open during the arrival and removal of chickens, exclosures covered at least 98% of the shed perimeters, and 100% of the perimeter bordering neighbor fields. Exclosure sheets were removed at the end of the study (December).

During the 5 weeks of the exclosure period, we conducted intensive eradication of rodents by trapping and poisoning inside all sheds of both farms, with an interval for estimating abundance by footprints (Table 1). Trapping effort included 446 cage trap-nights (traps 15 × 16 × 31 cm), 874 Sherman (8 × 9 × 23 cm) trap-nights and 637 snap trap-nights in Farm 1 (2 sheds) and 546 cage trap-nights, 1189 Sherman trap-nights and 1481 snap trap-nights in Farm 2 (4 sheds). At each trapping period, traps were set active for three consecutive nights. Traps were baited with a mixture of bovine fat, rolled oats and peanut butter. The anticoagulant used for poisoning was bromadiolone, (3-[3-(4'-bromobifenil-4-il)-3-hidroxi-1-fenilpropil]-4-hidroxicumarina), which is frequently used in the poultry farms of the area. We used a commercial bait of wheat grains coated with a formulation of 5 mg of bromadiolone per 100 mg of coloring, attractant and other inert compounds to give 0.05 mg bromadiolone/g bait. During the eradication period, we applied approximately 2.55 kg of bait per shed, distributed along

Table 1. Summary of the study design. FI: Abundance evaluation through the Footprint Index. Removal: Rodent removal by trapping and poisoning.

Farm 1	1st FI	1st Removal	2nd FI	2nd Removal	3rd FI	4th FI	5th FI
	25/4	29/4-2/5 5-9/5	13/5	20-23/5 26-30/5	17/6	23/9	23/12
Farm 2	1st FI	1st Removal	2nd Removal	2nd FI	3rd FI	4th FI	–
	16/5	30/5-3/6 17-20/6 24-27/6	1-4/7 4-7/7	11/7	23/9	23/12	

walls and in the ceiling inside PVC tubes or plastic cages (the number of bait stations depended on shed size, ranging from 10 to 30).

After the eradication period, we assessed three more times, every two-three months, the abundance at each shed of each farm by footprints (Table 1). The study period began in autumn and was prolonged to early summer. Because of logistical problems, we could not sample between the end of May and mid-June.

2.4. Rodent abundance estimators

We used one estimator based on footprints (Footprint Index) and three based on trapping (Trap Success, Number of individuals captured and Hayne estimator). We also estimated rodent density accounting for the number of individuals and the shed area.

Footprint Index (FI): Mean of scores of individual tracking stations per shed.

These estimations were conducted separately for mice and rats.

Trap success (TS): Number of individuals captured/[Number of traps* Number of nights]. We considered the total number of Sherman and snap traps placed for small rodents and cage and snap traps for rats, because mice are too small to activate cage traps and rats are too large to enter Sherman traps. Both rats and mice were captured with snap traps.

Number of individuals captured: Total number of accumulated individuals captured during the sampling sessions.

Hayne estimator: For this estimation, we conducted linear regressions between the capture at each day of sampling and the accumulated capture throughout the eradication period, as the dependent and independent variables, respectively. The abundance at the beginning of eradication was estimated using the x intercept when no captures occurred, as the ratio between the intercept and the slope of the regression (Seber 1982). This estimator provided a minimum number of individuals (because rodent eradication was also performed through poisoning) present at the beginning of eradication.

Density estimation (Individuals/ha): According to the estimators of the number of individuals present in each shed (after the number of animals captured and the Hayne estimator), we estimated rodent density per shed, accounting for their size.

2.5. Data analyses

To analyze whether the effectiveness of rodent control through time differed between exclosured and non-exclosured sheds, we used Generalized Least Squares Mixed Models in which the Footprint Index of each shed was the response variable and the explanatory variables were the treatment (exclosured, non-exclosured) and the time (with four levels corresponding to sampling dates) as fixed factors, with the farm as a random factor to account for the repeated measures (in time and for many sheds) that were performed in each of them. We only considered sampling sessions that were separated by the same time interval in both farms. We also included interaction terms. This analysis was conducted separately for mice and rats using R software (R Core Team 2013) with the lme4 package (Bates et al. 2015).

