MULTIPLE-SPECIES EXCLUSION FENCING AND TECHNOLOGY FOR MAINLAND SITES

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Abstract: Eradication of invasive vertebrate pests from increasingly large islands has become an important wildlife management and conservation tool internationally. Success on islands has prompted attempts to exclude and eradicate vertebrate pests from mainland sites. Early mainland exclusion efforts often failed due to ineffective or poorly maintained barriers to pest reinvasion. Over the last 10 years, we have conducted extensive experiments to design effective pest exclusion technology. We have determined the behaviour and physical abilities of many of the vertebrate pest species found in New Zealand and other parts of the world. Pest species have been tested against a variety of fence designs with the aim of developing 100% effective barriers. We found that fences which relied on the use of electrified wires proved ineffective for most species, whereas barriers that exceeded the physical capability of the target pests were reliable. Two multi-species fence designs excluded every pest tested. The designs excluded rodents (including mice), lagomorphs, mustelids, hedgehogs, brushtail possums, cats, dogs, feral pigs, goats, deer, Javan macaque and domestic livestock. The outcome of this research programme has been the commercial availability of two designs of Xcluder™ pest proof fence. Supporting components and technology, such as pest-free pedestrian and vehicle gates, waterway gates and remote surveillance systems to mitigate reinvasion risks have enabled projects to succeed. Over 20 exclusion barrier systems have now been constructed in areas up to 3,400 ha in size and have allowed multi-species eradication attempts. With the successful removal of vertebrate pests, many projects are now undertaking significant restoration programmes including the reintroduction of threatened wildlife species to mainland sites.

Key Words: barrier, behaviour, eradication, exclusion, house mouse, invasive species, mustelid, pest proof fencing, rodent, Xcluder™

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INTRODUCTION

Eradication of invasive vertebrate pests from increasingly large islands has become an important wildlife management and conservation tool internationally. Since the 1970s, rodents have been eradicated from an increasing number of islands around New Zealand and, more recently, elsewhere in the world (Veitch and Bell 1990, Taylor et al. 2000, Towns and Broome 2003). Success on these islands has now prompted attempts to exclude and eradicate multiple species of vertebrate pests from mainland sites (Speedy et al. 2007).

Exclusion fencing is being used internationally to protect areas of high conservation value or to create 'islands' of protected habitat for native fauna. It has proven a particularly valuable tool in aiding the reintroduction of threatened species to areas from which they have been previously eliminated or displaced by pests (e.g. Dufty et al. 1994, Moseby and O'Donnell 2003, Speedy et al. 2007). However, mainland pest exclusion and eradication relies on effective fence design to be a cost-effective and sustainable pest management strategy (Clapperton and Day 2001).

The design of an exclusion fence must be based on the behaviour and physical abilities of the animals it aims to exclude. Many historical exclusion fences were not experimentally tested (Long and Robley 2004), were focused on exclusion of single rather than multiple species (Aviss and Roberts 1994) and often failed because of faulty design, poor construction, or lack of maintenance (e.g., Day and Flight 2002). Often, the process of fence development has been undertaken by independent organisations and individuals around the world, leading to many fence designs, with varied success, for a diverse range of species and situations. Filling knowledge gaps about pest animal behaviour and physical abilities would allow development of optimal, cost-effective fence designs (Long and Robley 2004).

Fences that rely upon the responses of animals to electric wires have been used extensively overseas for pest control (McKillop and Sibly 1988). Electric fences are primarily psychological rather than physical barriers and are effective against some mammal pests, e.g. rabbits (*Oryctolagus cuniculus cuniculus*) (McKillop et al. 1993), and fox (*Vulpes vulpes*) (Minsky 1980). However, brushtail possums (*Trichosurus vulpecula*) quickly breach an electric fence during a power failure (Cowan and Rhodes 1992, Clapperton and Matthews 1996). Stoats (*Mustela erminea*) can move so quickly up a fence that they can pass the electrified wires between energy pulses (Day and MacGibbon 2002). When rodents, possums and cats (*Felis* spp.) are sufficiently motivated electrified wires do not prevent either species from crossing fences (Clapperton and Matthews 1996, Day and Flight 2002).

Physical barrier fences that exceed the behaviour and physical abilities of the target pest offer a much greater chance for effective exclusion. Barrier fences have been developed for single species, but have often still incorporated electric wires into the physical barrier design (e.g., fox, (Poole and McKillop 2002) and dingo (*Canis lupus dingo*, Bird et al. 1997)). Barrier fences have rarely been designed to exclude the entire suite of pests present at a site. In many cases, project managers have been resigned from the beginning to the fact that their fences will only contain a proportion of the target animals (Long and Robley 2004). One of the few groups that have experimentally evaluated barrier fence type designs for multiple pest species is the Karori Wildlife Sanctuary (Karori Wildlife Sanctuary Trust Inc. 1998). By measuring the physical abilities of the target species (e.g. maximum jump height, climbing ability etc.) they developed an effective barrier for all target pests except mice (Karori Wildlife Sanctuary Trust Inc. 2001).

This paper describes outcomes from over 10 years of research to design cost effective fences that are completely effective for multiple assemblages of pest species. The research started in 1996 (as a result of landowner desire to exclude herbivore animal pests from native plantings), and was initially focused on pests found in New Zealand. Research has since been extended to Australia, Hawaii and Mauritius. The entire focus of the research described in this paper has been to challenge the notion that no fence is likely to be 100% effective for 100% of the pests 100% of the time (Aviss and Roberts 1994, Coman and McCutchan 1994). This was achieved by designing and experimentally determining the efficacy of practical effective fences for ALL pest species present at a site. However, even the most effective fence design will only continue to be effective if it is regularly monitored for reinvasion risks and is well maintained (Sexton 1984, Coman and McCutchan 1994, Day and Flight 2002). Therefore, as the experimentally successful fence designs described in this paper have been built in the field (18 sites), in-situ analysis of their long term pest exclusion efficacy has been made and is described.

