Supplementary information

Dog demographics

In April and May 2015, we conducted a dog population survey in two districts representing urban and rural highland districts namely Bishoftu and Lemuna-bilbilo districts respectively. Following recommended guidelines for surveying roaming dog populations by the World Society for Animal Protection (1) we systematically selected 13 non-contagious wards bounded by roads in Bishoftu town district and 12 non-contagious wards in Lemuna-bilbilo district. We then adopted a sight-mark-resight approach for studying population abundance and modified it to mark-resight as previously applied by Hiby and colleagues (2). The dog counting (resight) was done for both restricted and freely roaming dogs twice after marking. For estimation of dog density (i.e. carrying capacity/km^2), the logit-normal mixed effects models were carried out in the freely available Program MARK, version 6.2, developed by Gary White, Colorado State University (http://www.phidot.org/software/mark/docs/book/) (3). However, during the household survey, we were not able to collect accurate information on average litter size (l), and frequency (/) and pup survival (s) estimates. Due to the potential similarities of agro-ecologies of Tanzania and Ethiopia, we adopted these missing parameters published from a published Tanzania study. The per capita birth rate (b) was assumed to be the product of the sex ratio (h), the average litter size (l), and frequency (f) and pup survival (s) (b =hlfs) (4). However, the sex ratio was obtained used from a household survey conducted in each district (details of the survey results will be published separately).

Human rabies exposure data collection and contact tracing

Economic model

Cost estimation for dog vaccination campaigns

The cost of rabies control by dog mass vaccination campaign was estimated by modifying an economic model developed by (5). Accordingly, the costs of mass canine vaccination (CMCV) include cost of the vaccine (C_{va}), cost of consumables (needle and syringe, ice bar, disinfectant and swab, certificate and collar) (C_{co}), cost of temporary vaccinators and supervisors (perdium and transportation) (C_{vs}), cost of training vaccinators and costs of information/advertising the campaign (C_{ti}), capital costs (refrigerator, muzzle and cool bags) (C_{cc}). The total cost of mass dog vaccination given by Equation 1.

$$CMCV = Cva + Cco + Cvs + Cti + Ccc \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Equation 1$$

To estimate the total cost campaign under each vaccination campaign strategy, the cost of vaccines and consumables which were estimated per vaccinated dog and multiplied by the number of dogs to be vaccinated under each vaccination coverage/strategy as predicted by the transmission dynamics model simulation. Costs of vaccinators and supervisors were estimated for the number of days required to vaccinate the required number of dogs under each strategy. While the cost of training vaccinators and information/advertising the campaign and capital costs were assumed to be the same irrespective of the vaccination coverage strategy. The vaccination campaign is assumed to be at a village level central point in urban (Bishoftu district) and door-to-door in rural (Lemuna-bilbilo district).

Cost of the vaccine

Cost of the vaccine, C_{va} depends on the price of the vaccine per dose (p_{va}), costs of transportation of the vaccine from manufacturer to each village (t_{va}), and the number of dogs to be vaccinated (n_{dv}) under each strategy (Equation 2). The rabies vaccine supposed to be sourced from the national veterinary institute in Ethiopia is assured to confer protection for at least one year (personal communication with

Dr. Berecha Bayissa, Rabies vaccine production department head at National Veterinary Institute, Bishoftu, Ethiopia).

$$Cva = (pva + tva)xndv \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. \ldots\ldots\ldots Equation 2$$

Cost of consumables

Cost of consumables, C_{co} depends on the price of syringes and needles (P_{sn}), ice bars (P_{ib}) required per vaccinated dog per day, disinfectant and swabs (P_{ds}), the price of a collar (P_{cl})and price of a certificate (P_{cr}) (Equation 3). A collar is assumed to help to distinguish between a vaccinated and unvaccinated dog is applied at vaccination spot and hoped to be durable at least until the vaccination campaign is over.

$$Cco = (Psn + (P\, ib/n\, capv) + Pds + Pcl + Pcr)xnvd \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. \ldots\ldots\ldots Equation 3$$

Where n_{capv} is the number of dogs to be vaccinated by one vaccinator team per day. The vaccination of dogs was assumed to be administered by a team of temporary vaccinators under a close supervision of a veterinarian. A recent central point vaccination campaign in Malawi recorded that a team of vaccinators were able to vaccinate, at most, 150 owned dogs daily (6), suggesting that the four-person vaccination teams might be able to vaccinate as many as 75 dogs daily in a rural area and 150 in an urban area.

Costs of vaccinators and supervisors

Costs of vaccinator, C_{vs} consist of the cost for temporary vaccinators (C_{tv}) and cost for supervisor of the vaccinators C_{sv} (Equation 4).

$$Cvs = Ctv + Csv \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Equation 4$$

Where, C_{tv} were calculated per day as the number of vaccination days required to vaccinate the dogs estimated under each vaccination strategy (n_{vdays}) multiplied by number of vaccination villages or team (n_{vv}), the daily rate (perdium) for temporary vaccinators in the team (P_{tv}), number of persons per vaccination team (v_t) and cost of fuel for temporary vaccinator team per day (f_{tv}) Equation 5.

$$Ctv = nvdays * (Ptv * vt + ftv) * nvv \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Equation 5$$

Cost for supervisor, C_{sv} was calculated based on the number of vaccination days (n_{vdays}), the perdium for supervisor (P_{sp}) and fuel cost for supervisor per day (f_{sp}) (Equation 6).

$$Csv = nvdays * (Psp + fsp) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Equation 6$$

Operationally, for the rural district, we assumed a vaccination campaign with coverage higher than 50% would require extra ‘’search days’’ incurring extra costs for vaccinators and supervisors and we considered 1, 2, 3, and 4 extra days for coverage 60%, 70%, 80%, and 90% respectively. In addition, when vaccination coverage is lower and fewer dogs are vaccinated (i.e 10%, 20%, 30%, 40%), because of the large size of each village (on average 43 km2 i.e. 27 villages in 1184 km2) vaccinators and supervisors would not cover in short period of time although there are fewer dogs to be vaccinated. Thus we assumed it requires an additional 4, 3, 2 and 1 extra days for coverage 10%, 20%, 30%, and

40% respectively. We also assumed higher transportation cost would be required for lower vaccination coverages as the vaccination team will stay a shorter time in one place and move to other neighborhood to meet spatial homogeneity assumption for vaccinated dogs. But in higher coverages beyond 50% vaccinators relatively stay longer in one neighborhood in which we did not consider the correction factor. So we assumed transportation cost multiplied by 4 for each vaccination coverages of 10% to 40% with an increment of 10%.

The number of vaccination days (n_{vdays}) was estimated assuming a team will be working on each village. Thus, the number of vaccination days equals to the total number of dogs to be vaccinated (n_{vd}) under each vaccination strategy divided by the number of dogs vaccinated each day across a number of villages (nv) (Equation 7).The number of vaccination days (n_{vdays}) for supervisors was extended by 50% for each coverage as they would complete documentation and reports following campaigns and the same additional transportation cost was also applied in both districts.

$$nvdays = n\,vd/(ncapv * nv) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Equation 7$$

Costs of training vaccinators and information/advertising the campaign (C_{ti})

Costs of training vaccinators and costs of information/advertising the campaign (C_{ti}) consist of the costs of meeting and training temporary vaccinators and costs of information campaign through printing and distribution of the leaflets and posters and the development and broadcast of the radio and television advertisements. We assumed a lump sum of 2000 Ethiopian Birr (ETB) assuming 1000 ETB (72 USD) for training vaccinators and 1000 ETB (72 USD) for information/advertising the campaign per village.

Capital costs

Capital costs, C_{cc} includes the yearly depreciation costs for cool bags, refrigerators, and muzzles. We assumed the same capital cost for all mass dog coverage strategies irrespective of the number of vaccination days in use (*Equation 8*).

$$Ccc = ((ncb * pcb + nrf * Prf + nmz * pmz)/lcmr) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Equation 8$$

Where n_{cb} is the number of cool bags needed each year per district accounting for number of villages/teams, p_{cb} the price of a cool bag, n_{rf} the number of refrigerators per district, P_{rf} the price of a refrigerator, n_{mz} the number of muzzles, p_{mz} the price of a muzzle, and l_{cmr} the number of life years of capital goods (cool bags, refrigerators, and muzzle). For simplification, we assumed the number of life years of capital goods to be 5 years and the salvage value afterward equal to zero.

Table 1: Economic input parameters used in estimating the cost of dog vaccination campaigns

Parameters	Description	Type of distribution	Value in USD		
			Urban	Rural	
C_{va}	Cost of rabies vaccine (USD)	point	0.56	0.56	NVI
T_{va}	Cost of transporting a dose of vaccine to a district (USD)	truncated normal	0.35	0.09	Market survey
P_{sn}	Cost of syringe, needle, certificate, and collar (USD)	truncated normal	0.55	0.52	Market survey
P_{ib}	Cost of ice bar for keeping vaccine cold in the icebox (USD)	truncated normal	0.93	0.93	Market survey
n_{capv}	Number of dogs vaccinated/day/team	triangular*	150	75	Expert opinion
n_{vv}	Number of vaccination villages	Point	9	27	assumption
P_{tv}	Daily perdium rate of temporary vaccinators (USD)	truncated normal	6.9	6.9	Survey
P_{sp}	Daily perdium rate of supervisors (USD)	truncated normal	7.8	7.8	Survey
v_t	Number of vaccinators per team	Point	4	4	assumption
F_{tv}	Cost of fuel for temporary vaccinators per day (USD)	truncated normal	9.3	18.5	Survey
f_{sp}	Cost of fuel for supervisors vaccinators per day (USD)	truncated normal	20.1	37.1	Survey
C_{ti}	Cost of training and campaign, lump sum (USD)	point	833	2500	Assumption
n_{cb}	Number of cool bags required	point	9	27	Assumption
p_{rf}	Number of refrigerators required	point	9	27	Assumption
p_{mz}	Number of muzzles required	point	9	27	Assumption
$lcmr$	Lifetime of capital goods	point	5	5	Assumption
p_{cb}	Price per cool bag (USD)	truncated normal	23.15	23.15	Market survey
P_{rf}	Price per refrigerator (USD)	truncated normal	694.4	694.44	Market survey
p_{mz}	Price per muzzle (USD)	truncated normal	23.1	23.1	Market survey

