Electronic Appendix for Duncan & Forsyth "Island latitude and human disturbance explain the persistence of mammal invaders in the New Zealand archipelago"

Outline of the methods used to model persistence times

Here we outline the methods used to model persistence times given interval, right and uncensored observations, and to incorporate the persistence time distributions predicted by stochastic population growth theory.

Definitions

T is a continuous random variable ≥0 representing the persistence time (time to natural extinction) of populations introduced to islands. T has a cumulative distribution function (cdf):

$$F(t) = P(T \le t) = \int_0^t f(x)dx$$

where $f(t)$ is the probability density function (pdf):

$$f(t) = \frac{dF(t)}{dt} = \lim_{\Delta t \to 0} \frac{P(t \le T < t + \Delta t)}{\Delta t}$$

The probability that a population survives to time t is the survivor function:

$$S(t) = P(T > t) = 1 - F(t) = \int_t^\infty f(x)dx$$

The hazard function specifies the instantaneous rate of failure at $T = t$ given that a population survived to time t:

$$h(t) = \lim_{\Delta t \to 0} \frac{P(t \le T < t + \Delta t \mid T \ge t)}{\Delta t} = \frac{f(t)}{S(t)}$$

Likelihood function for censored persistence time data

There are three types of censoring in our data:

1. Uncensored: the number of years the population persisted until extinction is known; $T = t$

The contribution to the likelihood for an observation with this type of censoring is:

$$L_{ob} = f(t)$$

2. Right censored: extinction is not observed but occurs after time t; $T > t$

The contribution to the likelihood for an observation with this type of censoring is:

$$L_{rt} = P(T > t) = S(t)$$

3. Interval censored: extinction occurs in the interval $(L,R]$; $L < T \leq R$

The contribution to the likelihood for an observation with this type of censoring is:

$$L_{in} = P(L < T \leq R) = S(L) - S(R)$$

Let:

ob: indicate the set of introduced populations that have uncensored (observed) persistence times

rt: indicate the set of introduced populations that have right censored persistence times

in: indicate the set of introduced populations that have interval censored persistence times

Then the log-likelihood for this sample is:

$$L = \sum_{i \in ob} \ln[f(t_i)] + \sum_{i \in rt} \ln[S(t_i)] + \sum_{i \in in} \ln[S(L_i) - S(R_i)]$$

Distribution of persistence times under environmental stochasticity

The inverse Gaussian distribution describes the distribution of persistence times for populations with density independent growth, unrestricted size, and where the risk of extinction is due to environmental stochasticity (Lande & Orzack 1988; Dennis *et al.* 1991).

The inverse Gaussian pdf is given by:

$$f(t) = \frac{n_0}{\sqrt{2\pi\sigma_e{}^2 t^3}} \exp\left[-\frac{(n_0 + \mu t)^2}{2\sigma_e{}^2 t} \right]$$

where:

t is time

n_0 is the initial starting value, which is the natural logarithm of initial population size (which can be adjusted for the initial age structure)

μ is the infinitesimal mean parameter, which is related to the population growth rate, r, such that $r = \mu + (\sigma_e^2/2)$

σ_e^2 is the infinitesimal variance of the process due to environmental stochasticity

The survival function has the form:

$$S(t) = \Phi\left[\frac{\mu t + n_0}{\sqrt{\sigma_e^2 t}}\right] - \exp\left(\frac{-2n_0\mu}{\sigma_e^2}\right)\Phi\left[\frac{\mu t - n_0}{\sqrt{\sigma_e^2 t}}\right]$$

where:

Φ is the standard normal cumulative distribution function (cdf)

Distribution of persistence times under demographic stochasticity

For populations with density independent growth, unrestricted size, and where the risk of extinction is due to demographic stochasticity, the survival function is given by (Engen *et al.* 2005):

$$S(t) = 1 - \exp\left[-\frac{2n_0 r}{\sigma_d^2(1-e^{-rt})}\right]$$

and the resulting pdf has the form:

$$f(t) = \exp\left[-\frac{2n_0 r}{\sigma_d^2(1-e^{-rt})}\right]\left[\frac{2n_0 r^2 e^{-rt}}{\sigma_d^2(1-e^{-rt})^2}\right]$$

where:

σ_d^2 is the infinitesimal variance of the process due to demographic stochasticity

