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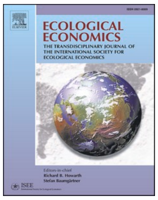

Predicting uptake of a malignant catarrhal fever vaccine by pastoralists in northern Tanzania: Opportunities for improving livelihoods and ecosystem health

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ABSTRACT

Malignant Catarhal Fever (MCF), caused by a virus transmitted from asymptomatic wildebeest, is a lethal disease in cattle that threatens livestock-based livelihoods and food security in many areas of Africa. Many herd owners reduce transmission risks by moving cattle away from infection hot-spots, but this imposes considerable economic burdens on their households. The advent of a partially-protective vaccine for cattle opens up new options for disease prevention. In a study of pastoral households in northern Tanzania, we use stated preference choice modelling to investigate how pastoralists would likely respond to the availability of such a vaccine. We show a high probability of likely vaccine uptake by herd owners, declining at higher vaccine costs. Acceptance increases with more efficaceous vaccines, in situations where vaccinated cattle are ear-tagged, and where vaccine is delivered through private vets. Through analysis of Normalized Density Vegetation Index (NDVI) data, we show that the reported MCF incidence over 5 years is highest in areas where the mean and interannual varibility in vegetative greeness is relatively low and where herds sizes are smaller. Trends towards lower rainfall and greater landscape-level constraints on cattle movement suggest that MCF avoidance through traditional movement away from wildebeest will become more challenging and that demand for an MCF vaccine will likely increase.

1. Introduction

Malignant catarrhal fever (MCF) is a lethal, viral infection that affects cattle in eastern and southern Africa (Plowright, 1965). The disease is caused by a gamma herpes virus, Alcelaphine herpesvirus 1 (AIHV-1), which is excreted by wildebeest calves under four months of age and transmitted (via aerosolized droplets or contaminated pasture) to cattle (Plowright et al., 1960). In East Africa, peak transmission of malignant catarrhal fever typically occurs after the annual wildebeest calving season when large herds of wildebeest move into the savannah plains, with the timing of their arrival linked to seasonal rainfall (Holdo et al., 2009a). These calving grounds often include areas inhabited by cattle-owning communities, particularly Maasai pastoralists. It is in these calving zones that cattle and wildebeest meet, making them hotspots for MCF transmission. MCF is an important cause of land-use conflict between pastoralists and conservation authorities (Lankester et al., 2016), contributing to escalating tensions over access to grazing lands around protected areas (Lankester and Davis, 2016).

The impact of MCF on livelihoods of cattle-keeping people, primarily pastoralists, in mixed-use buffer zone areas in northern Tanzania and southern Kenya is profound (Cleaveland et al., 2001; Bedelian et al., 2007). In areas where cattle come into contact with wildebeest calves, MCF was ranked the most important cattle disease by pastoralists (Bedelian et al., 2007; Cleaveland et al., 2001). To date, the only method of control that has been adopted is to separate cattle from wildebeest during the peak period of transmission (the wildebeest calving season).

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The process of moving cattle away from prime grazing sites to protect them from becoming infected with AlHV-1 has serious impacts on herd productivity and the individual health of cattle (Bedelian et al., 2007; Lankester et al., 2015). Lankester et al. (2015) explored the economic impact of MCF on pastoralist livelihoods in Tanzana, and showed that over the 5-month high risk period, 82% of cattle were moved away from home pastures to avoid MCF and, because the distance traveled to find safe pastures was over 20 km away, this resulted in 64% of milk being unavailable for consumption by household members who stayed at home. This has important impacts as livestock continues to provide the main source of household income, and milk remains a critical component of the diet (Hansen et al., 2011). Given current nutritional deficiencies reported in the region (Galvin et al., 2015), the dietary consequences of this reallocation of nutritional resources can be severe, especially for children. Moreover, losses in income to households resulting from MCF may well have adverse indirect impacts on investments in children's education (Marsh et al., 2016). In addition, the financial costs associated with MCF avoidance, which result primarily from lost opportunities to sell milk and the additional labor and time required to move the cattle away from the home pastures, are considerable (Lankester et al., 2015).

Over the past five decades, MCF has been a growing source of conflict between pastoralists and conservation authorities. In the Serengeti ecosystem, wildebeest numbers have risen more than 6-fold since the 1960s, increasing from ~200,000 individuals to current levels of 1.3 million. This increase has been explained by release of the wildebeest population from the limiting effects of rinderpest (which previously caused high annual mortality in wildebeest yearlings) following a mass cattle vaccination campaign (Holdo et al., 2009b). This increase in wildebeest numbers has been associated with a multidecadal expansion in the range of the migration, compounding other sources of rangeland loss for pastoralists, including the expansion of protected areas and the widespread conversion of rangelands to crop-based agriculture. These land-use changes are increasingly restricting access to remaining grazing lands, and limiting pasture options for avoiding wildebeest and associated disease/pathogen transmission risks.