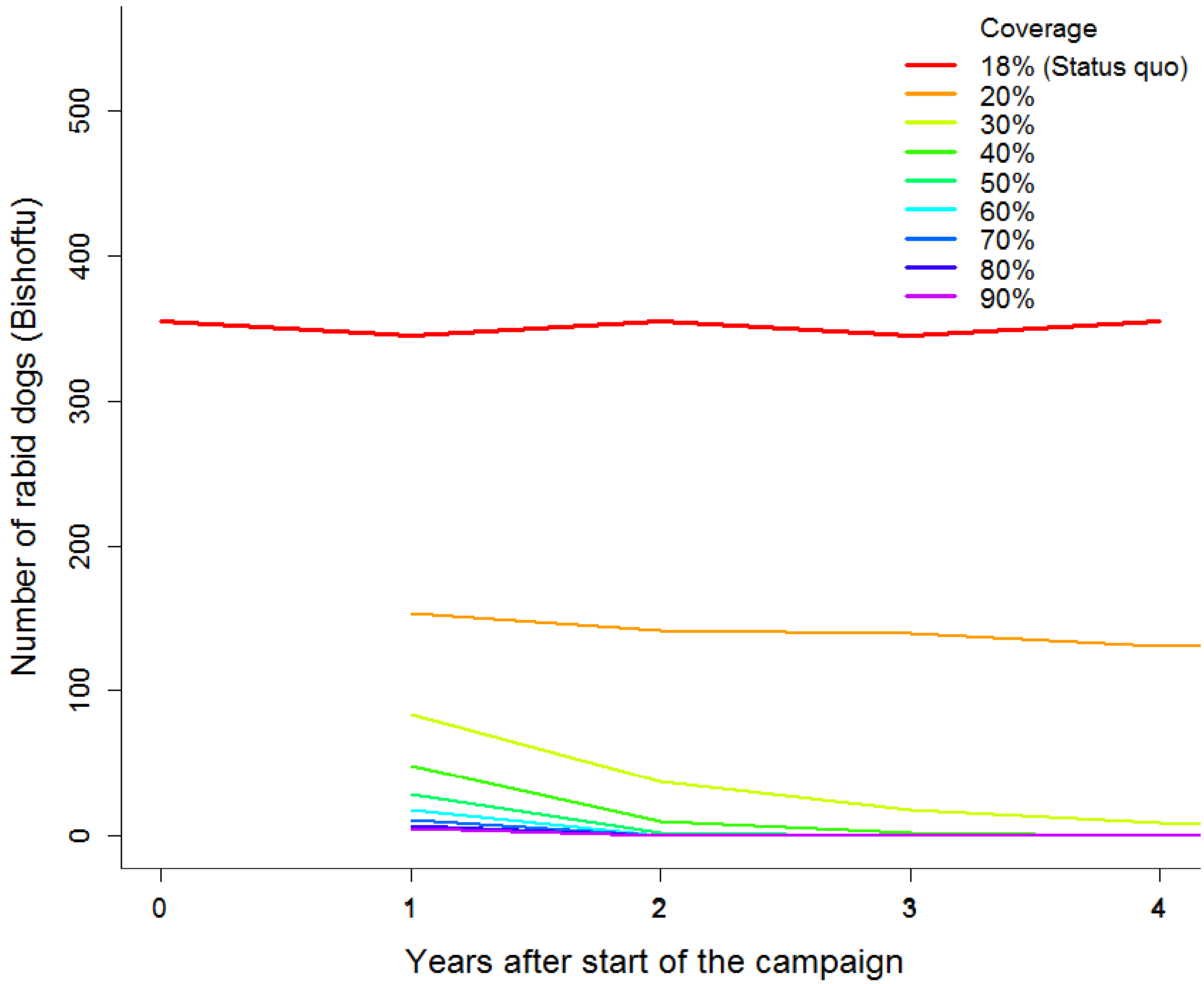
Table 2: Health and economic parameters, distributions and input estimates

Parameters	Description	Type of distribution	Values		Source
			Urban	Rural	
PET cost	Cost of PET per sufficient PEP dose	beta	23.2	30.4	(7)
[1]P1	Likelihood of a suspected rabid dog biting a person	multinomial	0.5	0.5	Computation after (8)
P2	Likelihood of a suspected rabid dog bite victim visit health center and receive sufficient doses of PEP	multinomial	0.85	0.55	Computation after (7)
[1]P3	Likelihood of victim doesn't receive PEP and die	multinomial	0.16	0.16	Computation after (7)
DALYs loss per human rabies case	Average DALYs loss per human rabies case in DALYs	multinomial	46.7	47.7	Computation after (7)
DALYs lost per rabid dog	P1*(1-P2)*P3*LYs loss		0.64	1.67	Computation
Cost of PET per rabid dog	P1*P2* Cost of PET per sufficient PEP dose		9.86	10.79	Computation after (7)

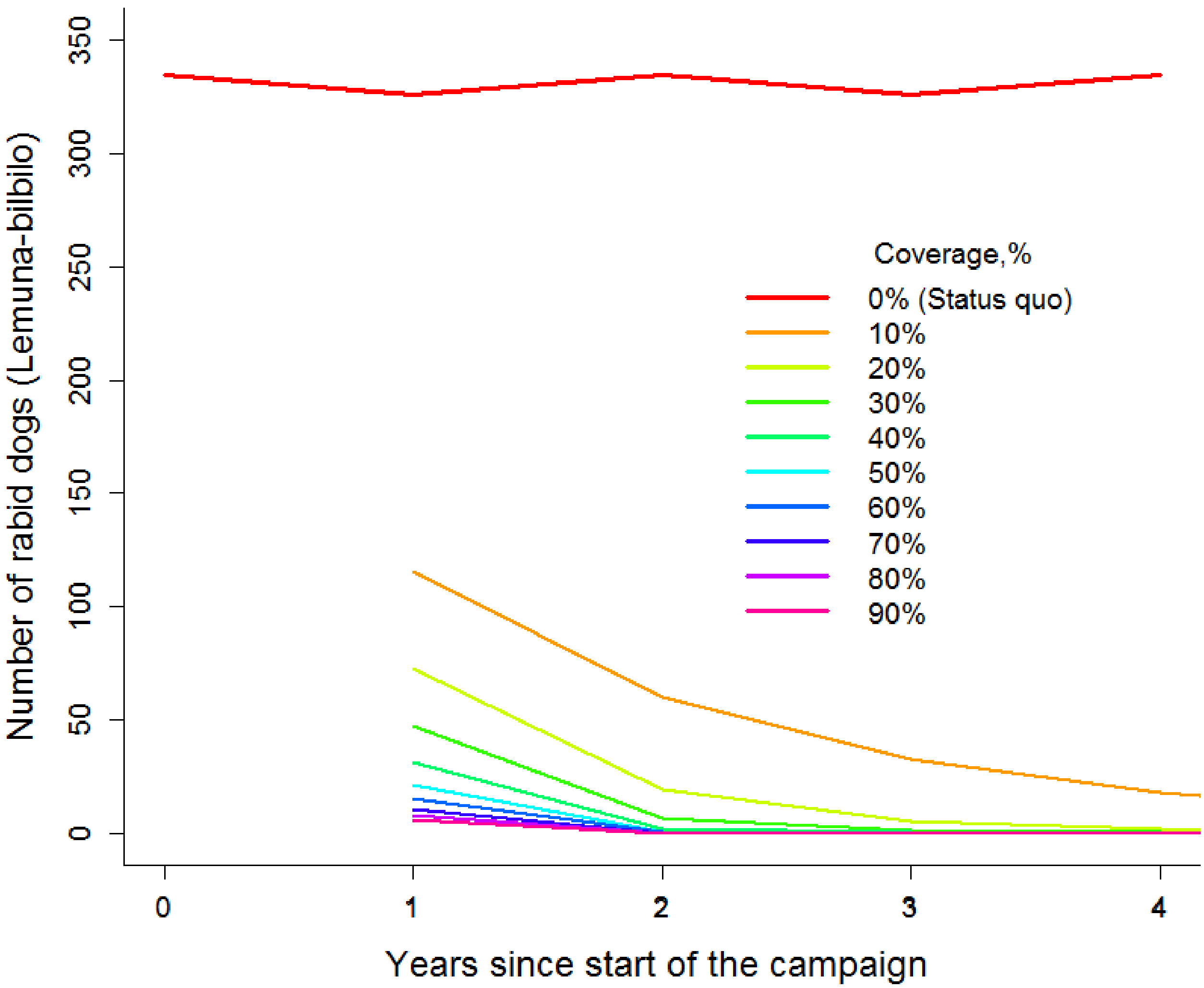
[1]P3= Likelihood of victim doesn't receive PEP and die ((Prob of bite on head *likelihood of death in case of untreated bite on head + Prob of bite on hand/arm*likelihood of death in case of untreated bite on hand/arm + Prob of bite on trunk *likelihood of death in case of untreated bite on trunk+Prob of bite on leg *likelihood of death in case of untreated bite on leg))*(1-P2).

Table 3: Parameters and inputs used to estimate economic loss related to livestock rabies (for rural district only).

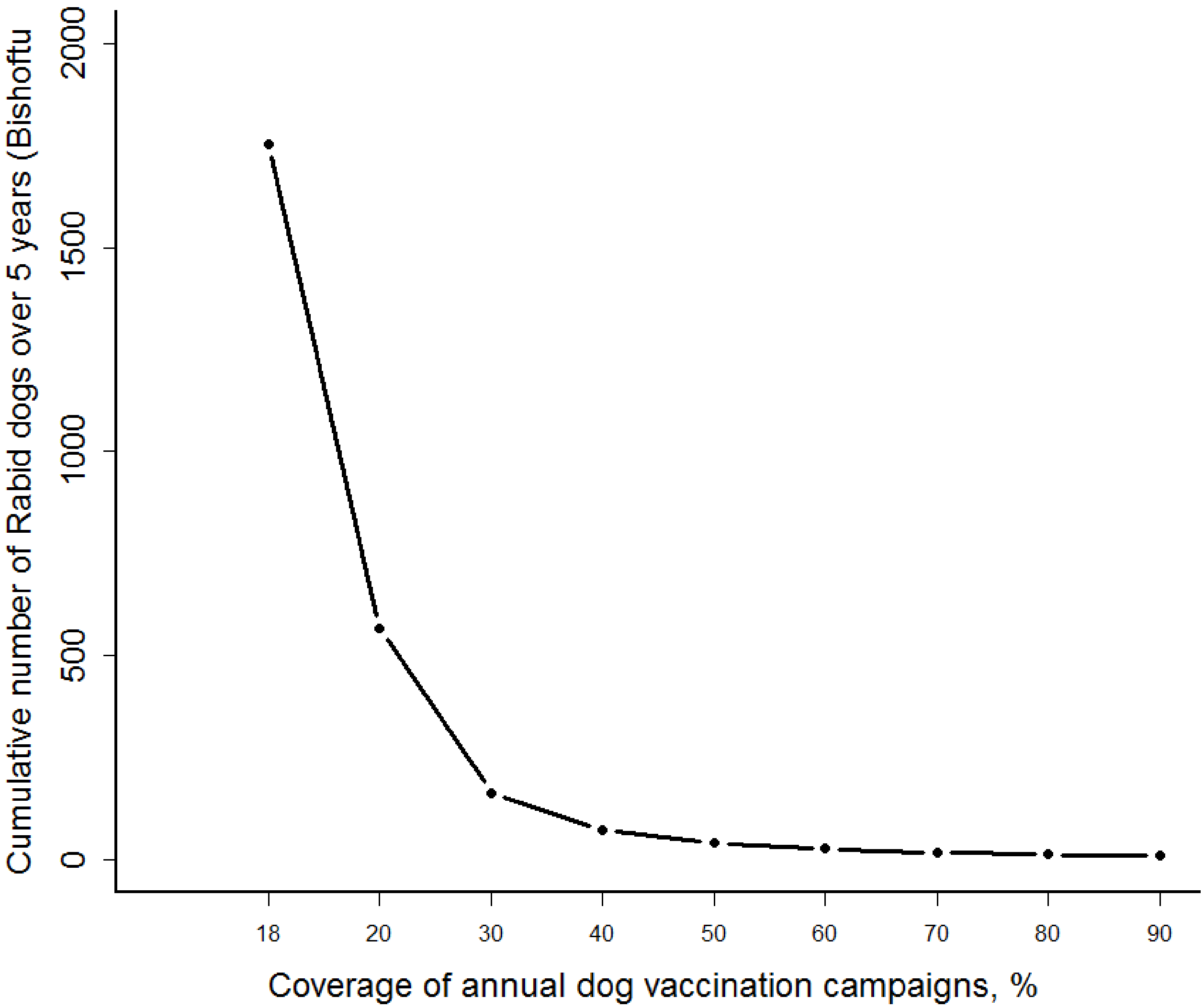
Parameters	Description	Value	Source
H_{inc}	Herd-level rabies incidence (%)	19.4	(9)
N_{herd}	Cattle per herd	14.5	(9)
L_{pah}	Loss per affected herd	147	(9)