Other distributions

The pdf and survival functions for the other distributions we fitted to the data (exponential, lognormal and Weibull) are presented in standard survival analysis texts (e.g., Tableman & Kim 2004)

Model estimation

We inserted the appropriate pdf and survival functions into the log-likelihood function and maximised this for our data using the built-in numerical optimization routines in the software package R version 2.0.1 (The R Development Core Team 2004). The functions for the distribution of persistence times assuming environmental and demographic stochasticity have three unknown parameters, one of which is initial population size. We lacked data on initial population size for most introductions in our dataset. We therefore set this initial value, n_0, to a constant value of 1 for all introductions. This choice of constant was arbitrary and makes no difference to our results: for other values the associated mean and variance parameters are scaled accordingly.

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Data

The following table lists the data and reference sources used in this study.

Table explanations:

Farm: 0 = never farmed

1 = farmed

Outcome: x = died out without direct human intervention, e = eradicated by humans, p = present at last record

T1 & T2: For eradicated and present species, T1 is the persistence time of the population (number of years following introduction until either eradication or the last recorded visit confirming an extant population). Species recorded as being introduced by settlers and that were still present on islands following a recent visit are given a minimum persistence time of 100 years. For extinct species, T1 and T2 are the upper and lower bounds defining the minimum and maximum number of years that a species persisted on an island until the population died out. If T2 is blank, then T1 is the known persistence time of the population until it died out. - indicates introductions where the persistence time of the population could not be determined.

Island	Island Group	Area (ha)	Lat. (deg)	Farm	Species	Outcome	T1 (years)	T2 (years)	Reference
Adams		9896	50.92	0	Goat	x	1	40	1-4
					Sheep	x	1	5	2, 5, 6
Allports		16	41.24	0	Possum	e	10		7, 8
					Rabbit	x	-		9
Anchor		1525	45.76	0	Cat	x	1	208	10, 11
					Pig	x	1	200	10
Antipodes	Antipodes	2025	49.67	0	Goat	x	1	15	3, 5, 12, 13
					Sheep	x	1	15	5, 6, 12, 13
Aorangi	Poor Knights	110	35.48	0	Pig	e	116		7, 14, 15
Arapawa		7785	41.23	1	Cat	p	100		11
					Goat	p	214		3, 16
					Pig	p	161		14, 17
					Rabbit	p	1		9
					Sheep	p	100		6
Auckland	Auckland	45675	50.75	0	Cat	p	184		2, 11, 12
					Goat	e	127		2, 3, 5, 7, 12, 16, 18
					Goat	x	1	38	5
					Pig	p	183		2, 5, 14, 18

					Possum	x	1	72	2, 19, 20
					Rabbit	x	1	9	5
					Sheep	x	1	70	2, 5, 12
Blumine		377	41.17	0	Pig	e	32		7, 14
Bravo		20	46.97	0	Possum	p	38		19, 20
Browns		58	36.83	0	Rabbit	p	20		7, 9
Burgess	Mokohinau	56	35.93	0	Goat	e	73		3, 7, 16, 21
Campbell	Campbell	11216	52.50	1	Cat	x	74	84	11, 12, 22
					Goat	x	15	73	3, 5, 12, 13
					Pig	x	1	18	5, 14, 23
					Rabbit	x	1	78	9
					Sheep	e	94		5-7, 12, 13, 24
					Sheep	x	1	6	5
Chatham	Chatham	90650	43.80	1	Cat	p	150		11
					Pig	p	140		14, 25, 26
					Possum	p	79		19
					Sheep	p	89		6, 25, 26
Codfish		1396	46.78	0	Possum	e	97		7, 8, 19, 20
Cuvier		170	36.44	1	Cat	e	75		7, 11, 27-29
					Goat	e	71		3, 7, 16, 27-29
D'Urville		16782	40.83	1	Cat	p	100		11
					Pig	p	100		14, 17
					Possum	x	-		19
					Rabbit	p	16		9
East		13	37.67	0	Goat	e	54		3, 7, 16, 30
Enderby	Auckland	710	50.51	0	Goat	x	25		31
					Pig	x	15		31
					Pig	x	20		31
					Rabbit	e	128		31
					Rabbit	x	5		31
					Sheep	x	5		31
					Sheep	x	5		31
Ernest		71	46.94	0	Goat	e	32		3, 7, 16
Ewing	Auckland	54	50.53	0	Goat	x	9	45	1-3, 5
					Goat	x	1	8	5
Figure-of-eight	Auckland	5	50.78	0	Goat	x	1	85	1, 2
					Sheep	x	1	85	1, 2
Forsyth		775	40.96	1	Cat	p	100		11
					Goat	p	-		3, 16
Friday	Auckland	1.5	50.50	0	Rabbit	e	5		2, 9
Great Barrier	Great Barrier	27761	36.09	1	Cat	p	100		11, 32
					Goat	p	17		3, 16, 32
					Pig	p	9		14, 32
					Rabbit	p	11		9, 32
Great King	Three Kings	408	34.10	0	Goat	e	57		3, 7, 16
Great Mercury	Mercury	1860	36.61	1	Cat	p	100		11
					Goat	p	83		3, 15, 33
Haulashore		6	41.27	0	Rabbit	p	31		9
Herekopare		28	46.87	0	Cat	e	46		7, 11, 34, 35
					Goat	e	3		7, 16
Inner Chetwode	Chetwode	242	40.89	0	Pig	e	26		7, 14, 36
					Pig	e	11		7, 14, 36
					Rabbit	x	1	50	9, 36
Kaikoura		535	36.18	1	Goat	p	-		16, 37
					Pig	p	5		
Kapiti		1970	40.85	1	Cat	e	29		7, 11