In parallel, conservationists are concerned about the impact of escalating human activities on the integrity of protected area systems. In both the Serengeti and Tarangire ecosystems in northern Tanzania, recent evidence suggests that increases in human settlements and livestock density near the borders of protected areas have restricted the movements of wild herbivores, compressing their spatial distributions and altering ecosystem processes such as fire and nutrient cycling (Borner, 1985; Morrison et al., 2016; Veldhuis et al., 2019). Nonetheless, there is no evidence of widespread increases in cattle numbers, and wildebeest utilisation has increased in several important mixed wildlife-livestock grazing areas, such as the Ngorongoro Conservation Area and Manyara Ranch (Veldhuis et al., 2019; König et al. 2020). While an MCF vaccine has the potential to increase herd sizes and enable cattle to graze within wildebeest calving areas for longer portions of the year, potentially intensifying conflict with conservationists, this increased access to high quality rangeland may also reduce tensions in pastoralist communities and contribute to higher household wellbeing.

New strategies to minimise the risks of MCF through cattle vaccination provide one solution to reducing conflict between pastoralists and conservationists, with opportunities for more equitable co-existence of livestock and wildlife. An experimental field study in Tanzania demonstrated that a novel MCF vaccine had a 56% efficacy at protecting cattle from infection (Lankester et al., 2016), whilst, a more recent trial in Kenya reported by Cook et al. (2019) found the same vaccine had a 81% protective effect. However, partly due to a lack of understanding of the potential demand from cattle owners and how this demand might vary with respect to different delivery strategies, there is currently no commercial production of this vaccine.

To investigate potential demand for a new vaccine for MCF, we designed and implemented a stated preference choice experiment with at-risk households in northern Tanzania. Choice experiments (also known as choice modelling) are a method originally implemented in market research that is now widely used in environmental economics, health economics and transport planning (Hanley and Czajkowski, 2019). Choice experiments allow the researcher to estimate the values that a sample of respondents place on the different attributes of a product, treatment or policy option, and their willingness to pay for increases in desired attributes (Hanley and Barbier, 2009). This ability to estimate values for the individual attributes of a yet-to-introduced product makes the choice experiment method a good choice of approach in our case, since we wished to understand how changes in the effectiveness, administration and price of yet-to-be-introduced vaccine would affect uptake across pastoralists in northern Tanzania. Despite concerns over the issue of hypothetical market bias (where indidivuals systematically under- or over-state their true Willingness to Pay for the good in question[1]), the method has been used to provide evidence for policy-making in the USA and UK (Johnston et al., 2017) and has also been employed to understand farmers' willingness to engage with livestock disease risk reduction strategies (Sok et al., 2017). Other relevant applications of the method include Scarpa et al. (2003) and Ruto et al. (2008), who look at cattle farmer's preferences for cattle traits in Kenya; Kairu-Wanyoike et al. (2014) who apply a stated preference approach to estimate farmer's willingness to pay for a vaccine against CBPP (Contagious Bovine Pleuropneumonia) in Kenya; and Iles et al. (2019), who study how this willingness to pay varies with information about local disease risk levels.[2]

Using choice experiment responses, we were able to quantify the willingness of respondents to participate in a future vaccine programme, and the determinants of variations in this demand across households. We speculated that one important driver of demand for MCF vaccine is the number of MCF cases experienced by an individual household, and therefore estimate this variable and its dependence on wildebeest abundance, grazing resources and cattle numbers.

2. Methods

The study was carried out in 12 pastoral villages selected randomly from a larger set of villages at risk from MCF in Ngorongoro, Simanjiro and Monduli Districts in northern Tanzania (Fig. 1). Wildebeest distribution and abundances in this region have been relatively well-documented through population-level surveys (Hopcraft et al., 2014; Morrison et al., 2016). Accordingly, we stratified a priori the study villages into three ‘wildebeest use’ categories: (1) low use, corresponding to villages at the periphery of the wildebeest range where exposure to MCF would require livestock to be moved into adjacent wildebeest areas (Sukenya and Naiti villages); (2) medium use, corresponding either to villages used by wildebeest intermittently as a migratory route (Selela and Oltukai villages) or as a low-density year-round range (Nainokanoka village); (3) high use, corresponding to villages used by wildebeest as a wet season grazing area during and after the MCF transmission period (Kakesio, Sakala, Oloirobi, Misigiyo, Osinon, Emboreet, Terrat villages). To validate the assumed wildebeest ‘use’, we tested the relationship between our categorical use variable and independently estimated densities of wildebeest from a combination of historical aerial census data and utilisation distributions derived from GPS telemetry. We found the two variables to be strongly related in the direction expected (see Fig. A1 in SI; $\beta_{\text{high-low}} - 5.33 \pm 0.65$, *t-value* =

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[1] As noted in Johnstone et al. (2017) a large body of research now exists which offers guidance to researchers on both the likely effect of stated preference study design on hypothetical market bias, and on which aspects of design are most important to demand revelation.

[2] For an interesting review of the effects of poverty on economic decision-making and in particular the use of trade-offs, see de Bruijn and Antonides (2021).