Coverage
18% (Status quo)
20%
30%
40%
50%
60%
70%
80%
90%
Number of rabid dogs (Bishoftu)
0
100
200
300
400
500
0
1
2
3
4
Years after start of the campaign

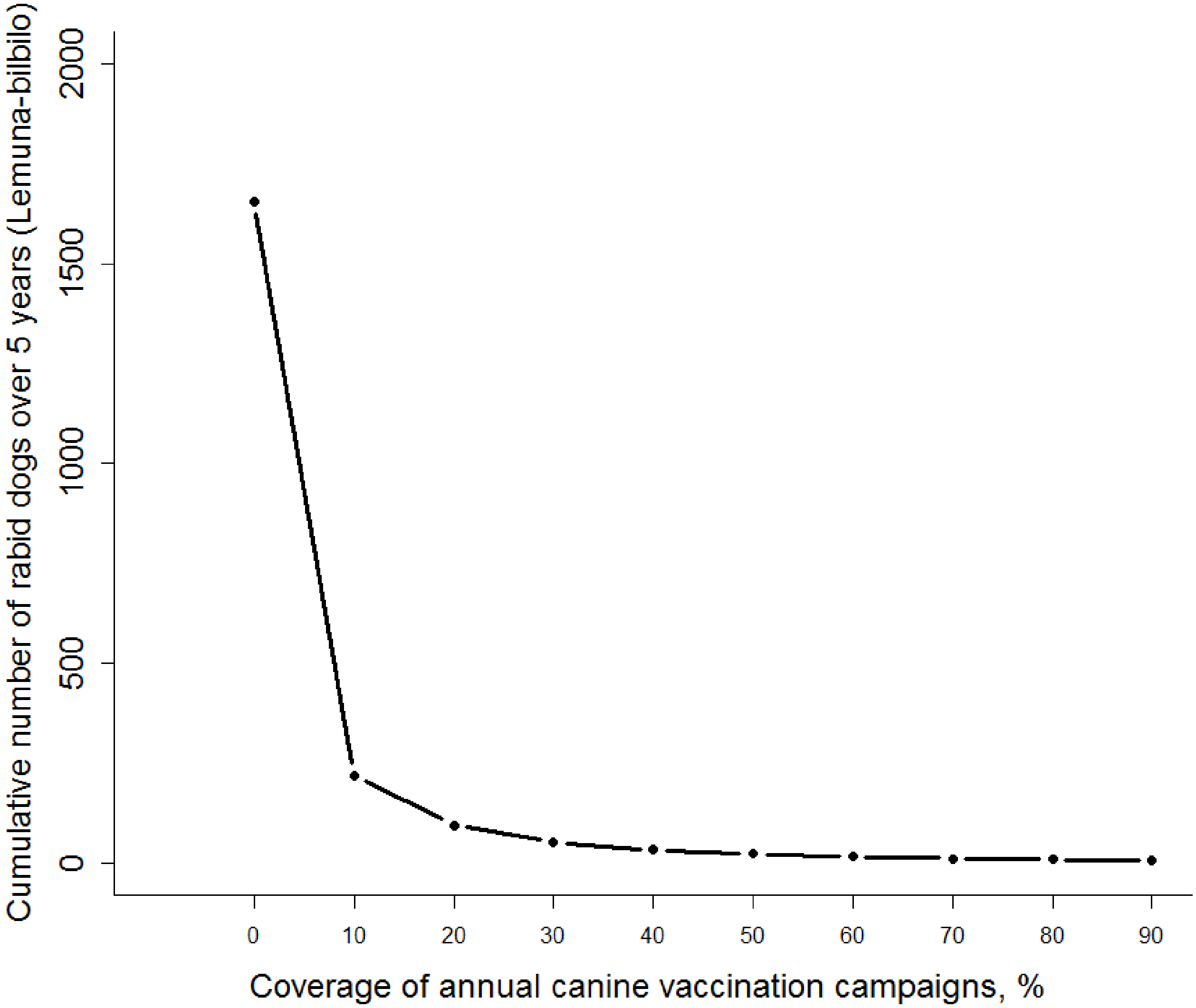
a)


Number of rabid dogs (Lemuna-bilbilo)
0
50
100
150
200
250
300
350
Coverage,%
0% (Status quo)
10%
20%
30%
40%
50%
60%
70%
80%
90%
0
1
2
3
4
Years since start of the campaign

b)

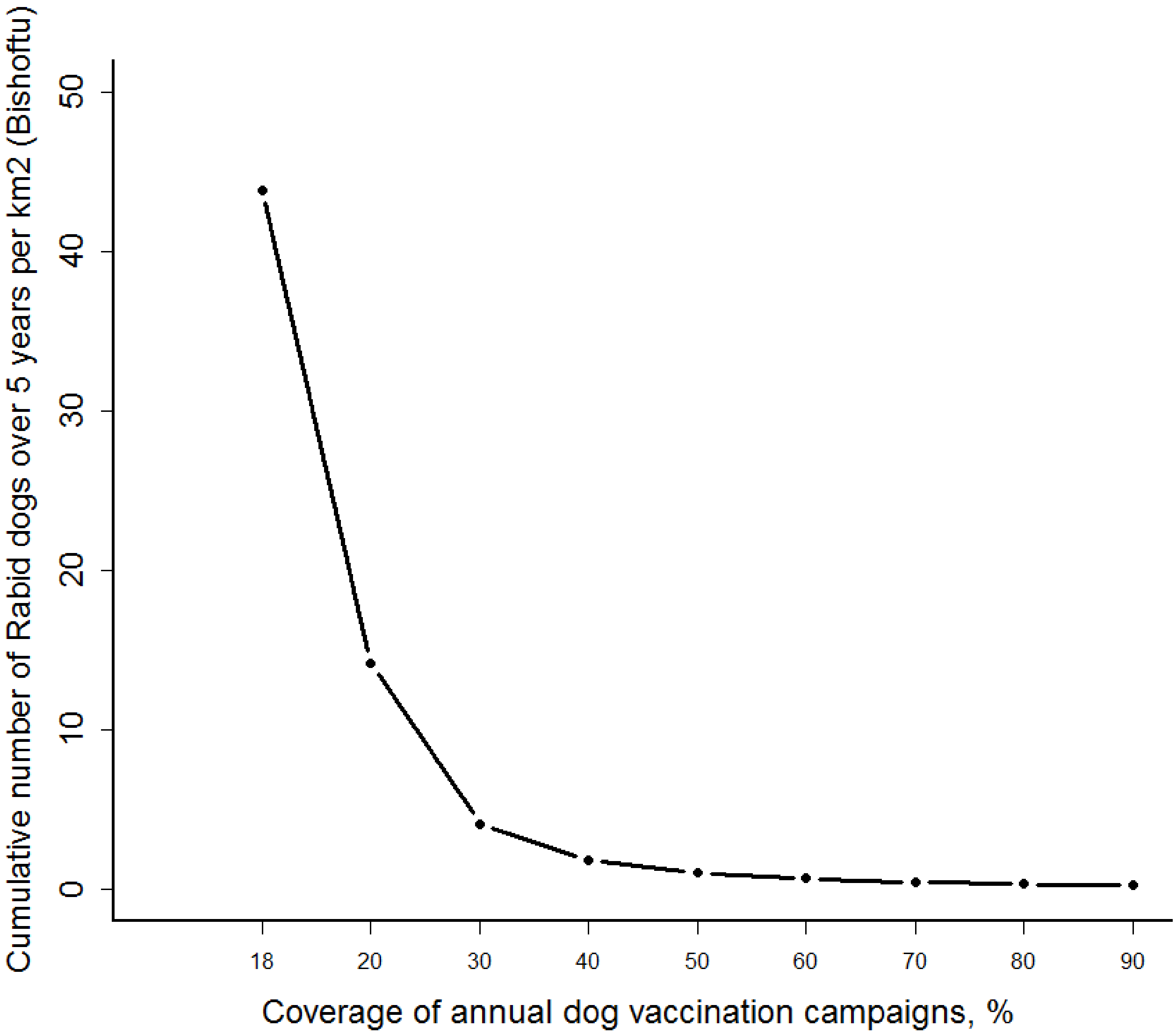

Cumulative number of Rabid dogs over 5 years (Bishoftu
0
500
1000
1500
2000
18
20
30
40
50
60
70
80
90
Coverage of annual dog vaccination campaigns, %

c)