METHODS

Fence Designs Tested

Three basic fence designs were experimentally evaluated for their efficacy to contain or exclude pests. The main designs tested were the electric fence, the Xcluder™ "Tui" fence and the Xcluder™ "Kiwi" fence (Figure 1).

The electric fence consisted of a wooden post and wire fence 1,200 mm high, with backing wires and wire mesh placed up its length. A 'skirt' of mesh was pinned to the ground and extended >300 mm horizontally out towards the pests. The mesh skirt was then covered with 50 mm of earth. For a description of how the wire mesh was chosen for these experiments see the "Wire mesh experiments" section below. Two 300 mm long steel outriggers were placed on the fence: one at the top, angled slightly upward, and one at 600 mm above the ground on the same angle. Each outrigger had an identical configuration of 5 wires (3 electrified wires and 2 ground wires) running parallel along the fence length. The electric wires were powered by a Gallagher fence energiser with an output of 58 pulses/sec at 8,500 volts per pulse. The inside electric wire was within 20 mm of the fence mesh and the outside wire was 300 mm from the vertical face of the mesh. Although several minor modifications were made to the design early in the research, this fence design remained similar to that previously described by Clapperton and Matthews (1996) as a brushtail possum barrier.

The Xcluder™ "Tui" fence was designed after the electric fence efficacy trials had been completed and we had learned something about the behaviour of the pests we wished to exclude. The Tui fence consisted of a base fence made of 1200 mm high wooden posts, with hi-tensile backing wires and wooden battens. The base

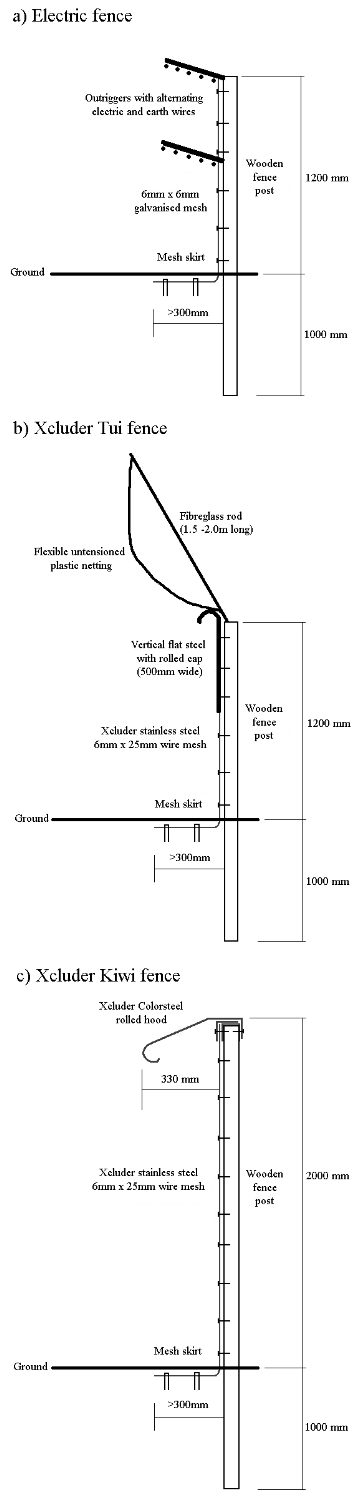

Figure 1. Configuration of the three main fence designs experimentally evaluated for their pest containment efficacy: a) electric fence; b) Xcluder^{TM} "Tui" fence; and c) Xcluder^{TM} "Kiwi" fence.

fence was very similar to a standard 9-wire post and batten livestock fence, commonly used in New Zealand. Attached to the base fence was wire mesh and a wire mesh skirt similar to that used on the electric fence. The wire mesh extended 800 mm up the face of the fence. A 500 mm wide flat vertical sheet of steel (Colorsteel®) was placed on to the top portion of the fence, overlapping the mesh at the bottom and extending to a height of 1,300 mm above the ground. An 80 mm wide half-circle 'cap' facing towards the pests was manufactured into the top of the flat steel sheet. Above the flat steel sheet a 1.5-2.0 m high section of flexible plastic woven horticultural 'bird' netting was suspended in a loosely tensioned fashion on supple fibreglass rods. The fibreglass rods were mounted in the fence so that they leaned slightly toward the pests, creating a sag in the plastic netting. The design of the fence was unique in that the bottom portion was sturdy and rigid, while the top portion was deliberately flexible and able to move freely in the wind or when animals climbed on it. Several small modifications to this design were made during the research process.

The Xcluder™ "Kiwi" fence design was built after our animal behaviour observations had been completed for both the electric fence and the Xcluder™ "Tui" fence, so it was designed to defeat all of the pest escape behaviours we had already observed. The fence consisted of a 2 m high base fence of wooden posts, backing wires and wooden battens. Wire mesh was affixed up the entire length of the base fence and a >300 mm wide mesh skirt facing the pests was pinned to the ground and covered. At the top of the fence a sheet of 600 mm wide steel (Colorsteel®) was folded and rolled to form a 'hood' that was mounted at the top of the fence and extended 330 mm horizontally towards the pests. The steel hood was mounted on custom-built brackets, so that it was sturdy and would not move when animals climbed or jumped on it.