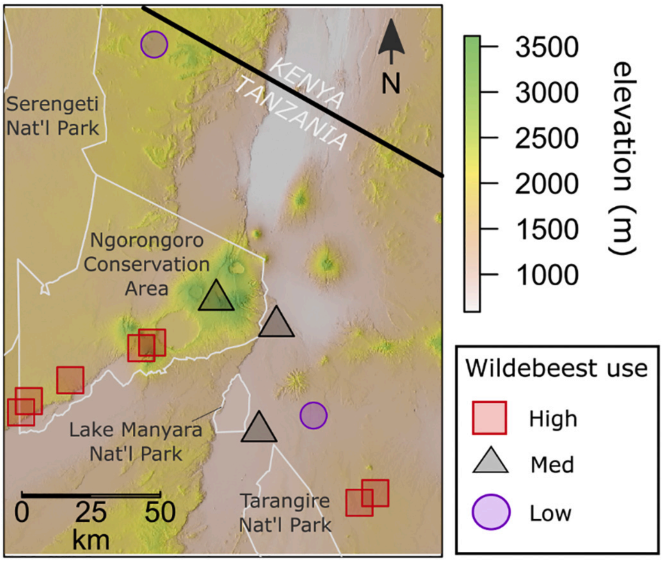

Fig. 1. Study area in northern Tanzania showing villages in which interviews were conducted . Symbols represent the three levels of wildebeest use- classified a priori based on wildebeest distribution patterns during the MCF transmission period (February–May) and used as predictors of MCF incidence (*c.f.* Fig. 4).

$-8.26, p < 0.001$; $\beta_{high\text{-}medium} - 2.60 \pm 0.65$, *t-value* $= -4.04$, $p < 0.001$). Because of incomplete and outdated coverage of wildebeest densities across all study households, we used the categorical use variable in our analysis.

A household survey was carried out between October 2018 and May 2019. Within each of the 12 villages, households were selected at random from a list of livestock-owning households provided by village leaders. Potential participants were informed about the purpose of the survey, how the information would be collected, used and stored, and finally asked to sign a consent form if they agreed to participate. Focus groups were undertaken with 56 members of the relevant population in 6 groups to help us understand how local people viewed the problem, and to test the attributes to be used in the choice experiment. A pilot survey of 20 households in the same study area was used to test the main survey design. The main survey involved face to face interviews with 204 heads of household that lasted approximately 40 min. All surveys were conducted in either Swahili (the national language of Tanzania) or Maa (the language spoken by the Maasai) according to the respondent's preferences.

The choice experiment was used to estimate the preferences of sampled households for a novel vaccine which could, hypothetically, be offered to them for purchase at some date in the near future. Choice cards were developed with different combinations of five attributes that were used to describe the circumstances under which the vaccine could be offered for sale. The attributes were selected on the basis of (a) literature on livestock vaccine adoption in East Africa, whereby price and efficacy have been identified as important attributes (e.g. Railey et al., 2018); (b) previous research and experience of factors known to affect livestock vaccination in Tanzania, including issues around trust in different animal health service providers, as well as popularity of ear tags for marking/identifying cattle vaccinated against East Coast Fever; and (c) key questions in relation to MCF vaccine development, in particular the frequency of vaccination. The current MCF vaccine requires two doses to be administered annually, and if this regimen proved to be a constraint on farmer adoption of the vaccine, future vaccine research would need to prioritise development of vaccines that would be effective when delivered through single-dose regimens. In contrast, while safety has been considered an important attribute in other studies (e.g. CBPP vaccination; Kairu-Wanyoike et al., 2014), it was not included among the attributes here as field trials have not raised any safety concerns in relation to the current vaccine (Lankester et al., 2016; Cook et al., 2019).

Table 1 provides information on the levels selected for each of these atributes and on the way these attributes were described to repondents. The combinations of the attribute levels presented in each of the choice tasks (i.e., the experimental design) were optimized for Bayesian D-error of the MNL model (Scarpa and Rose, 2008) using priors from the pilot study. Respondents were presented with a series of 12 choice cards, and, for each card, asked to choose one of two options: i) buy the vaccine with specified properties at a given price, or ii) do not buy.[3] An example is given in Fig. 2. No randomisation of choice tasks was used, in order to simplify survey implementation.

Choice data are initially modelled using a conditional multinomial logit model (MNL, Greene, 2018). Additionally, to account for preference heterogeneity we have estimated the latent class mixed logit model (LC-MXL, Mariel et al., 2020), in which class membership was a function of respondents' socio-demographic characteristics. To facilitate interpretation of the estimated coefficient, all models were estimated in Willingness to Pay (WTP)-space (Train and Weeks, 2005).[4]

Respondents were also asked to provide details on livestock owned, experience of MCF during the previous 5 years (2014–2018), and actions taken to reduce risks of MCF infection, as potential determinants of demand for vaccine (see Table A2 in SI). With respect to possible determinants of MCF incidence, we predicted this would be highest (1) in areas with abundant grazing resources that attract both cattle and

Table 1
Attributes and levels used in the choice experiment design.

Attribute	Levels and description
Vaccine price (TZS[a])	5 levels *(5000, 10,000, 15,000, 20,000, 25,000)*
Vaccine efficacy	3 levels (*50%, 75%, 90%)*
Authority providing vaccine	3 levels (*Private vet, government vet, NGO vet)*
Ear tagging provided	2 levels (*Yes and no)*
Vaccination frequency to achieve immunity	3 levels (*once a year, twice a year, once for life)*

Respondents were told:

"The hypothetical programs we are about to present will be described using five different attributes. They are as follows:

1. *Vaccine price - refers to what the vaccine may be priced at. Please consider it carefully when deciding if you would participate in a given program and vaccinate your cattle or not.*
2. *Vaccination efficacy - even if vaccinated, some cows may still get ill. Vaccines differ in terms of how effective they are. While some work in 50% of cases others may protect up to 90% of vaccinated cattle.*
3. *Authority - the new program could be administered by the government vet, Non-Governmental Organisation, or a private vet, and for some respondents this can matter and affect whether they participate or not.*
4. *Ear tagging - the program may require vaccinated cattle to be tagged, by putting a clip on the cattles' ears. This way vaccinated cattle can be easily distinguishable from untagged cows which have not been vaccinated.*
5. *Vaccination frequency - some vaccines are only administered once per cattle's life, while others may need to be administered every year, or twice a year to be effective.*

Put together, these attributes describe different vaccination schemes. For each of the cases we are about to present to you we would like to know whether you would be willing to participate in such a program and pay the cost - or not participate and pay no cost."