The relations between the Footprint Index and trapping estimations of mice and rat abundance (TS, number of individuals caught, Hayne and density estimators) were established through Type II quadratic regression analysis (Statistica 6.0). The coupled estimations of abundance through trapping and footprint records (Brown et al. 1996) were obtained considering FI values recorded within a week before the beginning of trapping. For Farm 1, in consequence, we had 2 sheds measured at 2 times (1st and 2nd FI) whereas for Farm 2, we had 4 sheds measured only one time. Considering both farms, the number of observations was 8.

For mice, footprint records were regressed with captures of all mice species, with only *M. musculus* captures and with only *A. azarae* captures. For rats, footprint indices were compared for both species (*R. norvegicus* and *R. rattus*) and only for *R. norvegicus*, because *R. rattus* was captured in only two sheds.

3. Results

We captured a total of 236 animals from 3 commensal species, *M. musculus*, *R. rattus* and *R. norvegicus*, and 4 native species: *A. azarae*, *C. laucha*, *C. musculinus* and *O. flavescens*. The number of

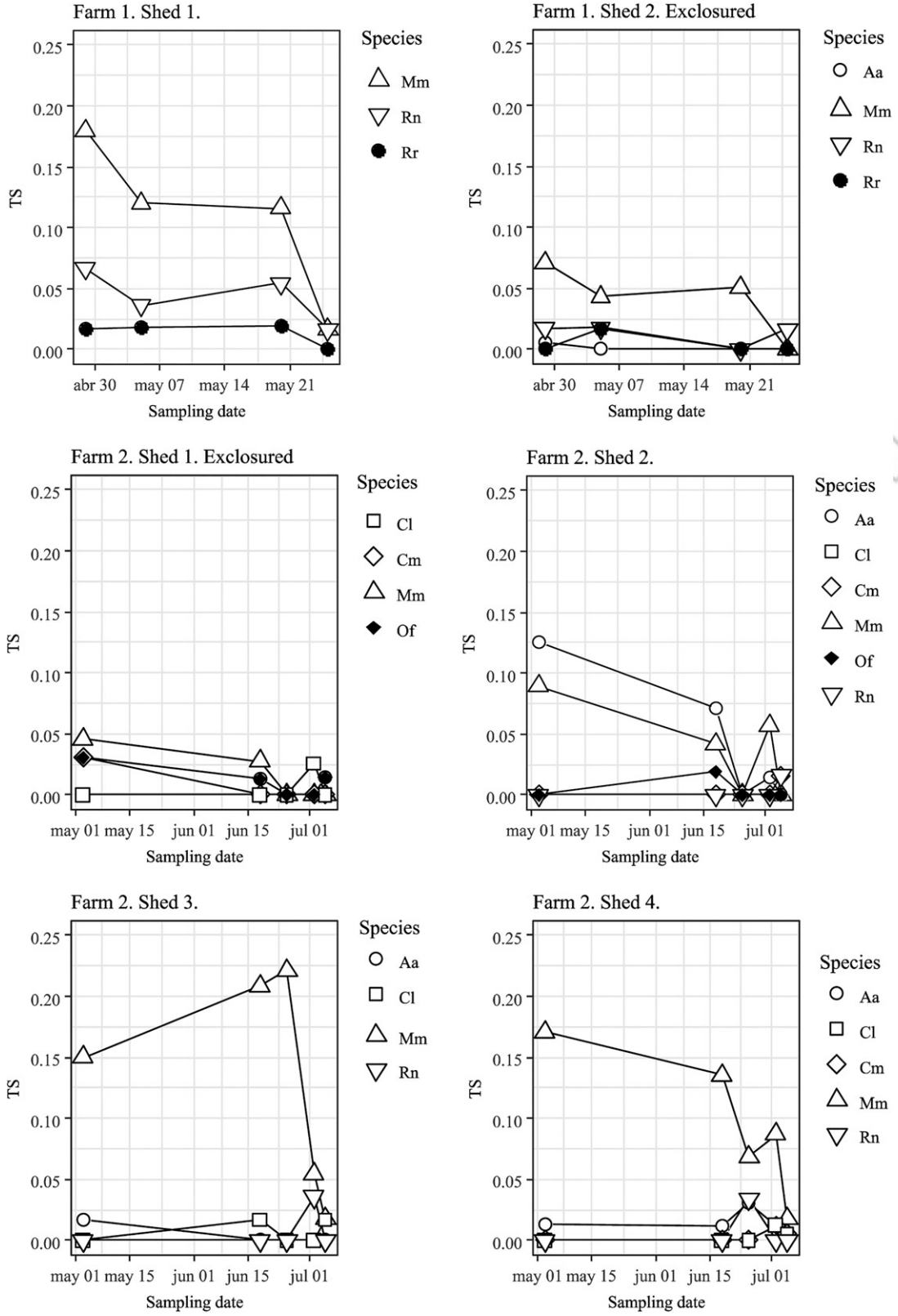

Figure 3. Variation of the Trapping Success of the different rodent species during the removal period for Farms 1 and 2.