For the experimental evaluation of fence efficacy with Hawaiian and Mauritian species and conditions, the Xcluder™ Kiwi fence was modified slightly. For the Hawaiian research, the wire mesh skirt at the base of the fence was modified to be fixed to lava substrates with a cement-based mix (see Burgett et al. 2007 for details). In Mauritius, the shape and length of the Xcluder fence hood was extended vertically to counter the extra reach of Javan macaque (shape and exact design of modified hood described in Day 2004).

Pest Species and Locations

Sixteen pest species were used during the course of our animal behaviour and fence efficacy experiments. The pest species used, the locations in which the trials were conducted for each species and the number of animals of each species tested are described in Table 1. The number of animals used in the experiments was variable for each species and fence design for three reasons. Firstly, some species were of particular interest because of their perceived better escape ability (e.g., mice [*Mus musculus*], ship rats [*Rattus rattus*], possums [*Pseudocheirus peregrinus*], and cats [*Felis catus*]), so the numbers tested was higher. Secondly, some species were difficult to capture, handle or test in an experimental situation, so we were forced to accept lower numbers of individuals (e.g., stoats [*Mustela erminea*], hares [*Lepus europaeus occidentalis*]). Thirdly, the experiments were conducted on the basis that once satisfied a fence had failed to contain a pest species, research with that fence design was discontinued for all species. Because of the variable animal numbers, the in-situ fence efficacy data (described below) is of greater importance in proving the efficacy of the designs for some species.

The animals used in the fence efficacy and animal behaviour experiments were caught in the wild using live-capture box traps and were transported to the experimental facility and tested within 24 hrs of capture. Animals were provided with food, water and shelter during their time in captivity. At the conclusion of experiments pest animals were humanely euthanized (as it is illegal and considered unethical to release pest animals back into the wild in New Zealand). All animal experiments were conducted with appropriate Animal Ethics Committee approval and permits for each location.

Wire Mesh Experiments

As the aim of this research project was to design fences that were effective for ALL vertebrate pests, the research began by determining the size and aperture of wire mesh required to contain the smallest of the target pests. In New Zealand, mice were the smallest target species and this later proved also to be the case in Hawaii and Mauritius. Therefore, the largest aperture of mesh required to prevent all independent juvenile mice from passing through a pest fence was considered the minimum standard required for construction of a total pest exclusion barrier.

Table 1. Species tested and numbers used for all animal behaviour and fence efficacy experiments, plus species not experimentally tested but present outside in-situ Xcluder™ Tui and Xcluder™ Kiwi fences (see Table 5 for in-situ sites).

Species	**Number tested**	**Locations tested**	**Outside in-situ fences**
House mouse (*Mus musculus*)	220	NZ, H, M	✓
Ship rat/Black rat (*Rattus rattus*)	108	NZ, H, M	✓
Norway rat (*Rattus norvegicus*)	33	NZ	✓
Ferret (*Mustela furo*)	14	NZ	✓
Stoat (*Mustela erminea*)	6	NZ	✓
Hedgehog (*Erinaceus europaeus occidentalis*)	10	NZ	✓
Rabbit (*Oryctolagus cuniculus cuniculus*)	22	NZ	✓
Hare (*Lepus europaeus occidentalis*)	7	NZ, M	✓
Brushtail possum (*Trichosurus vulpecula*)	87	NZ	✓
Cat (*Felis* sp.)	139	NZ	✓
Pig (*Sus scrofa*)	11	NZ, H, M	✓
Indian mongoose (*Herpestes javanicus*)	32	H, M	✓
Mouflon sheep (hybrid) (*Ovis musimon*)	12	H	
Indian house shrew (*Suncus murinus*)	12	M	✓
Javan macaque (*Macaca fascicularis*)	42	M	✓
Dog (*Canis familiaris*)	11	NZ, M	✓
Javan deer (*Cervus timorensis*)			✓
Pacific rat (*Rattus exulans*)			✓
Weasel (*Mustela nivalis vulgaris*)			✓
Goat (*Capra hircus*)			✓
Fallow deer (*Dama dama*)			✓
Red deer (*Cervus elephus*)			✓
White-tailed deer (*Odocoileus virginianus borealis*)			✓
Guttural toad (*Bufo guttularis*)			✓
Tenrec (*Tenrec ecaudatus*)			✓

NZ = New Zealand; H = Hawaii; M = Mauritius.

Wild mice were captured in live traps and housed in social groups in standard pet cages to form a breeding population. Once breeding was regularly producing juveniles, mice of known ages and sizes were placed in an experimental box to test what type and aperture of wire mesh they could pass through. The experimental box consisted of two chambers separated by a section of the wire mesh to be evaluated. Mice were placed on one side of the mesh and food, water and shelter were placed on the other side. The ability of mice to pass through the mesh was recorded for periods of up to 24 hrs. Different sizes and shapes of commercially available wire mesh (ranging from 25 mm aperture down to 4.4 mm aperture) were used to determine the maximum aperture that could be considered mouse proof.

In addition to wire mesh tests conducted specifically with mice, we also evaluated the size of mesh required to contain juveniles of most other species during our fence efficacy experiments.

Fence Efficacy and Animal Behaviour

A series of experimental facilities were constructed at the three locations in which we conducted our fence research (Cambridge, New Zealand; Kona, Hawaii; Mauritius). At each location, we built one or more experimental enclosures. Each enclosure was constructed with one of the pest proof fence designs facing into the enclosure around its perimeter. The enclosures were octagonal in shape and approximately 12 m across their width: enclosures in New Zealand and Mauritius were constructed on open areas of short mown grass, while the Hawaii enclosures were built on an old lava flow. For the smaller species, such as mice, ship rats, Norway rats (*Rattus norvegicus*), and house shrew (*Suncus murinus*), a much smaller enclosure of approximately 4 m^2 was used so that the animals could be physically observed during the experiment. A 2 m high covered observation tower was built beside the enclosures to allow observation and video recording of animal behaviour and fence interaction when pests were placed inside the enclosure in an "escape test".