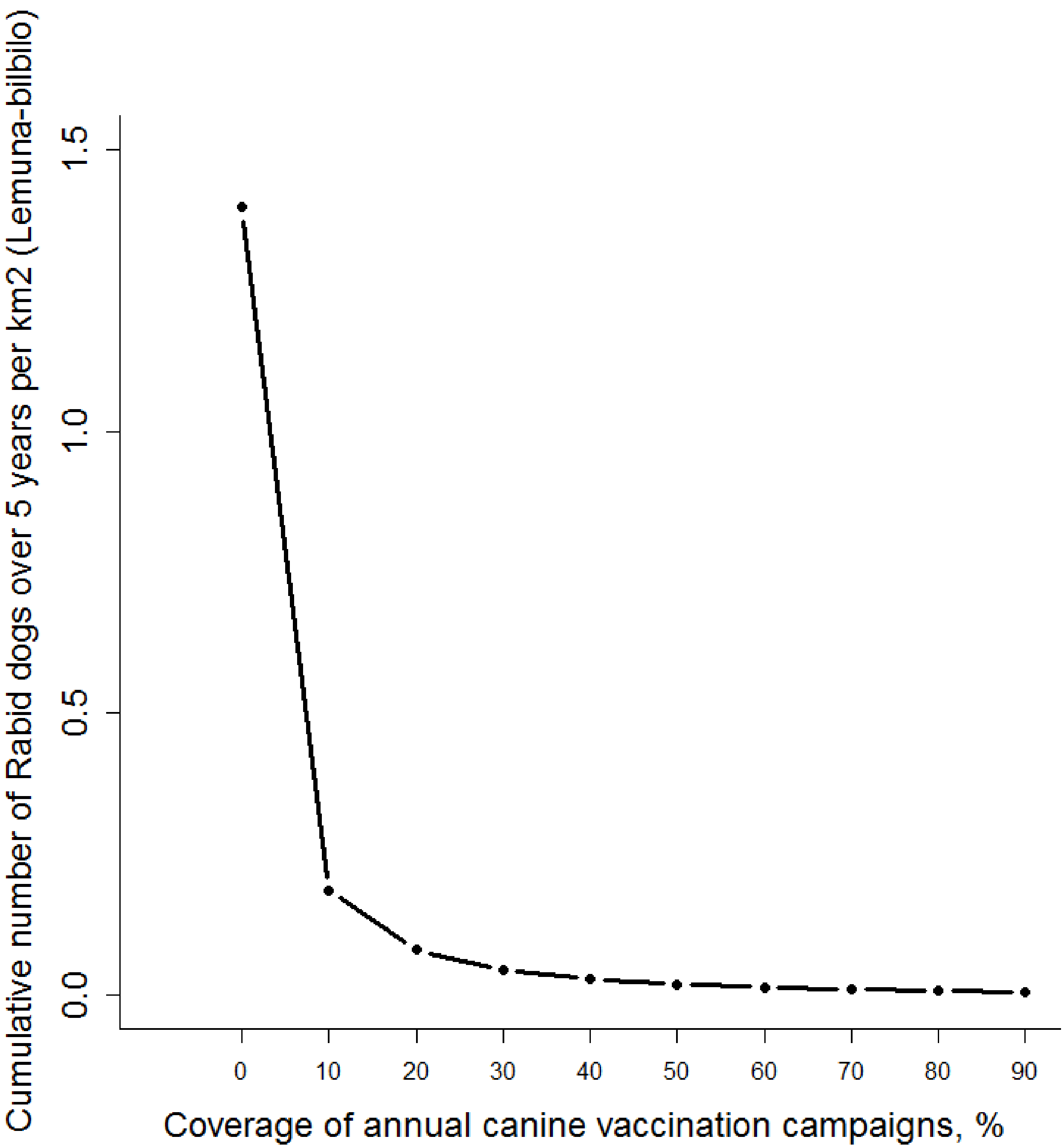

Cumulative number of rabid dogs over 5 years (Lemuna-bilbilo)
0
500
1000
1500
2000
0
10
20
30
40
50
60
70
80
90
Coverage of annual canine vaccination campaigns, %

159

160 d)


Cumulative number of Rabid dogs over 5 years per km2 (Bishoftu)
0
10
20
30
40
50
18
20
30
40
50
60
70
80
90
Coverage of annual dog vaccination campaigns, %

e)



f)

Figure 2: Total number of rabid dogs over 5 years for each vaccination coverage a) Bishoftu b) Lemuna-bilbilo, cumulative number of rabies dogs over a 5-year in c) Bishoftu d) Lemuna-bilbilo, and cumulative number of rabies dogs per km^2 in e) Bishoftu and f) Lemuna-bilbilo under different canine vaccination coverage strategies.

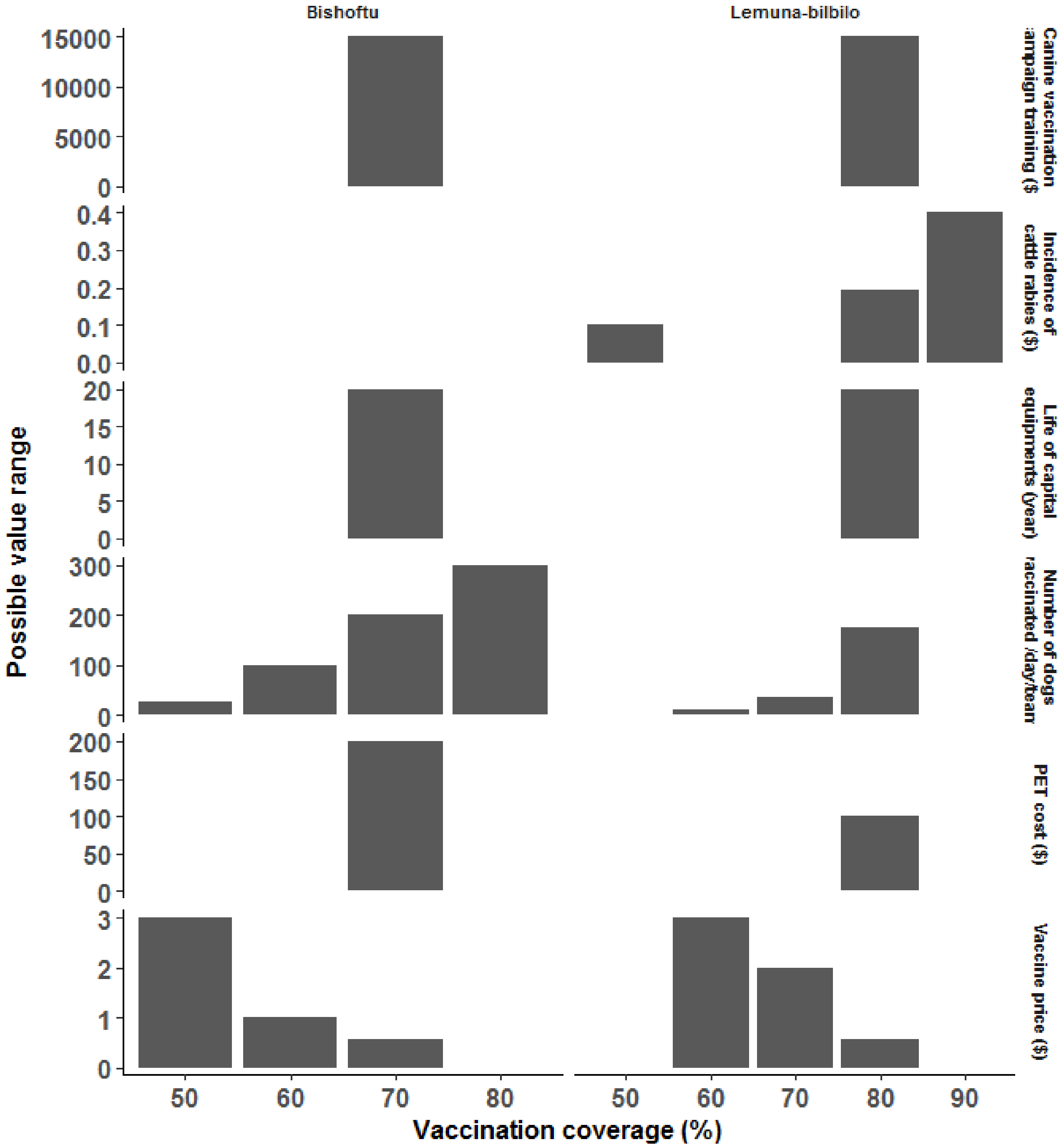
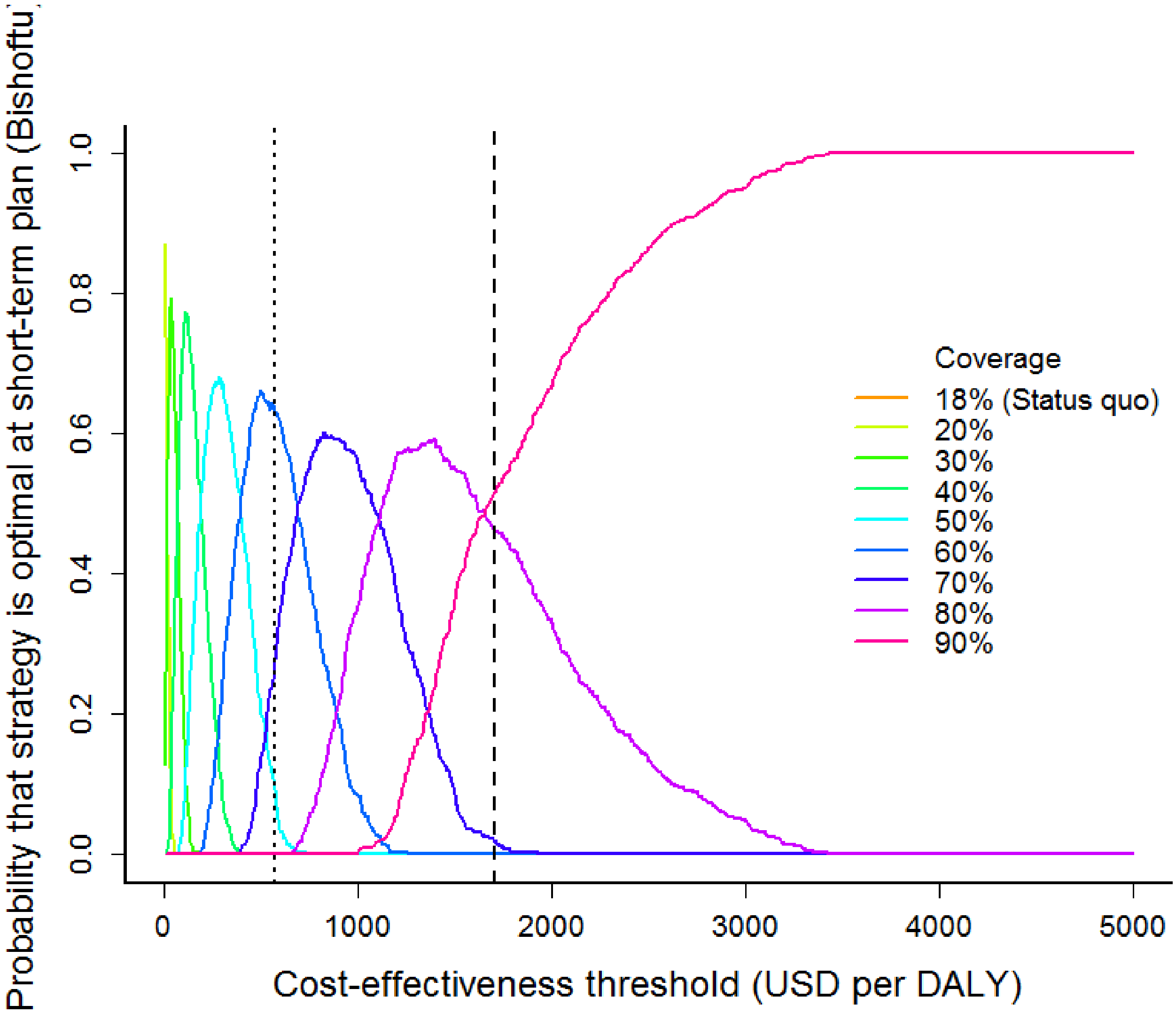
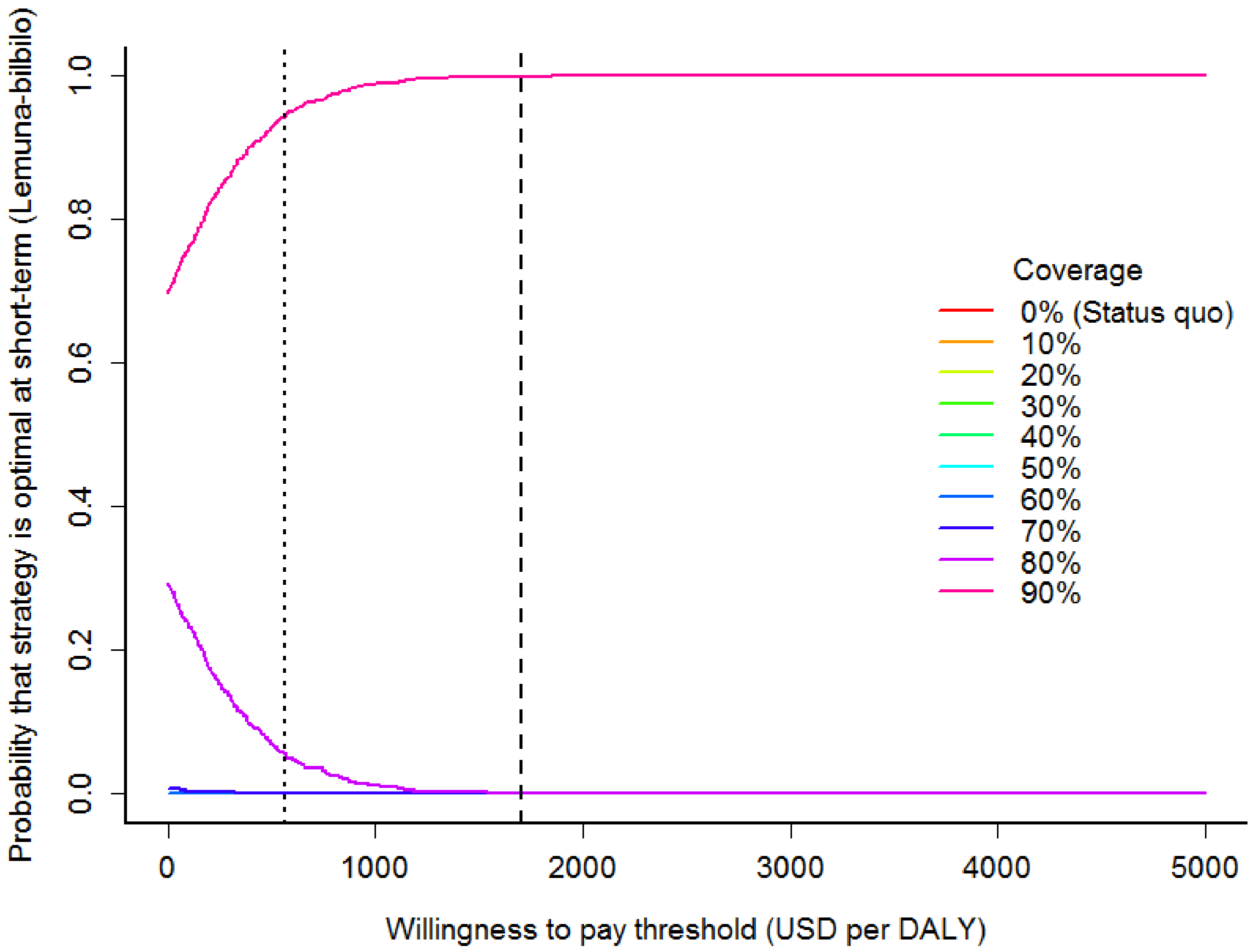