animals captured per shed varied from 13 to 75. *Mus musculus* was the most abundant species, contributing 68 and 78% of the total captures in the two sheds of Farm 1 and 30, 48, 90 and 82.7% in the four sheds of Farm 2. *Rattus norvegicus* was captured at least once in all sheds (with percentages of captures that ranged between 2.5 and 17%); whereas *R. rattus* was only present in both sheds of Farm 1. *Akodon azarae*, the most abundant species in crop field borders, was in 5 of 6 sheds of both farms with percentages ranging from 2.5 to 40% of total captures. *Oligoryzomys flavescens*, *C. laucha* and *C. musculinus* were only captured in Farm 2, representing less than 5% of captures. The last two species were captured at the end of the eradication period, when *M. musculus* was not captured.

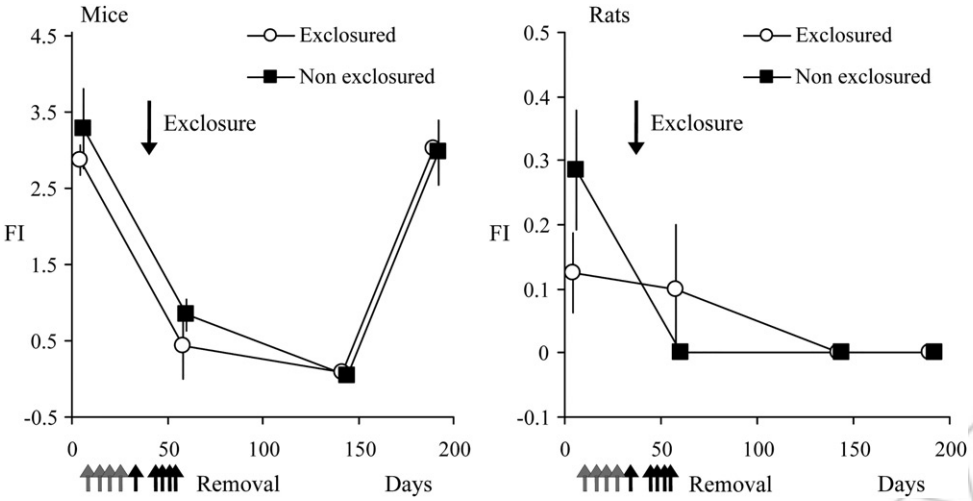

Figure 4. Variation of the mean Footprint Index for mice (including *M. musculus* and native species) and rats during the sampling periods for exclosured and non-exclosured sheds of both farms. The arrows below the x-axis indicate the periods of removal (in gray for Farm 1 and in black for Farm 2). The upper arrows show the moment of finalization of exclosure building.

Table 2. Results for the analysis for mice and rats of the effect of exclosure (Treatment) on population abundance (Footprint Index) variations through time after removal. In bold, significant effects are highlighted.

	numDF	denDF	*F*-value	*p*-value
Mice				
Intercept	**1**	**15**	**56.456**	**<0.001**
Treatment	1	15	0.167	0.689
Time	**3**	**15**	**41.421**	**<0.001**
Treatment: Time	3	15	0.262	0.852
Rats				
Intercept	**1**	**15**	**5.648**	**0.031**
Treatment	1	15	0.398	0.538
Time	**3**	**15**	**9.827**	**0.001**
Treatment: Time	3	15	2.034	0.152

3.1. Abundance variation through time according to trapping methods

The TS of all rodent species showed a decrease during the eradication period in both exclosured and not exclosured sheds. In both farms, all species reached TS values <0.02 (Figure 3). The number of rodents estimated at the beginning of the eradication period by the Hayne method showed strong variation among sheds (from 12.2 to 84 individuals per shed) and was similar to the total number of rodents captured (Appendix).

3.2. Abundance variation through time according to footprints and evaluation of the effect of exclosure in the population recovery

After the period of eradication, the FI of both mice and rats decreased in all sheds of both farms. In Farm 1, mice FI values were near 0 after eradication but then recovered to an average of 2.4. Rat FI values did not recover until the end of the experiment (Figure 4). In Farm 2, a similar trend was observed, and mice FI recovered to average values near 3, whereas rats showed a 0 value until the end of the experiment (Figure 4).