The escape test was used to determine the efficacy of different fence designs. Individual wild-caught pest animals were placed into one of the enclosures and observed from the observation tower for escape behaviours. Because the animals were wild, all exhibited motivation to escape from the barren enclosures. Observations for each animal focused on the pushing, digging, climbing, jumping and chewing abilities of each species. Video cameras were used to record all escape attempts, so that we could analyse in detail the escape behaviour and method. In addition, we made physical measurements of jumping heights and distances made by each animal.

Pest animals were tested under three different levels of motivation to escape: (1) animals were introduced to the enclosure and left with food, water and shelter to explore and escape without any human presence for up to 3 weeks (low pressure); (2) animals were introduced to the enclosure and were observed from the observation tower for at least the first 3 hours of the escape test (medium pressure); or (3) animals were introduced to the enclosure and the animal handler remained in the enclosure with the pest animal as it tried to escape (high pressure). Using this range of test situations, animals exhibited their full range of behaviour and physical abilities, from planned, calculated and methodical exploration of the enclosures, to vigorous and rapid physical escape attempts using their maximum physical abilities.

In-situ Efficacy of Fences

At the conclusion of our initial experimental research, a number of conservation groups chose to build either Xcluder™ "Tui" or Xcluder™ "Kiwi" fences around high value conservation areas. For all sites fenced with either fence design (and where the sites were already pest free or total pest eradication attempts have been undertaken; see Speedy et al. 2007 this proceedings for a summary of some of the sites), data on the long-term exclusion efficacy of the fences was collected as part of project management. At each of these sites various assemblages of pest species were present immediately outside the fences. These species posed immediate potential for reinvasion if fence designs were not satisfactory and ongoing potential for reinvasion if the integrity of the fences were compromised by human error, fence damage (e.g., tree fall, flooding damage), fence component failure, or malicious activity. Therefore, data collected from the in-situ sites, where pest reinvasion potential is continuous over extended periods, is considered to be the 'ultimate' measure of the long term efficacy of: (1) the exclusion fence designs; (2) all of the associated fence components required to make a pest-proof enclosure in a real site (e.g. vehicle and pedestrian gates, water gates etc); and (3) the ability of each project to manage reinvasion risk at their site.

At the in-situ sites, potential invaders included mixed assemblages of the 16 species tested experimentally, plus at least nine species that have not been experimentally tested for exclusion efficacy (Table 1). Data recorded at each in-situ site included a full description of the fence and it's associated components, proof of the presence of each pest species outside the fence, details and efficacy of eradication attempts inside the fence, details of any potential compromises to the integrity of the pest-proof fence over time, and records of any pest invasions into the fenced area and the outcome of the invasion. The data collected has been used in this paper to summarise the in-situ efficacy for fences at 18 sites.

RESULTS

Wire Mesh Experiments

Using different sizes of commercially available wire mesh, we determined that 100% of juvenile (but independent and mobile) mice were able to pass through welded mesh with a hole size of 10 x 10 mm, and one juvenile mouse passed through 8 x 8 mm aperture mesh (Table 2). The smallest aperture through which any mouse passed was a hole size of 7.1 x 40 mm. Adult mice were larger and therefore were restricted by mesh smaller than 10 x 10 mm, but 71% of adults passed through the 10 x 10 mm mesh (Table 2).

House shrew juveniles were also able to pass through 10 x 10 mm mesh. All other animal species tested were contained by mesh of 13 mm aperture or greater.

Because this research, programme aimed to design effective fences for ALL pest animals, mesh with an aperture of no more than 6 mm in one dimension (to provide a safety margin) was used on each fence design for all subsequent research. On the experimental Xcluder™ "Tui" and Xcluder™ "Kiwi" trial fences, 6 x 25 mm aperture 316 grade stainless steel mesh was used, and no pest animal ever passed through this mesh during our experiments.

Fence Efficacy and Animal Behaviour

Table 3 describes the number of animals of each species tested and the percentage that were contained in the escape test by the three main fence designs. The predominant escape behaviours exhibited by each species and their

Table 2. Summary of escapes made by mice, the smallest pest species tested in experiments, when placed in small cages made of various sizes and types of wire mesh.

Mesh hole size		Adult		Juvenile	
(Length mm x width mm)	**Mesh type**	**N**	**% escape**	**N**	**% escape**
25 x 25	Welded	35	100	24	100
2 x 25	Welded	16	100	15	100
19 mm diamond	Chainlink	23	100	15	100
13 mm hexagon	Welded	23	100	-	-
12 x 12	Welded	38	100	24	100
12 mm diamond	Chainlink	23	74	15	100
10 x 10	Welded	26	71	15	100
8 x 8	Welded	26	0	24	4*
6 x 40	Woven	38	0	33	0
6 x 32	Woven	29	0	24	0
6 x 25	Welded	29	0	24	0
6 x 12	Welded	29	0	24	0
6 x 6	Welded	29	0	17	0
5.3 x 24.3	Welded	68	0	43	0
4.4 x 40	Woven	35	0	26	0

* Smallest mesh hole through which a juvenile mouse passed was 7.1 x 40 mm.

Table 3. Number of pests of each species tested with the three main fence designs and the percentage of each species that were contained by each fence design.