Figure 3: One-way sensitivity analysis on the impact of economic parameters on recommended rabies vaccination coverage for a) Bishoftu b) Lemuna-bilbilo district.

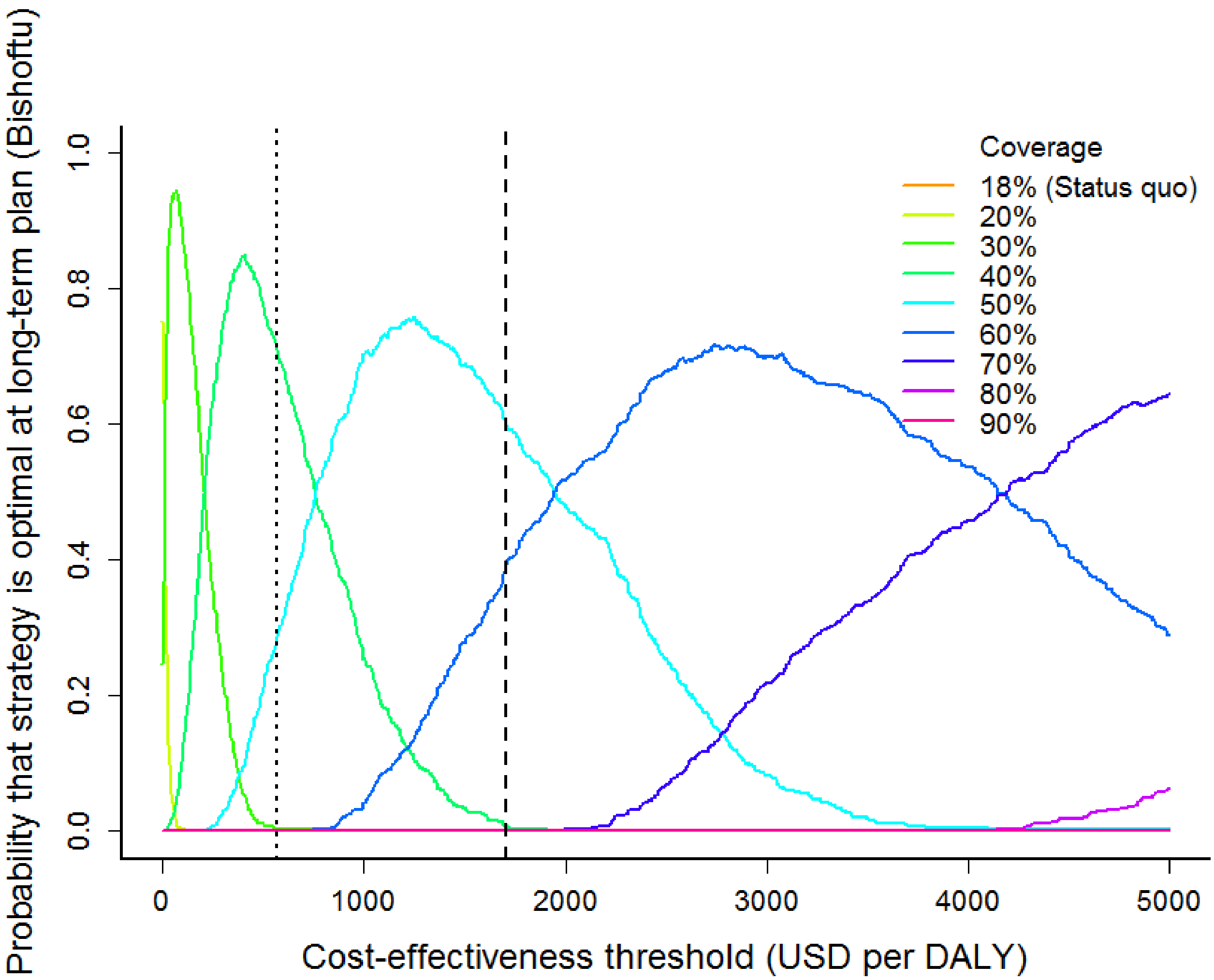

Probability that strategy is optimal at short-term plan (Bishoftu)
Cost-effectiveness threshold (USD per DALY)
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
5000
Coverage
18% (Status quo)
20%
30%
40%
50%
60%
70%
80%
90%

a)

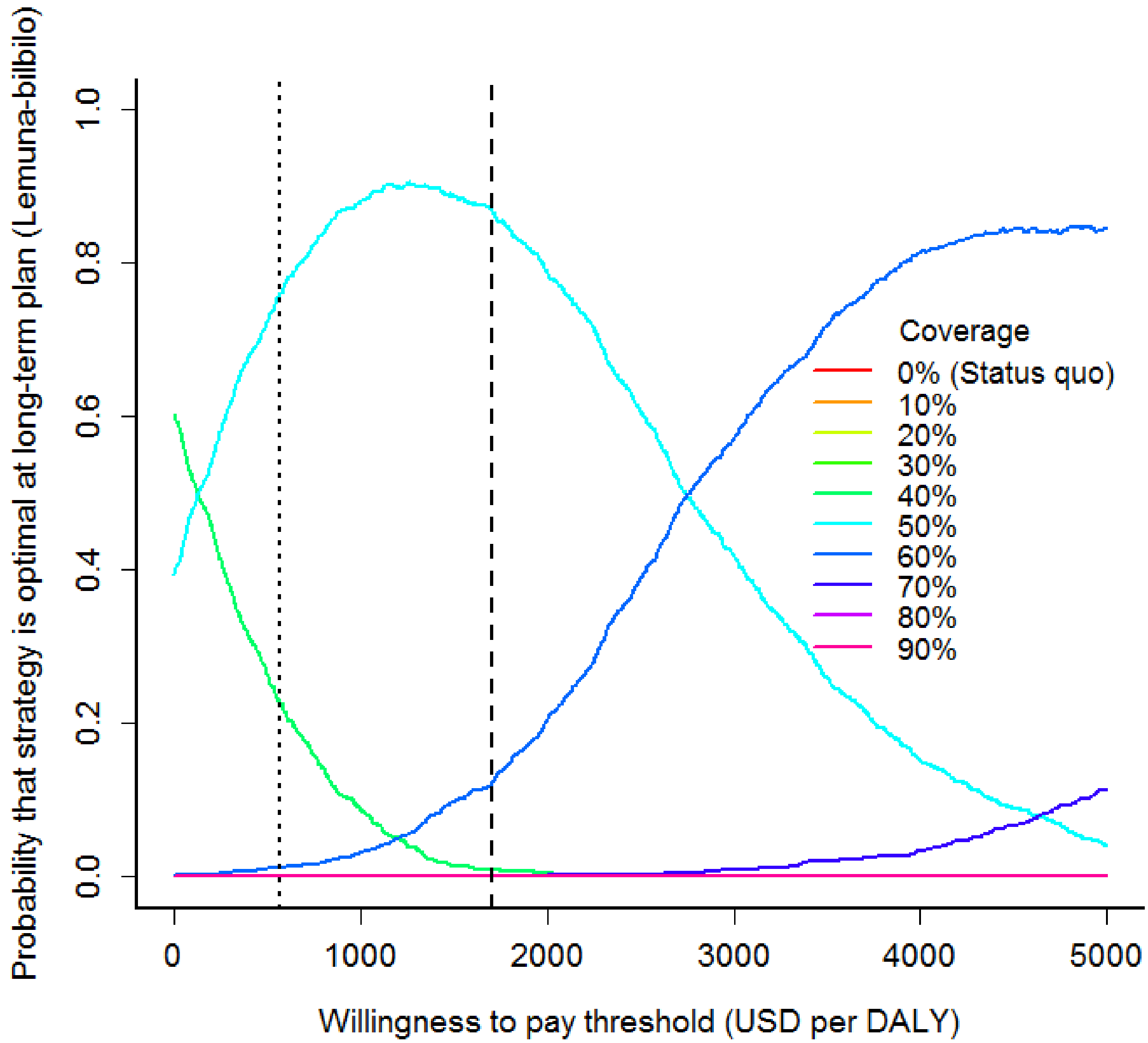


Probability that strategy is optimal at short-term (Lemuna-bilbilo)
1.0
0.8
0.6
0.4
0.2
0.0
0
1000
2000
3000
4000
5000
Willingness to pay threshold (USD per DALY)
Coverage
0% (Status quo)
10%
20%
30%
40%
50%
60%
70%
80%
90%

b)