[a] At the time of the study, 2277 Tanzanian shillings (TZS) were equivalent to one US$.

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[3] See Bech et al. (2011) on the importance of the number of choice sets in an experimental design.

[4] The models were estimated in Matlab, using a Discrete Choice Experiment (DCE) package available at https://github.com/czaj/DCE. The code and data for estimating the specific models presented in this study, as well as supplementary results, are available from http://czaj.org/research/supplementary-materials.

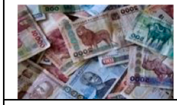
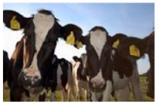
Attribute	Vaccine	No vaccine
Price per animal treated 	TZS 5,000	0
Efficacy 	75%	
Authority 	Private Vet	
Tagging 	Yes	
Vaccination Frequency 	Twice a year	
Choice (please choose ONE option only)	☐	☐

Fig. 2. Example of a choice card. Each respondent was presented with 12 such cards. Respondents ticked one of the choice boxes in each card to show whether or not they would purchase a vaccine with these characteristics.

wildebeest during the period of MCF tranmission, and (2) in areas where grazing resources were more unpredictable from year to year such that pastoralists may have had difficultly anticipating whether wildebeest would be present. Grazing resources were quantified using the Normalized Difference Vegetation Index (NDVI), a metric of vegetative greenness often used in studies of grazers as a proxy for grass forage availability (Pettorelli et al., 2005). NDVI values were generated from images collected aboard NASA's MODIS satellite that are atmospherically-corrected, filtered for quality (e.g. due to cloud cover) and aggregated every 16 days at a spatial resolution of 250m^2 per pixel. Around each household location, we created circular buffers with a radius of 7.72 km, corresponding to the median daily distance traveled by GPS-collared cattle in a separate study in Northern Tanzania (Ekwen, 2020). Because the grazing locations of cattle may have varied across the five years and were difficult to ascertain through interviews, we used spatially-averaged NDVI values within the 7.72 km buffer to represent vegetative greenness for each herd. We constrained the calculation of NDVI to the period of MCF transmission (February – June), and calculated mean(NDVI) across the five years in which interviewees reported MCF cases (2014–2018), and calculated sd(NDVI) across all years of available NDVI data (2000–2018). We assumed that mean(NDVI) reflected the relative availability of grazing resources for both wildebeest and cattle, and that sd(NDVI) reflected (1) the intrinsic unpredictability of a location's grazing resources across years during the MCF transmission period, and (2) the ratio of grassland to forest cover, with more forest cover resulting in lower sd(NDVI) values. NDVI values were rescaled to a mean of 0 and standard deviation of 1 prior to analysis.

MCF incidence was calculated as the number of cases reported by respondents over the previous five years, divided by the current number of cattle reported in the herd, and standardized as cases per 1000 cattle. Although we did not attempt to ascertain or confirm the number of reported cases, the disease is well recognised by cattle owners in MCF-risk areas, and all cattle deaths reported as suspected MCF cases in previous studies in northern Tanzania were subsequently confirmed by laboratory diagnosis (Cleaveland et al., 2001; Lankester et al., 2016). We fitted a generalized linear mixed effects model to MCF incidence data and assumed a negative binomial error distribution, using the ‘glmmTMB’ package in R (Brooks et al., 2017). We included several linear predictors in the model: (1) wildebeest use (‘low’, ‘medium’ and ‘high’), (2) number of cattle owned per household (i.e. ‘herd size’), (3) mean vegetative greenness (i.e. ‘mean(NDVI)’) and (4) standard deviation of vegetative greenness (i.e. ‘sd(NDVI)’). Village ID was used as a random intercept. We compared four nested candidate models using likelihood ratio tests. The model set evaluated the importance of wildebeest use, mean(NDVI) and sd(NDVI), relative to a global model.

3. Results

3.1. *Choice experiment*

The choice experiment involve a total of 2688 choice observations from 224 respondents, since pilot survey choice responses could be pooled with main survey responses. No respondent chose only the “purchase vaccine” or the “do not purchase vaccine” option in all 12 of their choices. Based on analysis not reported here, we found no evidence of fatigue effects across the sequence of choices.The estimation results are presented in Table 2.