	Electric fence		Xcluder™ Tui		Xcluder™ Kiwi	
Species	**N**	**% contained**	**N**	**% contained**	**N**	**% contained**
Mouse	13	61	30	100	167	100 [1]
Ship rat	5	40	22	100	87	100
Norway rat	6	100	17	100	16	100
Ferret	3	100	3	100	8	100
Stoat	4	25	4	100	2	100
Hedgehog	3	100	4	100	3	100
Rabbit	3	100	15	100	11	100
Hare	2	100	2	100	5	100
Possum	25	52	30	100	42	100
Cat	13	8	45	100	58	100
Pig					11	100
Mongoose					32	100
Mouflon sheep					12	100 [2]
House shrew					12	100
Javan macaque					42	100 [3]
Dog			3	100 [4]	11	100 [4]

[1] For mice tested on lava in Hawaii, the Xcluder™ Kiwi fence skirt had to be modified to be 100% effective (Burgett et al. 2007).
[2] Mouflon sheep (hybrids) were tested by D. Goltz at separate sheep-fence test facility (Burgett et al. 2007).
[3] For Javan macaque, the shape and length of the Xcluder™ Kiwi hood was lengthened.
[4] Dog numbers include both domestic working dogs (NZ) and feral dogs (Mauritius).

associated physical capabilities are summarised in Table 4. The electric fence effectively contained all tested Norway rats, ferrets, hedgehogs, rabbits and hares (although the number of individuals of each species tested was low). Behaviourally, these species attempted to push through the fence at the base or tried to dig under. Animals systematically patrolled the length of the experimental enclosure fences, appearing to search for perceived weak points and trying to push through gaps in the mesh. Pushing was often the first and most common escape behaviour exhibited, especially by non-climbing pest species. However, none of the pests tested were able to push though the mesh or make any significant impacts on the wire mesh to create holes. Pushing behaviour did not result in any escapes for any pests on any of the fence designs.

Norway rats, rabbits, hares and stoats all dug directly at the base of the fence and, on encountering the horizontal mesh skirt below the surface, began digging further out from the fence to a maximum distance of 200 mm. These animals then began digging against the fence in a new position. None of the digging animals chose to start digging more than 250 mm from the fence and none found the leading edge of the mesh or were able to dig under the skirt (even when housed in the enclosures for as long as 3 weeks). None of

Table 4. Summary of behavioural responses and physical abilities of pest species when trying to cross various pest proof fence designs and components.

Species	Push	Dig	Climb	Jump height (mm)	Chew	Mesh hole size to contain (mm)	Contained by electric wire	Learn
Mouse	✓ [1]	✓	✓✓ [2]	400	✓	6	X [3]	✓
Ship rat	✓	✓	✓✓	800	✓	13	X	✓
Norway rat	✓	✓✓	✓	800	✓	13	✓	✓
Ferret	✓	X	✓	X	✓	13+	✓	✓
Stoat	✓	✓✓	✓✓	1,200+	✓	13	X	✓
Hedgehog	✓✓	X	X	X	X	50	✓	✓
Rabbit	✓	✓✓	X	X	✓	50	✓	✓
Hare	✓	✓✓	X	800	✓	50	✓	✓
Possum	✓	X	✓✓	1,200+	✓	50	X	✓
Cat	✓✓	X	✓✓	1,800+	✓	50	X	✓
Pig	✓✓	✓	X	X	✓	100	NT [4]	✓
Mongoose	✓	X	✓✓	X	✓	50	NT	✓
Mouflon sheep	✓✓	X	X	1,800+	X	100	NT	✓
House shrew	✓✓	✓	✓✓	300	✓	10	NT	✓
Javan macaque	✓	X	✓✓	<1,800	X	100	NT	✓
Dog	✓	✓✓	X	1,800+	✓	100	NT	✓

[1] ✓ = exhibits behaviour regularly and competently.
[2] ✓✓ = excels at behaviour and uses very frequently during escape attempts.
[3] X = does not usually exhibit behaviour.
[4] NT = Not tested.

the species contained by the electric fence chose to climb the fence repeatedly, and therefore they did not significantly challenge the electrified outriggers: none of these animals made any attempts to climb around the outside of the outriggers and all appeared to be repelled by the first shock they received when investigating the wire.

The electric fence did not contain mice, ship rats, stoats, brushtail possums or cats, who after trying to push through the fence, or digging at the base, all attempted to escape by climbing and jumping. Mice were able to climb or jump up the wire mesh and 39% of those tested passed between the mesh and the inside electric wire (20 mm gap) without receiving a shock. Those that received a shock were knocked to the ground. Ship rats ran and jumped up the fence mesh and 60% climbed under, through or around the electric wire outriggers. On occasions, they received shocks that knocked them to the ground, but this did not prevent the persistent animals from passing the wires. Stoats ran up the mesh on the fence and through the electric wires extremely quickly: 3 individuals never received shocks from the wires, as they passed over them between pulses (~1 sec apart). The one stoat that received a shock did not subsequently cross the fence. Possums and cats climbed and jumped at the electric fence regularly without being under any pressure to do so. While 52% of possums and 8% of cats were contained by the electric fence, most continued to attempt to cross the fence by climbing and jumping despite receiving multiple shocks. One possum received 42 shocks before finally crossing around the outside of the outriggers. Both possums and cats were able to jump to the top of the top outrigger directly from the ground.

The Xcluder™ "Tui" fence contained all pest animals that were tested against it (Table 3). The mesh and mesh skirt at the base of the fence functioned exactly the same in these experiments as has been described above for the pushing and digging behaviour of animals during the electric fence trials. No pest animals were able to push through the mesh or dig under the skirt.