					Goat	e	98		3, 7, 16
					Possum	e	94		7, 8, 19, 20
					Sheep	e	73		6, 7
Kawau		2050	36.42	1	Cat	p	100		11
					Possum	p	121		19, 20
Korapuki	Mercury	18	36.66	0	Rabbit	e	88		7, 9
Leper	Mokopuna	1	41.25	0	Rabbit	e	4		7, 9
Little Barrier		3083	36.20	0	Cat	e	113		7, 11, 38
Macauley	Kermadecs	306	30.23	0	Goat	e	134		3, 7, 16
					Pig	x	-		14
Macquarie		12785	54.5	0	Cat	p	170		39
					Rabbit	p	112		39
					Sheep	x	7		39, 40
					Sheep	x	1	22	39, 41
					Goat	e	12		39, 40
					Goat	e	9		39, 41
Mahurangi		23	36.55	0	Goat	e	15		3, 42
Mangere	Chatham	113	44.30	1	Cat	e	57		9, 11, 43
					Goat	x	-		3, 44
					Rabbit	x	1	100	7, 9
					Sheep	e	68		6, 7
Masked	Auckland	5	50.75	0	Cat	p	-		2, 11
Maud		309	41.03	1	Goat	e	11		3, 7, 16
					Rabbit	e	79		9
Mayor		1277	37.70	0	Cat	p	64		11
					Pig	p	45		7, 14, 45
Mokinui	Moggy	86	47.15	0	Cat	p	72		34, 46, 47
Monumental	Auckland	4	50.83	0	Goat	x	1	86	1, 2
Motuara		59	41.09	1	Pig	e	111		7, 48
					Rabbit	x	1	202	9
Motuihe		195	36.82	1	Cat	p	9		7
					Cat	e	78		11
					Rabbit	x	1	26	9, 48
					Rabbit	p	70		9
Motukaha		0.4	36.77	0	Rabbit	x	-		49
Motukahaua		22	36.66	0	Rabbit	p	21		9, 50, 51
Motukawanui	Cavalli	380	35.00	1	Pig	x	-		14
Motumaire		5	35.28	0	Rabbit	p	-		9
Motunau		3.5	43.06	0	Rabbit	e	112		7, 9, 52
Motuoruhi		57	36.74	0	Goat	e	-		3, 51
					Pig	e	-		14, 51
Moturoa		157	35.22	0	Rabbit	p	-		9
Moturua		24	36.70	0	Rabbit	p	7		9, 50, 51
Moturua		162	35.23	0	Cat	p	-		53
					Pig	x	1	123	54
Motutapere		50	36.78	0	Possum	e	95		8
Motutapu		1560	36.76	1	Cat	p	-		11
					Possum	e	128		8, 19
					Rabbit	p	109		9
Motuwi		22	36.68	0	Rabbit	p	-		9, 50
Native		60	46.92	0	Goat	x	1	102	37
					Pig	x	-		14
					Possum	p	28		19, 20
					Rabbit	e	8		7, 9
Ngawhiti		1.5	40.81	0	Rabbit	e	5		9