The first (baseline) model is the MNL used to illustrate the general effect of choice attributes on farmers choosing to vaccinate or not. The utility function is rescaled to be money-metric, so the estimated coefficient can be directly interpreted as WTP (in 10,000 TZS). The signs and relative values illustrate the relative impact of the treatment attributes on respondents' choices. We find that for the MNL model, higher efficacy of the vaccine substantially and significantly increased the probability of choosing the treatment. Respondents would be willing to pay 325 TZS extra for each percentage point increase of efficacy of the vaccination. The frequency of vaccine administration was not seen as an important factor on average. However, ear tagging vaccinated cattle made the program seem significantly more attractive (valued at over 14,000 TZS) and hence more likely to be accepted. Vaccines administered by private vets were seen as preferrable to NGO vets (WTP 1450 TZS higher), with government vets in between, on average (although not statistically significant). As expected, we find that the higher the cost of the vaccine, the less likely it is to be purchased.

The next model presented in Table 2 (the latent class model) is a more elaborate and better fitted model assuming the existence of preference heterogeneity in the form of distinct classes. While membership of individuals in these classes is probabilistic (the classes are latent), their mixture represents overal preferences of the population. Individuals of class 1 preferences value efficacy of the vaccine at 331 TZS per percentage point, tagging at 1736 TZS and prefer private or NGO to government vets. The average class 1 membership probability is 42%, with higher income individuals and households with more MCF cases in the past more likely to belong to this class, relative to class 3 (which is used as a reference). The WTP of class 2 respondents for efficacy increase is higher than class 1 respondents (490 TZS per percentage point), their WTP for a vaccination program that includes tagging is 1532 TZS and they are indifferent with respect to who administers the vaccines. The average class 2 membership probability is 51%, significantly increased for respondents with higher household income. Class 3 represents the lowest share of preferences (6.5%), with significant WTP for the vaccination program (1924 TZS), relative to no vaccination, but no sensitivity to changes in efficacy. Respondents of these type are actually against tagging – it reduces their WTP by 1443 TZS. They prefer private or government vets, relative to NGO vets.

Table 2
Estimation results of the models of respondents' WTP for the attributes of the vaccine.

	Multinomial logit model	Latent class model		
		Class 1	Class 2	Class 3
No vaccine (alternative specific constant)	0.4738 (0.3474)	1.1102 (0.7180)	0.4993 (1.0530)	−1.9426** (0.9331)
Efficacy (%)	3.2544*** (0.4083)	3.3076*** (0.7057)	4.9025** (2.4091)	0.0138 (1.0645)
Frequency (per year)	0.0043 (0.0720)	0.1338 (0.1089)	−0.2496 (0.3140)	0.1113 (0.0932)
Tagging	1.4131*** (0.1860)	1.7361*** (0.2724)	1.5324*** (0.5785)	−1.4427*** (0.3807)
Private vet (vs. NGO vet)	0.3749** (0.1623)	0.5026* (0.2802)	−0.1952 (0.5790)	1.8030*** (0.2136)
Government vet (vs. NGO vet)	0.1485 (0.1304)	0.3954** (0.1917)	−0.2987 (0.5461)	−0.1141 (0.1447)
Cost (10,000 TZS)	−0.8223*** (0.0732)	−1.4924*** (0.4536)	−0.4707** (0.2298)	−4.1229*** (1.1565)
Class membership				
Constant		3.7943*** (1.4023)	4.0133*** (1.5564)	0 (fixed)
log(MCF cases)		1.6827** (0.8242)	1.0455 (0.8005)	0 (fixed)
log(household income)		2.4975** (1.0089)	2.8534*** (1.0018)	0 (fixed)
Average class probabilities		42.20%	51.29%	6.51%
Model diagnostics				
LL at convergence	−1478.63		−1436.93	
LL at constant (s) only	−1673.40		−1673.40	
McFadden's pseudo-R^2	0.1164		0.1413	
Ben-Akiva-Lerman's pseudo-R^2	0.5813		0.5911	
AIC/n	1.1054		1.0892	
BIC/n	1.1207		1.1485	
n (observations)	2688		2688	
r (respondents)	224		224	
k (parameters)	7		27	

Note: *, **, *** indicate significance at 10%, 5%, and 1% level, respectively. Standard errors given in parentheses.

The simulated WTP for a highest-valued vaccination program (with 90% efficacy, frequency of administration of once per year, tagging included, and administered by a private vet) was valued at 42,391 TZS for individuals with class 1 preferences, 50,005 TZS for class 2, and 24,266 TZS for class 3. Noting that whilst the class membership of all individuals in the sample is probabilistic, it is possible to simulate overall (average) WTP for such a vaccine program at 45,116 TZS with a 95% confidence interval of 31,529 to 58,324 TZS.

The results of the latent class model (see Fig. 3) were then used to predict how the probability of accepting the hypothetical offered vaccine treatment offered differs for various cost levels. As expected, the probability of accepting the vaccination program approaches unity for costs close to zero. As the cost increases, the probability of acceptance becomes lower – for costs exceeding 60,000 TZS it falls below 0.25. The estimated probability of acceptance translates to the expected share of farmers adopting the treatment at different cost levels. As a result, it can be used to design future policies offering MCF treatments.