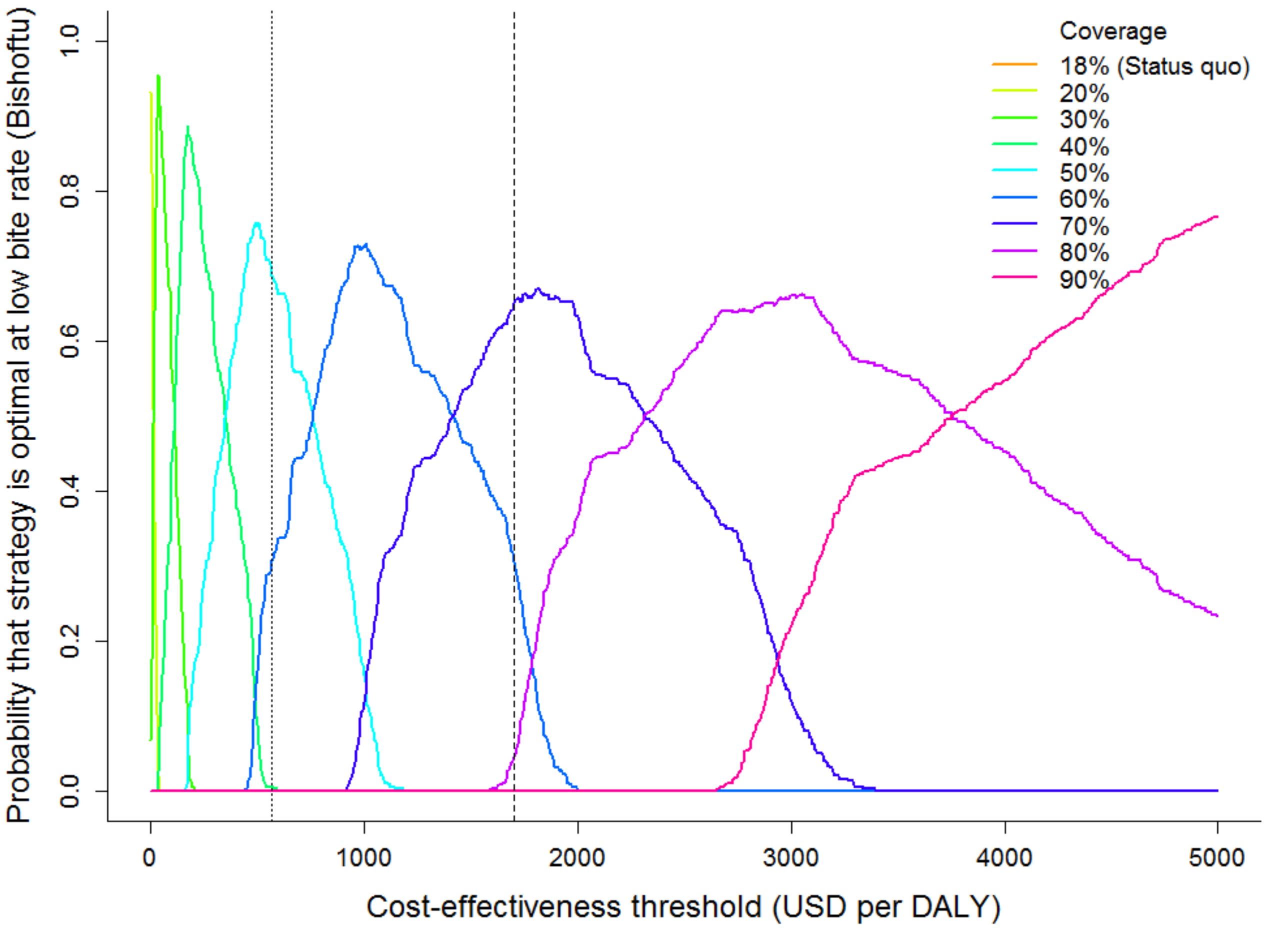

Probability that strategy is optimal at long-term plan (Bishoftu)
Cost-effectiveness threshold (USD per DALY)
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
5000
Coverage
18% (Status quo)
20%
30%
40%
50%
60%
70%
80%
90%

c)



d)

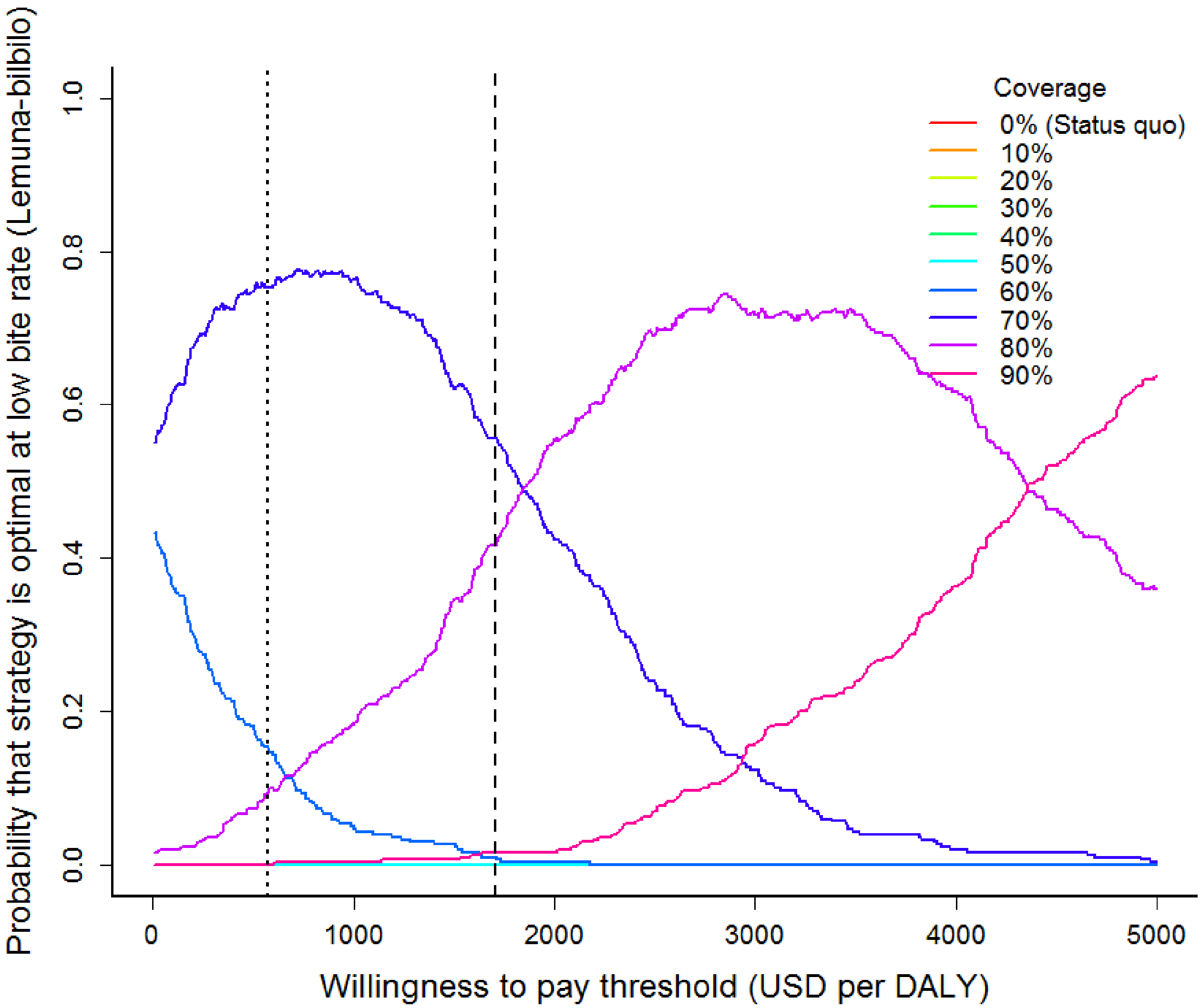
Figure 4: Two-way sensitivity analysis for recommended canine vaccination coverage strategy under a) short-term plan of annual vaccination campaign (3 years and 5% discount rate) a) Bishoftu, b) Lemuna-bilbilo, and long-term plan of annual vaccination campaign (10 years and 1% discount rate) for c) Bishoftu and d) Lemuna-bilbilo districts.



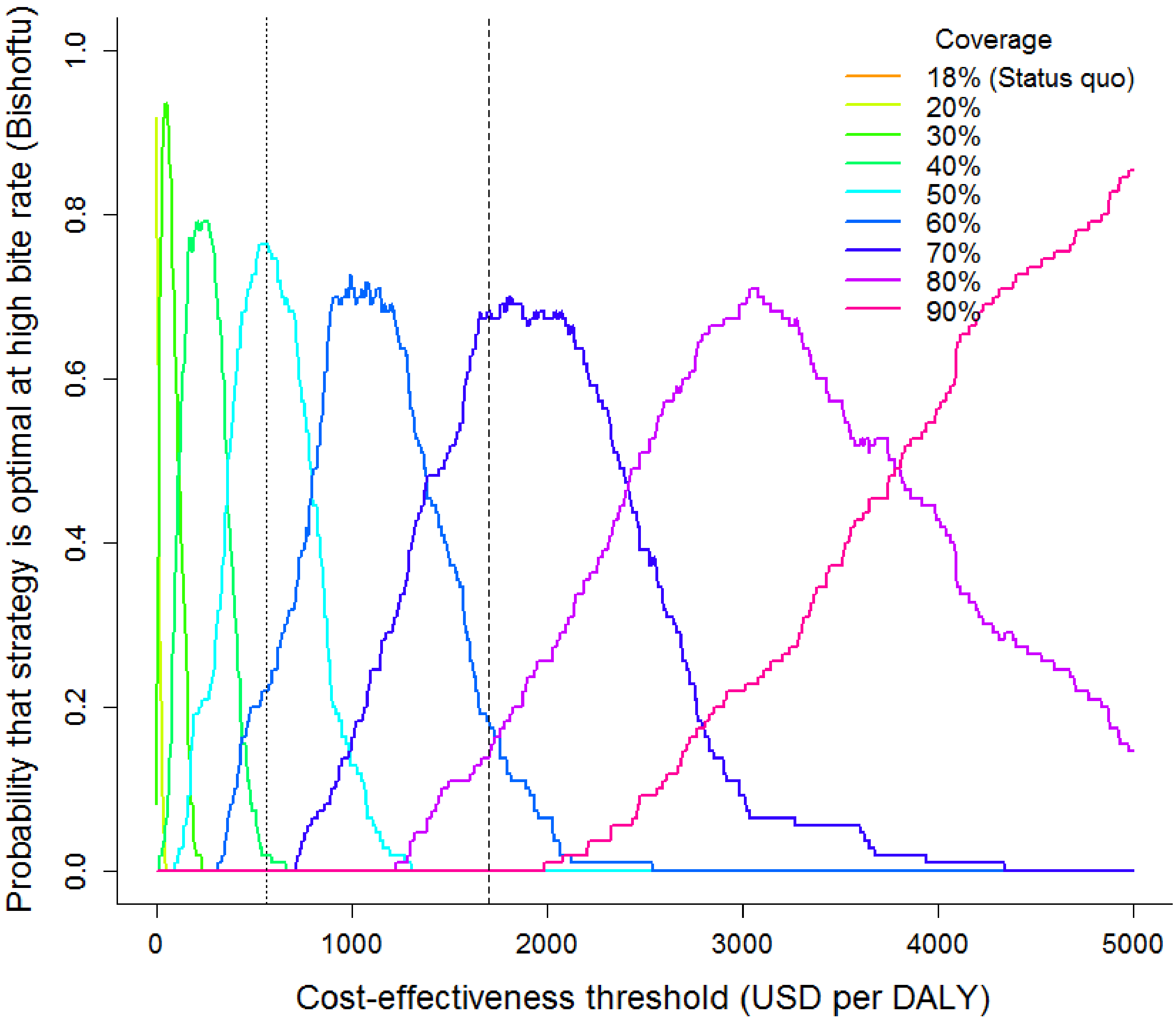
Probability that strategy is optimal at low bite rate (Bishoftu)
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
5000
Cost-effectiveness threshold (USD per DALY)
Coverage
18% (Status quo)
20%
30%
40%
50%
60%
70%
80%
90%