Northern Junction	Junction	1	36.24	0	Rabbit	p	-		55
Nukutaunga	Cavalli	13	34.98	0	Goat	e	-		7, 16, 56
Ocean	Auckland	8	50.53	0	Goat	e	77		1, 2, 5, 7, 16
					Sheep	e	4		2, 12
Ohinau	Ohena	43	36.73	0	Rabbit	p	92		9
Okokewa	Great Barrier	7.5	36.14	0	Rabbit	p	-		9
Otata	Noises	15	38.70	0	Rabbit	e	15		7, 9, 15, 57
Outer Chetwode	Chetwode	81	40.89	1	Pig	e	9		7
					Pig	e	7		7
Pararaki	Sugarloaf	0.8	39.05	0	Rabbit	x	-		9, 58, 59
Penguin	Slipper	10	37.07	0	Rabbit	p	9		9, 15
Pickersgill		103	41.17	0	Pig	e	-		17
Pitt	Chatham	6203	44.30	1	Cat	p	122		11, 25
					Pig	p	100		14, 60
					Sheep	p	100		6
Ponui		1795	36.86	1	Cat	p	129		11, 61
					Pig	e	66		62
					Rabbit	x	-		
Pourewa		42	38.39	0	Goat	e	43		37
Puangiangi	Rangitoto	69	40.77	0	Rabbit	p	35		9
Putauhina		141	47.20	0	Cat	x	-		11, 46, 47
Quail		88	43.63	1	Rabbit	p	137		7, 9
Rakitu		328	36.13	1	Cat	x	-		11, 63
					Goat	p	-		16
					Pig	e	10		14
Rangiahua		65	36.23	1	Rabbit	p	-		55
Rangipukea		34	36.83	0	Possum	p	70		19
Rangitoto		2321	36.81	0	Cat	p	-		11
					Possum	e	129		8, 19, 20
Raoul	Kermadecs	2938	29.25	1	Cat	p	154		7, 11, 64
					Goat	e	148		3, 7, 16, 64
					Pig	e	-		14
Rose	Auckland	75	50.50	0	Rabbit	e	147		2, 5, 9, 31
					Sheep	x	12		2, 31
Ruapuke		1525	46.77	0	Cat	p	100		11
					Pig	p	110		14, 60
					Possum	p	75		19, 20
Shoe	Auckland	0.5	50.53	0	Pig	x	-		2
Shoe		52	37.00	0	Rabbit	p	9		9, 15, 65
Snares	Snares	280	48.10	0	Goat	x	1	12	5, 13, 66, 67
					Goat	x	1	9	5, 13, 66, 67
South East	Chatham	219	44.35	1	Goat	e	16		3, 7, 16
					Sheep	e	46		6, 7
southern Junction	Junction	7.5	36.24	0	Rabbit	x	1	20	9, 55
Stanley	Mercury	100	36.63	0	Rabbit	e	91		9, 68
Steep-to		61	46.10	0	Goat	x	-		3
Stephens		150	40.67	1	Cat	e	33		7, 11
Stewart		174600	47.00	1	Cat	p	100		11
					Pig	e	48		7, 14, 60
					Possum	p	100		19, 20
					Rabbit	e	8		7, 9
					Rabbit	x	1	80	9
Tahoramaurea		0.8	40.89	0	Rabbit	x	1	77	9
Taieri		6.9	46.05	0	Rabbit	p	-		9
Takangaroa	Mayne	6	36.27	0	Rabbit	e	20		7, 9

Tarakaipa		35	41.07	0	Possum	e	31		8, 19, 20
Tinui		91	40.78	0	Pig	p	10		
Tiritiri Matangi		196	36.60	1	Cat	e	10		11
					Rabbit	e	14	28	7, 9, 69
Tommy		15	46.96	0	Possum	x	1	28	19, 20
Tuputupungahau		13	34.79	0	Pig	e	16		7
Waiheke		9333	36.77	1	Cat	p	100		11
					Rabbit	p	72		9
Whale		173	37.87	0	Cat	x	1	31	11
					Goat	e	87		3, 7, 16, 70, 71
					Rabbit	e	20		7, 9, 70-72
Whanganui		282	36.78	1	Possum	e	95		8, 19, 20

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