The flat sheet of smooth steel with a rolled cap at the top prevented all species except cats from climbing up the fence. Animals climbed the mesh to the base of the steel and then reached, scratched and jumped at the steel to try and move forward. The 500 mm wide sheet with cap provided no foot-holds and was too wide for all animals except cats to reach or jump across. One exception to this pattern of behaviour was observed in earlier research. Stoats were able to jump across a 600 mm wide sheet of flat steel from the wire mesh just below the sheet (T. Day, unpublished data). This ability prompted the use of a rolled cap at the top of the sheet that was used on the Xcluder™ "Tui" fence design described here. Positioning the top of the sheet 1,300 mm above the ground meant that cats were the only species able to jump above it directly from the ground (see jumping heights for individual species in Table 4).

The flexible plastic netting suspended on fibreglass rods contained all cats that jumped at and attempted to climb it. The unstable nature of the netting did not allow any cats sufficient grip to climb to the top and over it. For larger cats their body weight caused the netting to collapse toward the ground until the cats hind legs touched the ground. When this occurred all cats let go of the netting. In earlier trials using similar netting at the top of a fence, two large male cats were able to climb up and over a 900 mm high section of the same netting suspended on rods.

The Xcluder™ "Kiwi" fence also contained all pest animals that were experimentally tested against it (Table 3). Again the mesh and mesh skirt functioned in the same manner as we had previously observed for the electric and Xcluder™ "Tui" fences. Pest animals readily climbed to the top of the 2 m high mesh on the Kiwi fence, but no animals were able jump to the top of the fence directly from the ground (Table 4). As there were no gaps bigger than 6 mm anywhere in the fence, no animals were able to squeeze through the fence at any point. The 330 mm wide hood at the top of the Xcluder™ "Kiwi" fence forced climbing and jumping animals to reach or jump outwards and away from the fence in an attempt to move around the sheet. Javan macaque and cats had the longest reach around the hood (the hood was lengthened to 330 wide x 600 mm long for Javan macaque), but both species were unable to grip the smooth surface of the hood and could not pull themselves around to the top of the fence.

Several behavioural characteristics common to most pest species and all fence designs were observed during these experiments. Pest animals focused over 75% of all escape attempts at corners in the fence rather than on straight sections. Animals tended to run along the base of the fence and only attempt to dig, push, climb or jump over the fence when they encountered a change in fence direction. As such, the corners of the fence (especially the inside angles) received much more escape 'pressure' than the straight sections of the fence. Further, in our early research, stoats, possums and cats effectively used tight corners ($<120^o$) to assist them to jump higher or further than we observed on straight sections of fence. For example, on more than one occasion, stoats, possums and cats all crossed 600 mm wide flat sheets of steel in 90^o corners by jumping back and across the corner to the top of the opposing flat sheet.

Sequential analysis of the behaviour of individual animals during the escape test clearly showed evidence of animal learning, using a process of trial and error. Many animals would attempt a method of escape repeatedly until they appeared 'satisfied' they could not escape via that method. They would then modify their escape behaviour and try again until they were either successful or modified their behaviour again. Most animals only stopped trying to escape from the fences when they appeared to have exhausted all potential avenues for escape and had displayed a full range of escape behaviours and physical abilities.

In-situ Efficacy of Fences

Data collected at the in-situ sites demonstrated that Xcluder™ "Tui" and Xcluder™ "Kiwi" fences can effectively exclude all target pest animals in the long term as long as the integrity of the fence has not been compromised (Table 5). Effective pest monitoring regimes inside all fenced sites revealed no evidence of pest animal incursion past either fence type without a specific fence risk event. This data supports the efficacy data collected experimentally. Several new pest species that were not tested experimentally, as well as the suite of pest species that were tested, were confirmed to be present immediately outside one or more of the in-situ or experimental fences (Table 1). None of these species were detected inside any of the fenced sites, except after known reinvasion risk events. No unexplainable pest animal detections (detections without an associated known compromise to the fence) were recorded at any of the in-situ sites.

Pest animal reinvasion events were recorded at nine of the 18 monitored sites (Table 5). After known compromises to fence integrity, mice, ship rats, brushtail possums, stoats, cats or white-tailed deer (*Odocoileus virginianus*)were all found inside pest-proof fenced areas immediately following the compromise. Reasons recorded for the fence integrity to be compromised in-situ included: (1) vehicle or pedestrian gates being left open; (2) human error (platform or vehicle being accidentally left close to the pest fence allowing animals to jump over); (3) erosion damage under the base of the fence; and (4) tree falls crushing the fence and leaving an opening. In two cases (Young Nicks Head and Macraes Flat) the reinvasion led to the re-establishment of mouse populations inside the fence. None of the other invasions resulted in any long-term pest presence inside the fence, so did not compromise the long-term pest-free goals of the sites. Only two sites with fence lengths greater than 1 km had no recorded invasion: Pitt Island (40 ha) and Maungatautari North enclosure (35 ha).

At Mt. Maungatautari, detailed records of every invasion risk event and the response to it has been recorded for the 47 km of Xcluder™ "Kiwi fence. At least 12 significant risk events (1 by vehicle gate open, 1 by water gate jammed open, 10 by tree falls) were recorded over a three year period (T. Day, unpublished data, P. de Monchy, personal communication). These risk events resulted in three recorded invasions: two events each resulting in a rat detection; one event resulting in a mouse detection. The detected invaders were removed in all three cases (as evidenced by animal capture and subsequent cessation of animal tracking). On all three occasions where invasion resulted, there was a significant time delay (between 6 and 24 hrs) between the fence compromise and staff being able to repair the breach. In contrast, when the remote surveillance system at Maungatautari was used, it enabled response in less than 3 hrs and no animal invasion was detected.

DISCUSSION

This research has clearly demonstrated experimentally and in-situ that completely effective multi-species exclusion fence designs are possible. In an experimental situation, two of the fence designs we evaluated, the Xcluder™ "Tui" fence and the Xcluder™ "Kiwi" fence, excluded every individual from the 16 species we tested. In addition, nine further species found at the in-situ sites were excluded by one or other of the fence designs. While the number of individual animals tested experimentally was low for some species, the in-situ data provides excellent evidence of the long-term efficacy of the fence designs.