192

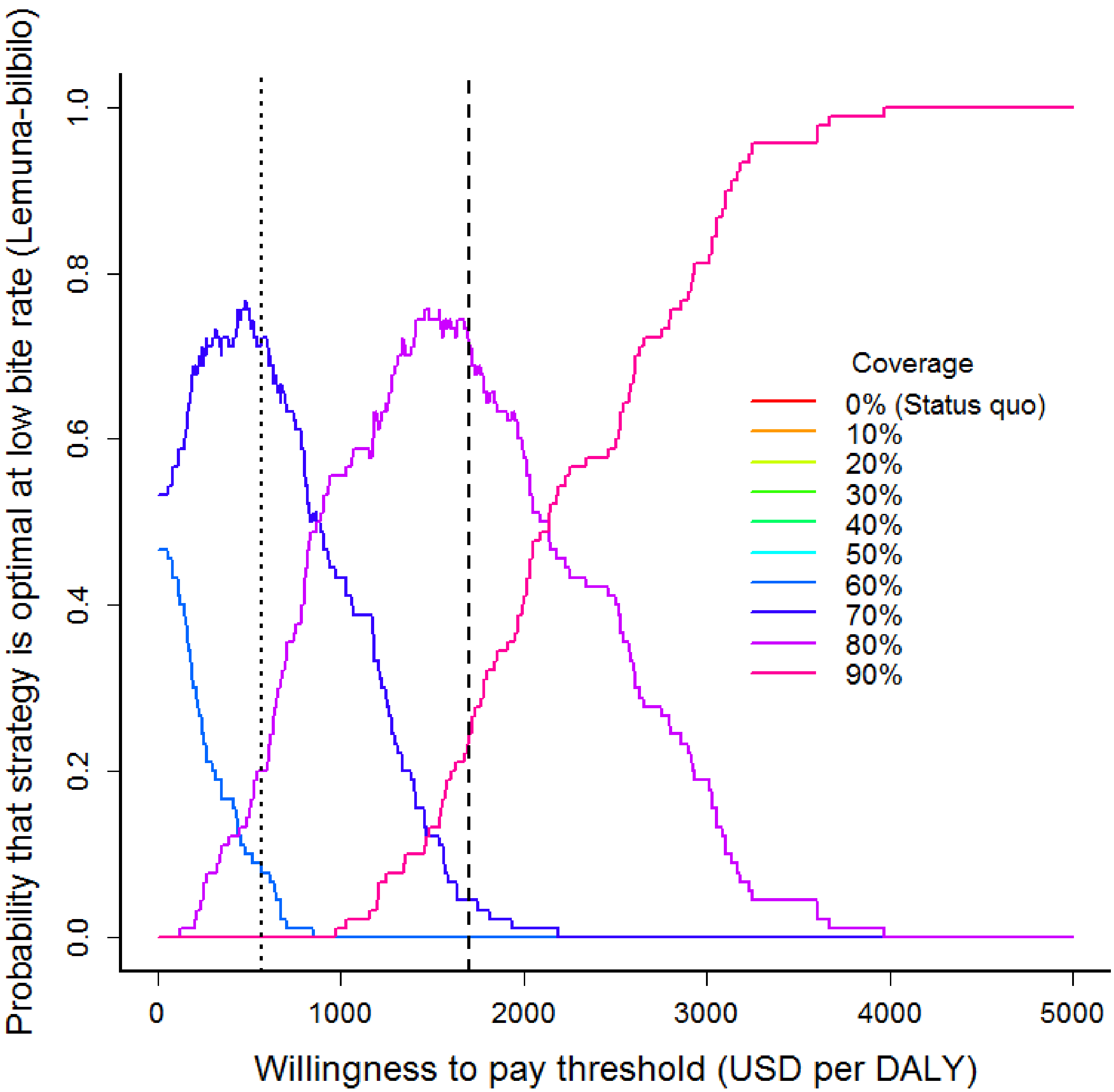
193 a)


Probability that strategy is optimal at low bite rate (Lemuna-bilbilo)
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
5000
Willingness to pay threshold (USD per DALY)
Coverage
0% (Status quo)
10%
20%
30%
40%
50%
60%
70%
80%
90%

b)

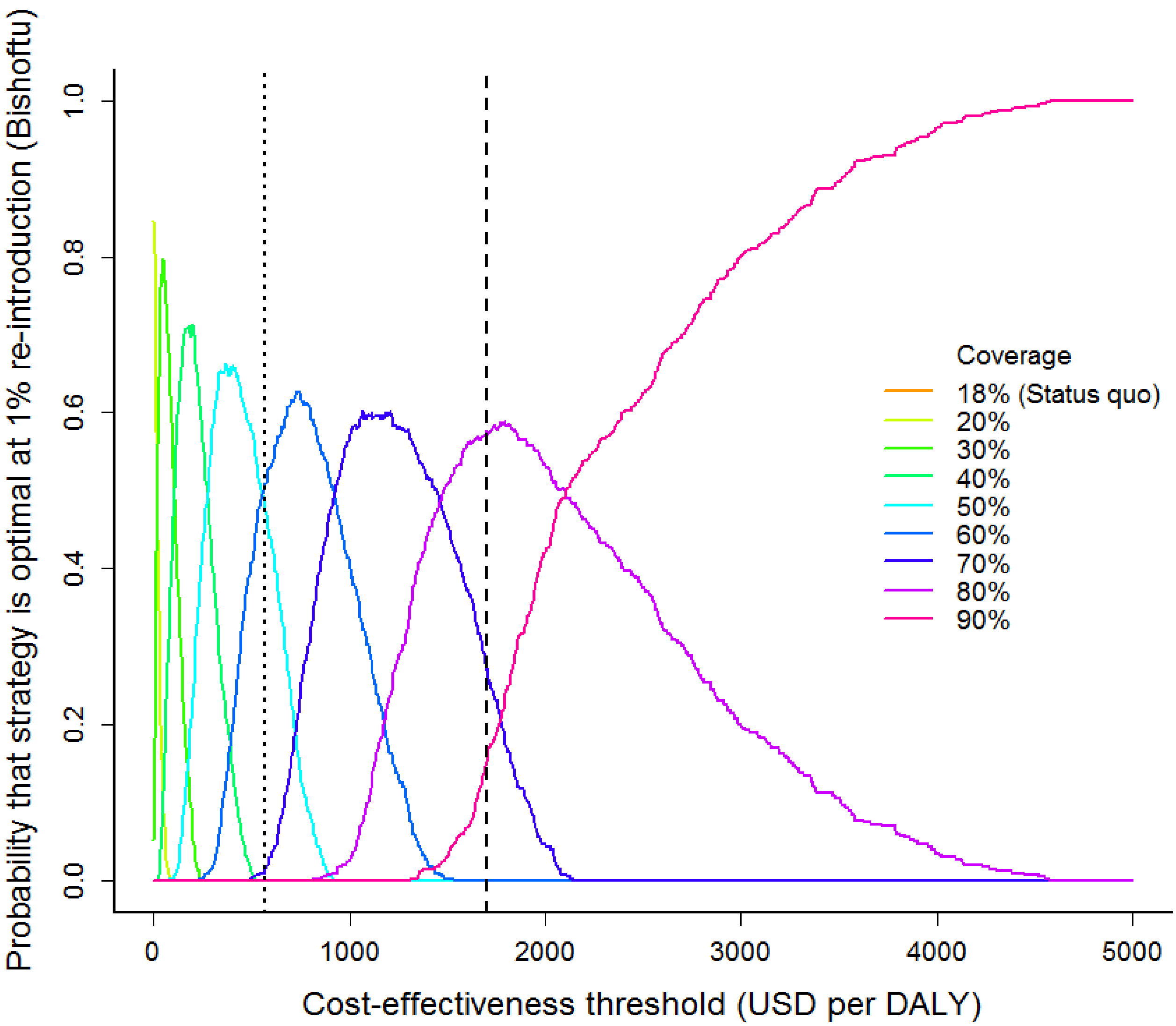

Coverage
18% (Status quo)
20%
30%
40%
50%
60%
70%
80%
90%
Probability that strategy is optimal at high bite rate (Bishoftu)
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
5000
Cost-effectiveness threshold (USD per DALY)

c)