According to the Generalized Least Squares Mixed Models, the effect of time on mice FI was significant, whereas the effect of exclosure and the interaction between time and exclosure were not significant (Table 2), indicating that exclosured and non-exclosured sheds showed similar variations in mice abundances throughout the experiment (Figure 4). The mice Footprint Indices decreased significantly between the first sampling (before eradication) and samplings 2 and 3 ($p < 0.001$), whereas at the last sampling (December), the FI did not differ from initial values ($p = 0.480$), showing a recovery in abundance.

For rats, as for mice, an effect of exclosure on abundance was not detected, and the trend of abundance variation through time was similar for exclosured and non-exclosured sheds (Table 2, Figure 4). All FI values after eradication were significantly lower than initial values, showing that these species did not recover after eradication ($p < 0.001$ for all times).

3.3. Relations among footprint indices and trapping estimators of rodent abundance

Footprint indices of mice were positively and significantly related to mice density but not to other trapping estimators or to TS values (Table 3). For rats, footprint indices were positively and significantly related to rat and *R. norvegicus* TS, to the number of rats captured, to the Hayne estimator of the number of *R. norvegicus* and to rat density. Rat density estimators based on the trapping success (TS) showed better adjustment to Footprint indices (FI) than the other capture estimators (Table 4).

Table 3. Results of the Type II regression models for the relation between trapping estimators of total mice and *M. musculus* abundance and Footprint Indices of mice. We show the values of coefficients for the regression of the different trapping estimators as dependent variables and the FI as the independent variable. TS: Trapping Success; Capt: Number of individuals captured; Hayne: Number of individuals estimated by Hayne; Dens: (Number of individuals captured/shed area in hectares). Mice: *M. musculus* + *A. azarae* + *C. laucha* + *C. musculinus* + *O. flavescens*. Mm: *Mus musculus*. r^2: Correlation coefficient; *p*: *p*-value; I: Intercept; S: Slope. In bold, significant relations are highlighted.

	Mice TS	Mm TS	Mice Capt	Mm Capt	Mice Hayne	Mm Hayne	Mice Dens	Mm Dens
r^2	0.36	0.05	0.28	0.14	0.30	0.18	**0.53**	0. 35
P	0.11	0.59	0.18	0.37	0.16	0.29	**0.04**	0.12
I	0.04	0.07	−6.22	1.42	−12.41	−3.55	**−311.49**	−209.52
S	0.04	0.01	12.97	8.40	15.51	10.58	**235.61**	178.16
N	8	8	8	8	8	8	**8**	8

Table 4. Results of the Type II regression models for the relation between trapping estimators of abundance and Footprint Indices of rats. We show the values of coefficients for the regression of the different trapping estimators as dependent variables and the FI as the independent variable. TS: Trapping Success; Capt: Number of individuals captured; Hayne: number of individuals estimated by Hayne; Dens: (Number of individuals captured/shed area in hectares). Rats: *Rattus norvegicus* and *Rattus rattus*, Rn: *Rattus norvegicus*. r^2: Correlation coefficient; *p*: *p*-value; I: Intercept; S: Slope. In bold, significant relations are highlighted.

	Rats TS	Rn TS	Rats Capt	Rn Capt	Rats Hayne	Rn Hayne	Rats Dens	Rn Dens
R^2	**0.79**	**0.73**	0.46	0.47	**0.52**	**0.55**	0.45	**0.54**
P	**0.00**	**0.01**	0.06	0.06	**0.04**	**0.03**	0.07	**0.04**
I	**−0.02**	**−0.01**	0.34	0.54	**0.64**	**0.16**	15.50	**7.87**
S	**0.14**	**0.10**	12.51	9.38	**13.97**	**11.54**	97.01	**85.14**
N	**8**	**8**	8	8	**8**	**8**	8	**8**

4. Discussion

In this work, we conducted an extensive eradication of rodents, both by trapping and poisoning, which was effective in reducing abundance until 3–4 months for mice, whereas rats did not recover their numbers until the end of the experiment, 8 months after the beginning of eradication. Significant reductions in rodent activity after anticoagulant applications without eradication by trapping were also achieved in poultry farms of Pakistan (Shahwar et al. 2015). Our results were independent of the treatment for both mice and rats, suggesting that the exclosure did not prevent the recovery of mice populations, in contrast to the expectation according to our hypothesis. This result suggests that mice eradication was not complete and recovery was due to reproduction of remnant individuals. Rats did not recover in any treatment until the end of the experiment, but the low abundance found at the beginning of the experiment does not allow an accurate conclusion.