Mice, as the smallest of pests studied and encountered in our research, dictated the maximum mesh aperture and gap that could be allowed on any part of the fences if complete pest exclusion was to be achieved: to provide a small margin for error, there should be no gap on a fence bigger than 6 mm if mouse exclusion is desired. To achieve this tolerance in the field, precise construction techniques and exceptional product quality are required. On the in-situ fences, 6 x 25 mm aperture stainless steel welded wire mesh was used. This mesh provided the strength, consistent aperture and tolerance required to achieve success in the field. At Karori Wildlife Sanctuary, mice reinvaded because apertures on the woven mesh used did not consistently remain less than 6 mm (Karori Wildlife Sanctuary Inc. 2001).

As has been found by previous researchers (e.g., Minsky 1980, McKillop and Sibly 1988, McKillop et al. 1993), the electric fence design tested in this research effectively contained species with poor

Table 5. Detail of in-situ sites fenced with Xcluder™ "Tui" or Xcluder™ "Kiwi fence designs, the number pest species present outside the fence, evidence of pest exclusion efficacy and reinvasion events.

Project (ha)	Fence design	Fence length (km)	Fence age (yrs)	Species outside/ excluded	Fence reinvasion events (reasons for reinvasion) and outcomes
Warrenheip (16)	Tui	2.3	8	12 / 12	Mice, rat, possum (**gate open/erosion damage**) all eradicated
Pitt Island (40)	Tui	3.0	7	2 / 2	No invasion
Rapanui Point (1)	Kiwi	0.6	4	7 / 7	No invasion
Lord Howe Island (<1)	Tui	0.2	4	2 / 2	No invasion
Mt Bruce (<1)	Kiwi	0.22	4	11 / 11	No invasion
Kiwi Encounter (<1)	Kiwi	0.2	3	12 / 12	No invasion
Mauritius (<1)	Kiwi	0.05	3	12 / 12	No invasion
Riccarton Bush (7)	Kiwi	1.1	3	8 / 8	Cat (**human error**) eradicated
Maungatautari north exclosure (35)	Kiwi	2.8	3	11 / 11	No invasion
Maungatautari south exclosure (65)	Kiwi	3.5	3	11 / 11	Rat (**tree fall**) eradicated
Tawharanui (660)	Kiwi	2.8	3	11 / 8	Mice, rat, stoat (**Open fence ends at sea**) Rats, stoat eradicated
Young Nicks Head (30)	Kiwi	0.6	2	7 / 6	Mice (**erosion damage**) Mice re-established
Bushy Park (98)	Kiwi	4.7	2	11 / 11	Rat (**gate open**) eradicated
Godley Head (<1)	Kiwi	0.05	2	2 / 2	No invasion
Macrae's Flat (22)	Kiwi	1.7	2	11 / 7	Mice, stoat, possum (**gate open, possible erosion**) Stoat, possum eradicated Mice re-established
Motu (<1)	Kiwi	0.4	1	11/ 11	No invasion
Horseshoe Bay (160)	Kiwi	2.2	1	7 / 5	Rats, White-tailed deer (**Open fence ends at sea**) [1]
Mt Maungatautari (3,300)	Kiwi	39	6 mon	15 / 15	Mouse (**tree fall**) eradicated

[1] Fence ends are being modified in Spring 2007 to exclude rodent passage.

climbing abilities such as hedgehogs, ferrets, rabbits and hares. It did not effectively contain pest species with good climbing and jumping abilities. Others have also found the effectiveness of electric fences to be inconsistent for agile species such as possums (Clapperton and Matthews 1996, Day and Flight 2002), stoats (Day and MacGibbon 2002), cats (Long and Robley 2004) and fox (Poole and McKillop 2002). Electric fences are essentially psychological barriers that do not pose challenges beyond the physical ability of many species. As such, they can be crossed at will by any animal with sufficient motivation to so do, as demonstrated here by possums and cats receiving multiple shocks before escaping.

The mesh skirt at the base of the fence was highly effective at preventing animals from pushing or digging under the fence. Despite being more than physically capable of digging under, the animals did not perceive where the outer edge of the skirt began and preferentially focused digging attention at the base of the fence, on top of the skirt. Even after being housed in the experimental enclosures for up to three weeks, rabbits did not dig under the skirt. Our early data (unpublished), and that of others (e.g. Karori Wildlife Sanctuary, Inc. 1998) found that species such as rabbits could dig under up to 1 m of vertically buried mesh relatively easily. We also found that rats could dig under a mesh skirt if a log or similar object was placed on top of the skirt at its leading edge: they used the solid edge as a point to dig against and, once accidentally under the edge of the skirt, easily dug out. The use of a mesh skirt has become a standard feature of exclusion fences around the world after being proven to be the most successful method for rabbit fences in Australia over many years (Long and Robley 2004). However, mesh skirts do not always eliminate the problem of hole formation under a fence (e.g. Marks 1998, Fleming et al. 2001), so ongoing fence line maintenance is essential for continued fence integrity.