3.2. Predictors of MCF incidence

The most parsimonius model of MCF incidence in cattle included wildebeest use, log-herd size, mean(NDVI) and sd(NDVI) as significant predictors (see Table A1 in SI). MCF incidence increased in cattle herds

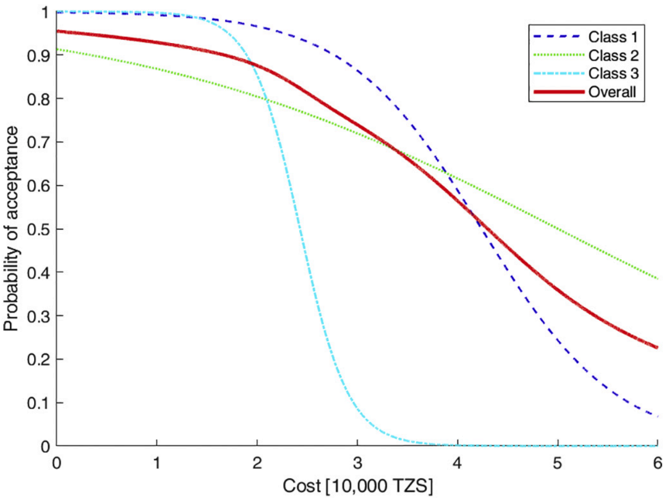


Fig. 3. The estimated probability of accepting the treatment program at various levels of its cost (in Tanzanian shillings), for three different latent classes of preferences.

that occurred in 'medium' wildebeest use areas, relative to herds in 'high wildebeest use' areas ($\beta = 0.44 \pm 0.12$, z-value $= 3.63$, $p < 0.01$) though MCF incidence was not different between low and high use areas ($\beta = 0.24 \pm 0.16$, z-value $= 1.49$, $p = 0.13$; Fig. 4a). Herd size was strongly negatively associated with MCF incidence ($\beta = -0.95 \pm 0.07$, z-value $= -13.95$, $p < 0.01$; Fig. 4b). MCF incidence in cattle herds decreased with higher mean NDVI ($\beta = -0.12 \pm 0.05$, z-value $= -2.45$, $p = 0.01$; Fig. 4c) and decreased with greater variability in NDVI ($\beta = -0.27 \pm 0.06$, z-value $= -4.66$, $p < 0.01$; Fig. 4d).

4. Discussion

MCF has long been a serious threat to pastoral livelihoods in East Africa, with pastoralists living in risky areas consistently ranking MCF as among the livestock diseases of greatest concern (Cleaveland et al., 2001; Bedelian et al., 2007). Over the past six decades, efforts have been made to develop effective cattle vaccines to minimise disease risks and to reduce the high costs of movement avoidance strategies (Lankester et al., 2015). Now that a partially-protective vaccine has been developed (Lankester et al., 2016; Cook et al., 2019), this study set out to identify factors influencing the likely adoption of MCF cattle vaccines in pastoral communities.

We found that as the vaccine price increases, the probability of farmers choosing to adopt the vaccine decreases (Fig. 3). However, the probability of acceptance was high across all prices included in the choice experiment (up to TZS 25,000) reflecting the anticipated high demand for vaccine. This contrasts with the study by Kairu-Wanyoike et al. (2014) in Kenya for CBPP vaccination, which found that a large fraction of farmers were not willing to pay for vaccination, and indeed for around 1/3rd of farmers would require compensation to allow animals to be vaccinated freely. Vaccine efficacy was a further significant factor in herd-owners choosing to vaccinate. Studies of foot-and-mouth disease (FMD) vaccination among agropastoral farmers in Tanzania similarly show that vaccine performance is a key factor underlying farmers' decisions on vaccination (Railey et al., 2018). Pastoral livestock-owners in this area are also well aware of problems associated with livestock vaccine performance, for example, in relation to currently-available FMD vaccines, which have limited effectiveness against circulating FMD virus strains in Kenya (Lyons et al., 2015). Existing vaccines against another cattle disease, contagious bovine pleuropnuemonia, also have low efficacy (52–77%, Nkando et al., 2012), although willingness-to-pay studies in Kenya indicate that, for this disease, pastoralists are influenced more by concerns about harmful side effects of vaccination and the frequency of vaccination than factors affecting efficacy (Kairu-Wanyoike et al., 2014). Given that field trials showed only partial protection of a new MCF vaccine (up to 81%),