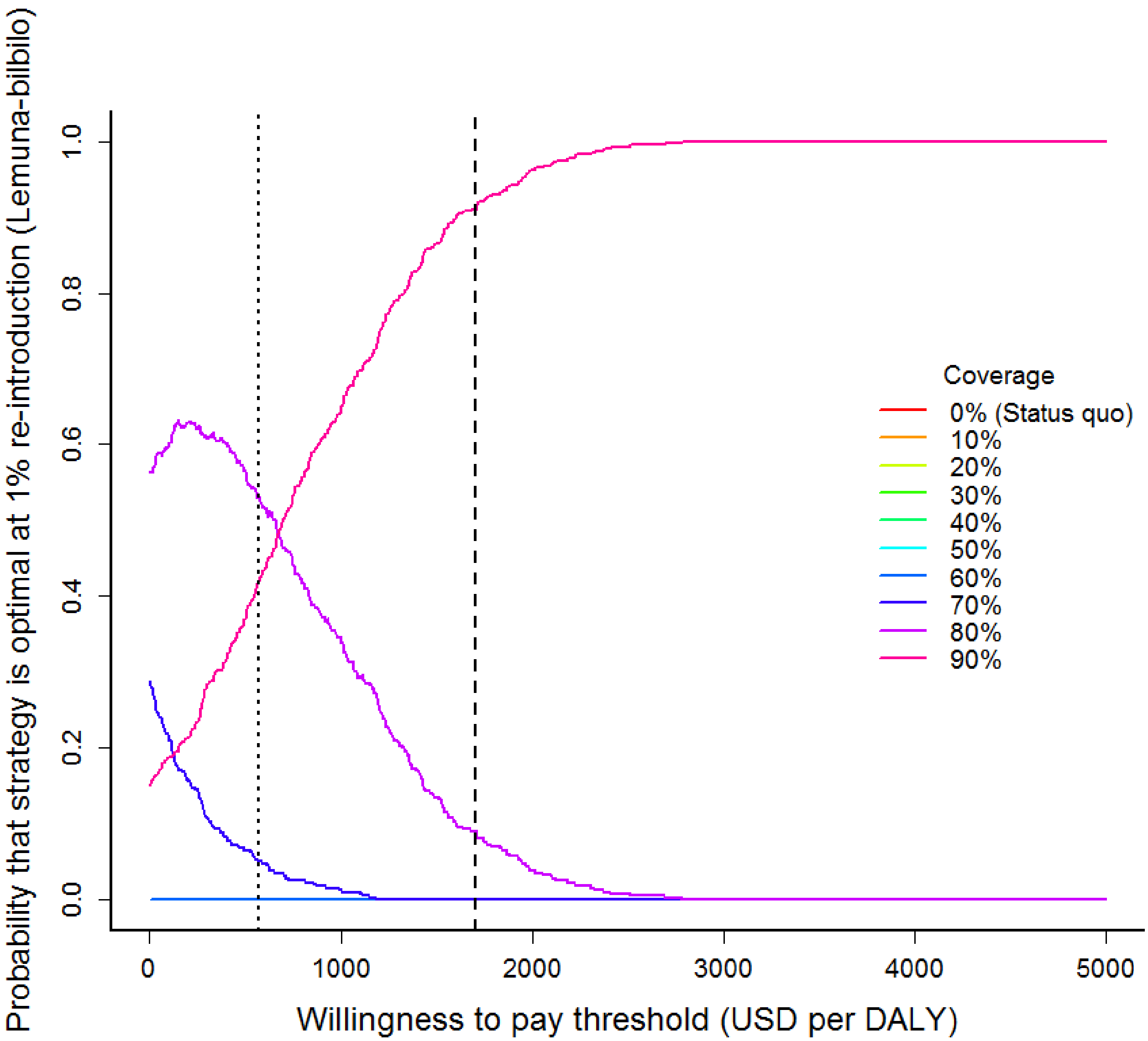


d)

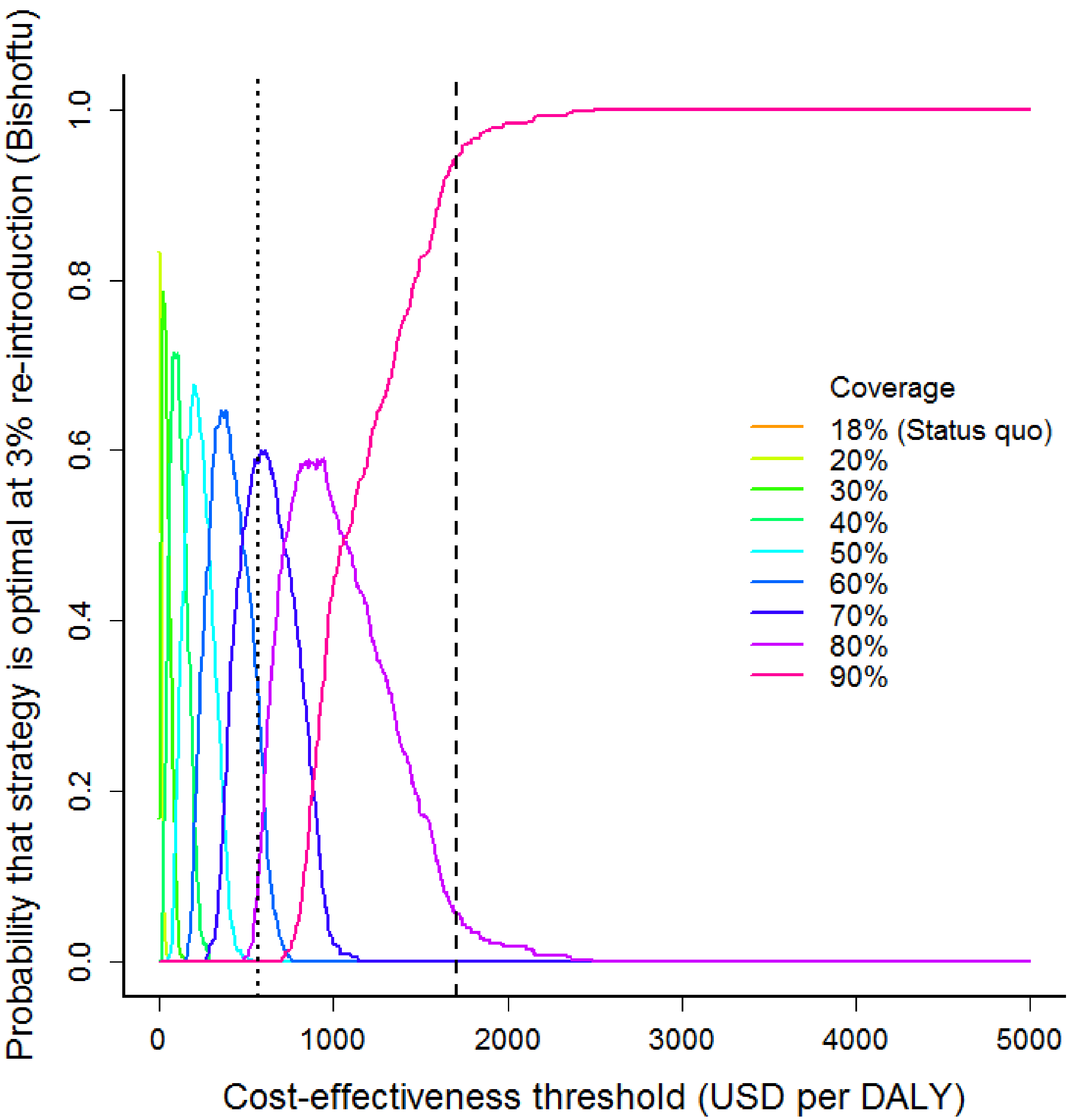
Figure 5: One-way sensitivity analysis on the impact of lower (0.2) bite rate on recommended rabies vaccination coverage in a) Bishoftu b) Lemuna-bilbilo district and higher (0.99) bite rate on recommended rabies vaccination coverage in c) Bishoftu d) Lemuna-bilbilo district


Probability that strategy is optimal at 1% re-introduction (Bishoftu)
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
5000
Cost-effectiveness threshold (USD per DALY)
Coverage
18% (Status quo)
20%
30%
40%
50%
60%
70%
80%
90%

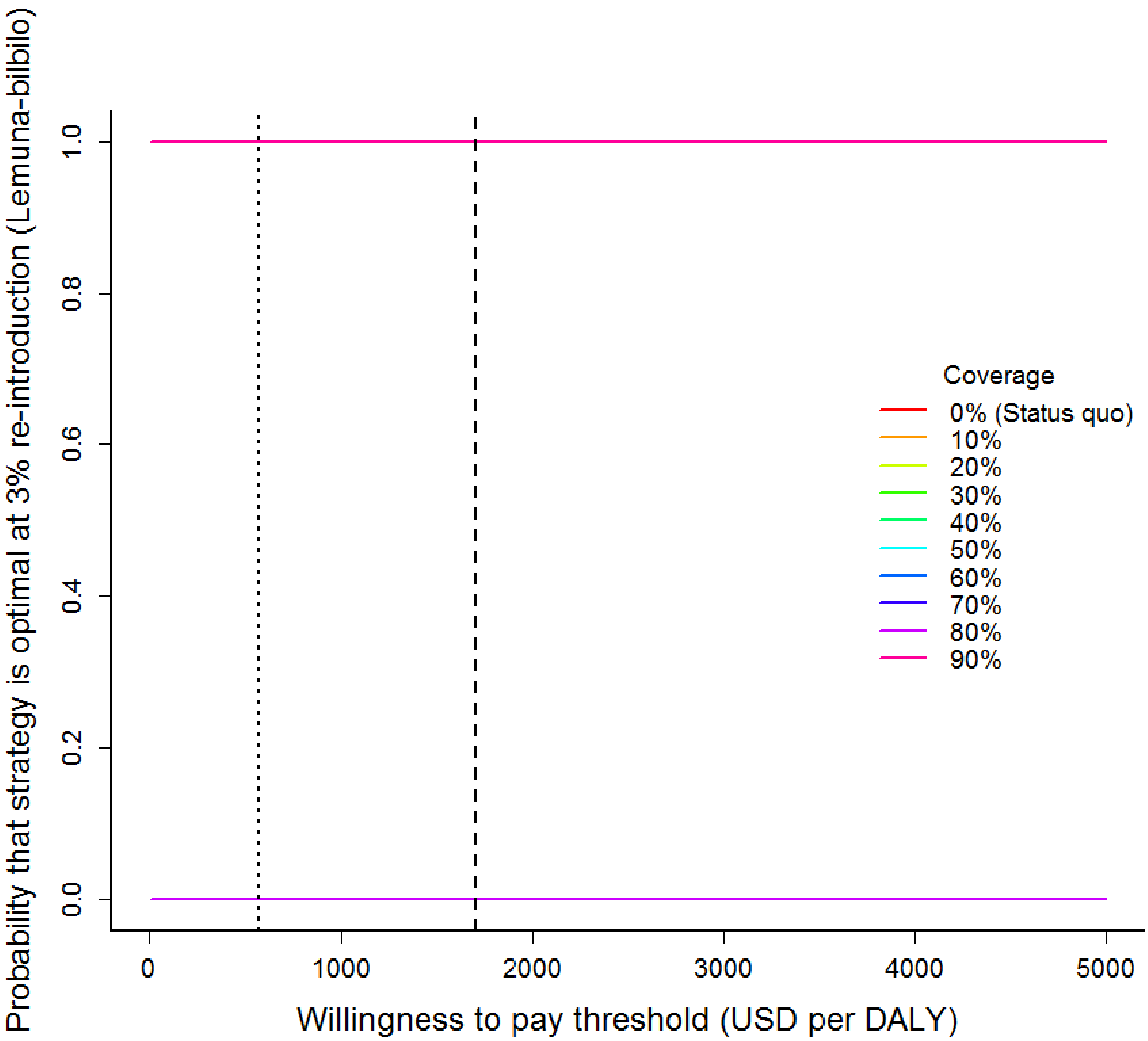
a)


Probability that strategy is optimal at 1% re-introduction (Lemuna-bilbilo)
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
5000
Willingness to pay threshold (USD per DALY)
Coverage
0% (Status quo)
10%
20%
30%
40%
50%
60%
70%
80%
90%

b)


Probability that strategy is optimal at 3% re-introduction (Bishoftu)
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
5000
Cost-effectiveness threshold (USD per DALY)
Coverage
18% (Status quo)
20%
30%
40%
50%
60%
70%
80%
90%

c)



d)

Figure 6: One-way sensitivity analysis on the impact of 1% rabies re-introduction on recommended rabies vaccination coverage in a) Bishoftu b) Lemuna-bilbilo district and 3% rabies re-introduction on recommended optimal rabies vaccination coverage in c) Bishoftu d) Lemuna-bilbilo district

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