This result is consistent with previous results that found that *M. musculus* populations isolated on farms most likely recover after control by reproduction of surviving individuals (León et al. 2007; 2010; 2013). For rats, we found low numbers on both farms before eradication, decreasing the chances of recovery from remaining individuals, whereas the absence of recolonization might be a consequence of low density in the surrounding fields.

An alternative explanation for the absence of differences between treatments is that exclosures were not effective in preventing reinvasion, because farm owners frequently left the doors open during the arrival and removal of chickens (which occurred every 45 days and lasted 1–2 days). We considered that during most of the study period, 98% of shed perimeters were closed, and only at the end of the experiment, the farmers removed the sheets of the exclosures because they caused an increase in temperature near the sheds; however, the entrance of rodents to sheds because of incomplete exclosure could not be discarded. To harmonize rodent exclusion measures with the management of the farm, surrounding the entire area of sheds instead of each of them individually would be an improvement, resulting in more practical movement of farm workers and less cost. Rodent management should also be improved through the implementation of control programs oriented not only to technical aspects but also toward farmer behavior and attitudes, because farmers usually minimize the damage caused by rodents or consider that the costs of a more effective control are not compensated by the benefits. This type of program does not exist in Buenos Aires Province, and farm owners perform rodent control individually.

FI values were significantly related to at least one trapping estimator of abundance for both mice and rats, suggesting that the index is useful to monitor infestation without sanitary risks to personnel. The positive intercepts of the regression of FI versus trapping estimators suggested that rodents were detected by the powder tracks even when in low abundance.

Standard management of rodents in farms of the area, with periodic application of anticoagulants, does not prevent rodent infestation even in the short-term (Gómez Villafañe et al. 2001), whereas in the present work, the effect of intensive culling was sustained at least 4 months. The combination of rodenticide application with trapping methods decreases the risk of selecting resistant individuals who may recover the population (Guidobono et al. 2010).

Initially, we wanted to assess consumption of food and mortality of chickens, but obtaining reliable data from farm managers was impossible. According to our estimations of the number of rodents (rats and mice) per shed, the consumption of chicken food in highly infested sheds could be approximately 40 kg during the breeding period (45 days). Compared with the global cost of feeding all the chickens of a shed, rodent consumption might appear insignificant, but considering that they also inflict damages to building structures and present sanitary risks to humans and domestic animals, rodent control is justified in the most effective manner. In one of the studied farms, we found *M. musculus* individuals infected with *Leptospira*, highlighting the risk that the presence of rodents poses for farm workers (León et al. 2017). According to our study, FI values greater than 1 are indicators of rodent abundance levels that imply a high probability of occurrence of *Leptospira, Brucella, Trichinella* and metacestodes on farms (Lovera et al. 2017).

Although we studied only 2 poultry farms, many farms of the area have similar levels of infestation, and in consequence, our results may also be applicable to other farms.

Our conclusions about the absence of an effect of exclosures on population recovery must not be generalized, because we assessed the exclosures under particular conditions, which could be highly improved. Barriers could be effective when implemented during shed construction, before rodent colonization, and could minimize the use of toxic baits and reduce unwanted effects on non target species.

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Disclosure statement

We declare no conflict of interest.

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Appendix

Number of individuals of the different rodent species captured per shed and the number of individuals estimated at the initiation of the eradication period by the Hayne method (between brackets).

	M. musculus	*A. azarae*	*O. flavescens*	*C. musculinus*	*C. laucha*	*R. norvegicus*	*R. rattus*
Farm 1							
Exclosure	17	1	0	0	0	3	1
	(15.8)	(1)	–	–	–	(2.5)	(1)
Control	46	0	0	0	0	10	3
	(47.1)	–	–	–	–	(10.9)	(2.9)
Farm 2							
Exclosure	4	2	3	0	2	2	0
	(3.9)	(2.0)	(3)	–	(2)	(2)	–
Control	12	10	1	1	0	1	0
	(11.9)	(9.6)	(1)	(1)	–	(1)	–
Control	36	1	0	0	2	1	0
	(53.6)	(1)	–	–	(2)	(1)	–
Control	62	7	0	2	2	2	0
	(62.2)	(15.1)	–	(2)	(2)	(4.8)	–