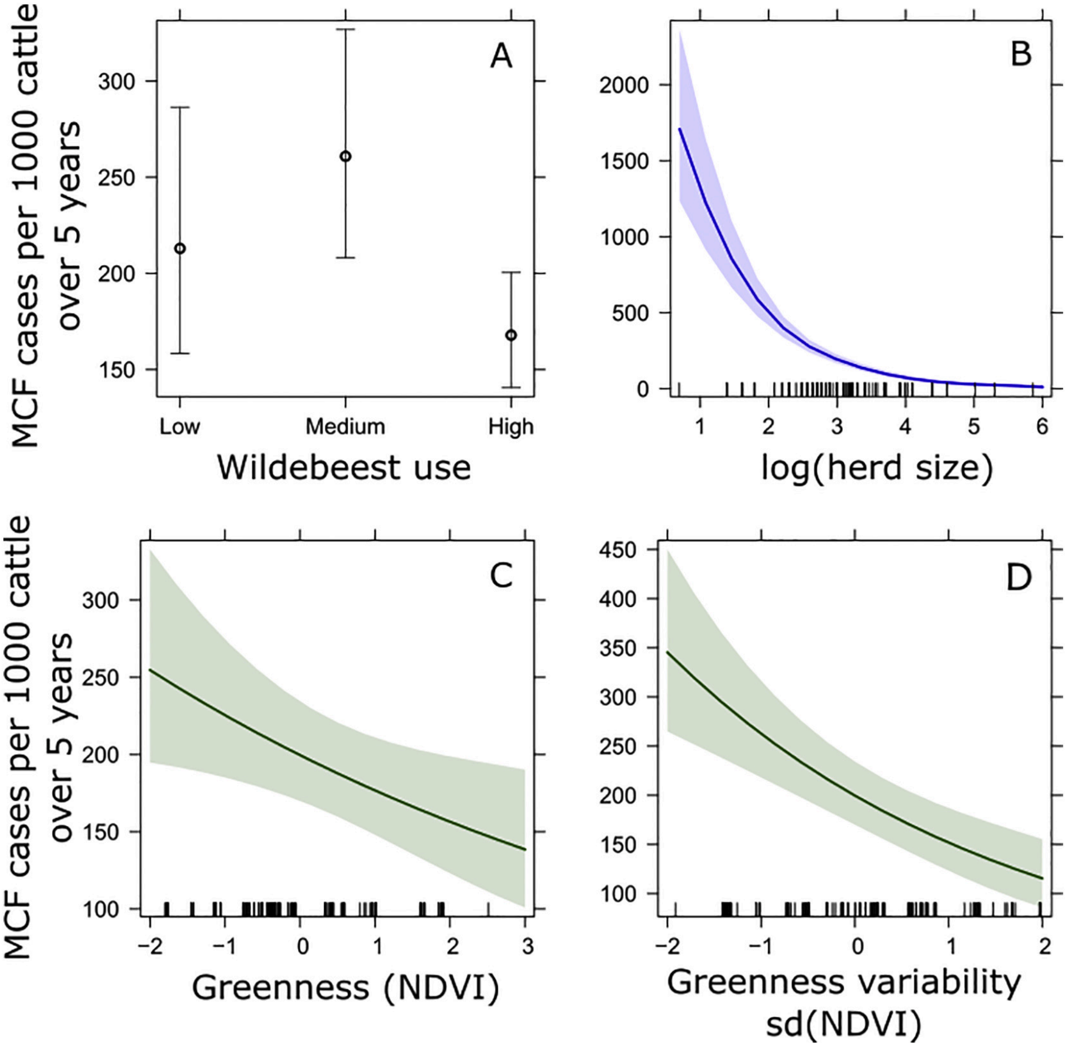


Fig. 4. Predicted MCF incidence across pastoralist households in Northern Tanzania over last five years as a function of (A) wildebeest use, (B) number of cattle owned per household (i.e. 'herd size', natural log-transformed), (C) mean vegetative greeness, and (D) interannual variability in the long-term (2000–2018) vegeative greenness. NDVI metrics (C-D) were limited to the MCF transmission period (February–May).

information about vaccine efficacy will need to be conveyed very clearly for effective decision-making.

In our study, frequency of vaccination was not generally seen as an important factor although, understandably, owners of large herds preferred less frequent vaccination. This finding provides reassurance that the current two-dose administration required for the new MCF vaccine, along with annual boosters, will not deter most cattle owners. Side effects were not included among the attributes, as field trials have not raised any safety concerns (Lankester et al., 2016; Cook et al., 2019).

A clear finding from our study was that ear-tagging vaccinated cattle made the program significantly more likely to be accepted. This suggests that such visible demonstrations of vaccination status are likely to have benefits for farmers in relation to an increased value of cattle that can be shown to have been vaccinated. This is consistent with results of a household survey in northern Tanzania, showing that farmers vaccinating against East Coast Fever (ECF) expect their cattle to have a 10–20% greater market value than non-adopters and that, for indigenous cattle, sale value of vaccinated animals was 10–20% higher than for unvaccinated animals (N. Gammon, GALVmed, personal communication). An important point in interpreting results of our study in relation to ECF study is that farmers may not have been aware of differences in the duration of immunity between ECF and MCF vaccines. For ECF, a single vaccination confers life-long immunity whereas the MCF vaccine is likely to need regular booster vaccinations, and tagging may therefore not provide such a reliable indicator of protection as for ECF.

The attitudes of Tanzanian pastoralists towards animal health providers have been shaped by many social, economic and historical influences (Davis and Sharp, 2020). We were therefore interested to investigate whether vaccine was administered by government, private or NGO vets would affect adoption. In this study, owners expressed a preference for vaccine delivered by private vets over government and NGO vets. Further work will be needed to explore the reasons for these preferences and how this may affect future vaccination efforts.

Reported MCF incidence was relatively high in areas with low vegetative greenness over the 5 year period (Fig. 4c), likely reflecting the fact wildebeest and cattle prefer low NDVI areas in the wet season because of high nutrient concentrations in grasses in these areas (Stabach et al., 2016). Reported MCF incidence was also negatively associated with the long-term variability in NDVI, suggesting that, across years, sites with more predictable grazing resouces carry greater MCF risks. Households associated with low sd(NDVI) were located adjacent to forested areas in the Ngorongoro Conservation Area where grassland habitat is only available in the downslope direction (generally west or northwest). Thus, forests may act as a habitat barrier that constrains cattle movements making it more difficult to access areas away from wildebeest. Other spatial constraints on cattle movement such as cultivated land, human settlements or protected areas may similarly benefit most from MCF cattle vaccination.