Exclusion of climbing and jumping animals in these experiments was achieved by the use of either a flat vertical sheet of steel, flexible plastic netting mounted on fibreglass rods (both on the Xcluder™ "Tui" design), or a smooth fixed steel hood placed at the top of the fence and protruding beyond the reach of the pest animals (Xcluder™ "Kiwi" fence). In all cases, these structures exceeded the physical abilities of the target pests. The 500 mm wide flat sheet of steel was too wide for mice, rats, stoats and possums to climb or jump across and when the top was placed at 1300 mm above the ground, it was too high for them to jump to the top. Similar physical limitations for these pest species have been observed by other researchers designing barrier fences (Karori Wildlife Sanctuary, Inc. 1998). Cats were extremely wary of climbing the unstable surface provided by the untensioned plastic netting (Day and MacGibbon 2002), preferring to let go rather than climb the netting once it began to collapse on them. Floppy wire mesh fences have been tried for cat exclusion in Australia (Coman and McCutchan 1994), but have had variable success, perhaps because of inconsistencies in mesh tensioning (Long and Robley 2004). When faced with the Xcluder™ Kiwi fence, cats jumped as high as 1800 mm directly from the ground. However, the hood at the top of the fence prevented animals from reaching or jumping to the top of the fence. A similar hood design was used successfully at Karori Wildlife Sanctuary to exclude pests (Karori Wildlife Sanctuary, Inc. 1998).

The behavioural patterns exhibited by pest animals trying to escape through, under or over fences in this research was similar to that observed by others. Most animals first attempted to escape by pushing through or under the fence (Lund and De Silva 1994, Long and Robley 2004). Therefore, the lower sections of the fence in particular must be meticulously constructed and maintained. The escape pressure on the fence was greatest at corners (especially inside angles), as animals walked or ran along the fence-line until they reached a corner and attempted to cross (Thompson 1979, Long and Robley 2004). Some animals in our trials and those of others appear to learn through trial and error to negotiate fences (Patterson 1977, Clapperton and Matthews 1996) and there was evidence of individuals learning to breach fences by watching successful breaches by conspecifics (Bird 1994, McKillop and Wilson 1999). In our research, Javan macaque that learned to cross substandard fence designs, subsequently assisted other members of the troop to cross the fence (Day 2004). Therefore, where learning and teaching are involved, the true effectiveness of a fence may not become apparent for a period of time after its construction. This has implications for the length of time over which experimental fence trials need to be conducted to ensure that animals that are initially deterred by a fence do not later learn to cross it (Long and Robley 2004). The in-situ efficacy data collected in this research provides good evidence that the fence designs tested were not overcome by animal learning.

Data from the in-situ fence sites clearly demonstrated two things. Firstly, the Xcluder™ "Tui" and Xcluder™ "Kiwi" fence designs are highly effective multispecies pest exclusion barriers. If constructed to exacting standards, the designs can be implemented in practice, withstand ongoing pressure from a suite of pest animals. Additional pest-proof components required to allow access while securing fence sites (e.g. double-doored pedestrian and vehicle gates, waterway gates for streams, etc.) were used at all in-situ sites and did not compromise the efficacy or integrity of the fenced areas unless accidentally left open.

Secondly, evidence from the in-situ sites highlighted that reinvasion of pests into areas protected by fences is a significant risk. All but two of the larger in-situ fence projects we have collected data from have had at least one invasion event since completion of their fence and eradication. Reinvasion risk events came from several sources, including human error, gates being left open, erosion damage and tree falls. The data suggests that reinvasion risk may be best considered as a matter of 'when', not 'if' (Day 2006), and proactive plans for managing reinvasion should be an integral part of any exclusion fencing project. These plans may include technology that minimises risk (e.g. the use of double-doored pedestrian and vehicle gates, gate alarms to alert managers to risk and remote surveillance systems to provide 'live' monitoring of fence integrity at all times) and staffing and infrastructure that enables immediate response. While most invasion events did not lead to re-establishment of pest populations, complete prevention of invasion would always be much better than curing an invasion problem after the fact.

When effective invasion risk management systems are implemented properly, reinvasion appears to be avoidable and fenced sanctuaries can be kept pest-free. Remote surveillance technology has been developed to immediately alert caretakers of risk events, such as tree falls, gates open, etc. At Mt. Maungatautari, multiple reinvasion risk events have occurred along the 47 km perimeter fence over several years, with none resulting in pest reinvasion if caretakers have responded to the risk immediately (within 3 hrs). Three pest invasion events were recorded at Maungatautari when immediate response plans were unable to be implemented for over 6 hrs. Ongoing research is being conducted at several exclusion fenced sites to further enhance the ability of projects to prevent invasion (see Speedy et al. 2007, this volume for details). This research includes measuring the risk of reinvasion by pest animals, understanding the behaviour of reinvaders, and designing the best methods for reinvasion prevention and (where required) cure.

The successful eradication of pest animals from within fenced areas (Speedy et al. 2007, this volume) and the fact that the areas have been kept pest-free for increasingly longer time periods has enabled exciting biological changes to begin. Research is underway on several fronts to measure these changes as they occur. One of the most significant early conservation gains from fence projects in New Zealand has been their use as pest-free havens for threatened species. Reintroduction of species such as North Island brown kiwi (*Apteryx australis mantelli*), black robin (*Petroica traversi*), takahe (*Notornis mantelli*) and tuatara (*Sphenodon punctatus*) to places from which they were long ago displaced by pest animals has occurred at several of the in-situ sites. The upsurge in exclusion fence projects in all major regions of New Zealand has led to significant and meaningful community engagement and education, with many projects being proposed, funded and driven by local communities, rather than by pest or conservation managers.

Further research with exclusion fencing is advancing on a number of fronts. The designs described here continue to be tested with additional pest species, such as fox and snakes. Surveillance technology continues to develop and fencing materials, methods and construction techniques are being improved continuously with experience. While it is still too early in the evolution of complete pest exclusion and eradication projects in New Zealand to fully quantify their true costs and benefits, the signs are encouraging. It appears that significant biological, social and economic gains are possible from these ambitious projects when appropriate exclusion technology, monitoring systems and expertise are used.

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