With changes in climate in East Africa likely resulting in lower overall rainfall and increasing unpredictability (Nicholson, 2017; Borhara et al., 2020), and with reduced availability of grazing lands (Reid, 2012), pastoralists are likely to face increasingly difficult decisions about reducing risks from MCF. The challenges of climate change are reinforced by results showing that areas with medium wildebeest use experience the highest incidence of MCF. In areas with consistently high levels of wildebeest use, transmission risk is likely to be deemed large enough for pastoralists always to choose to move cattle away from wildebeest to avoid MCF. In areas with low levels of wildebeest use, transmission risk and disease incidence are both likely to be low, regardless of whether people move cattle or not. However, in areas with medium wildebeest use, the decision around expected costs and benefits of avoidance may be less clear, leading to high-incidence years when a 'wrong' decision is made. Additional, broad-scale distribution data of wildebeest are needed to assess relative risks in different areas (e.g. Tarangire versus Ngorongoro ecosystems).

Given that MCF is transmitted only from wildebeest, and not from cattle to cattle, we would not have expected incidence to increase with herd size. However, the finding of a higher incidence of MCF in smaller herds suggests that small herds are at greater risk from exposure to MCF from wildebeest. Several factors may explain these findings. First, cattle owning families with small herds may be less likely than families with large herds to move cattle away from the permanent boma to avoid MCF. Pastoral families with small herds are likely to be more impoverished and suffer greater insecurity than families with large herds, and the loss of available milk associated with moving cattle away from the permanent household in order to avoid MCF may not be tolerable. Second, families with small herds may have a lower social status and are less influential than families with larger herds, who are likely to have preferential access to 'safer' village grazing areas away from wildebeest. Third, moving herds away from grazing areas around the family home requires herders to be with the cattle for several months (Lankester et al., 2015). Families with smaller herds may not have access to, or funds to pay for, the labour (family members or brought in help) required to do this. The finding of a higher incidence of MCF in smaller herds highlights the problem that MCF, like many other infectious diseases, is likely to have a disproportionate impact on more impoverished families. Vaccine affordability is therefore likely to be a major consideration if MCF vaccination is to achieve optimal benefits in addressing livelihood and food security needs of the poor.

In addition to the livelihood benefits that an MCF vaccine might bring, there are also likely to be complex ecological implications of vaccine use [Homewood et al., 2006]. For example, vaccine availability would likely lead to a change in traditional MCF avoidance strategies, releasing cattle owners from the need to move their herds away from wildebeest each year, possibly resulting in detrimental grazing competition in critical buffer zones near the boundaries of protected areas that are vital for wildebeest populations during their calving season. Further, changes to wildebeest behaviour or movements, or increasing levels of livestock predation and retaliatory killing of predators that follow the wildebeest migration, could excacerbate the 'squeezing' of wildlife into increasingly confined areas of the Serengeti and Tarangire National Parks, threatening the long-term integrity of the ecosystems (Veldhuis et al., 2019).

A further concern is that increased profits generated through livestock may be invested in commercial cultivation and the ecologically damaging trend towards fragmentation and fencing of rangelands that has been seen in many parts of East Africa (Lamprey and Reid, 2004; Homewood et al., 2009; Morrison et al., 2016), with potentially complex implications for the regional ecology. One study showed no evidence that the increased income generated from improved livestock survival was being invested in commercial mechanized cultivation. Rather, it suggested that livestock keeping would become profitable enough that pastoralists focus their labour primarily on livestock production and trade, while keeping some subsistence level of cultivation (Homewood et al., 2009). Indeed, improvements in livestock health through reductions in disease risks might help sustain traditional livestock-based livelihoods, whilst reducing the need to keep large herds as an insurance against drought and disease, resulting in smaller and less ecologically impactful herds. It is clear, however, that the drivers of land use change and conversion of rangelands around wildlife-protected areas are numerous and complex. These not only include factors associated with food security but fears of land alienation from the expansion of commercial agriculture and conservation, as well as policies that encourage Maasai to adopt more settled land use practices in line with Tanzanian norms, including cultivation (Davis, 2011). As such the social and ecological consequences of an MCF vaccine are likely to be hard to predict, and further research is required to address the question of how the availability of an MCF vaccine will impact land-use patterns and rangeland utilisation.

5. Conclusions

Results from this study indicate a high willingness among pastoralists to adopt efficacious vaccines to prevent MCF in their cattle. Adoption of an MCF vaccine is likely to have important consequences for livestock movement and grazing patterns in pastoral rangeleands adjacent to the Serengeti National Park and in other areas where wildebeest can be found, with cattle being able to graze more safely in proximity to wildebeest herds during the MCF risk period. By grazing on higher quality pasture nearer to permanent bomas, cattle would gain body condition more rapidly after the dry season and yield a more reliable supply of milk to families, thereby improving pastoralist nutrition and household well-being.

The prospect of an MCF vaccine is tantalising and challenging, but the opportunity now needs to be taken to investigate the ecological impacts that an effective MCF vacine might have on fragile rangeand ecosystems and to explore whether vaccination could support an ecologically sustainable and more equitable model of wildlife-livestock co-existence across Africa.

Ethical statement

Data was collected in accordance with the ethical standards of the University of Glasgow and the national research committees COSTECH and TAWIRI in Tanzania; and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. This study was approved by the Tanzania Wildlife Research Institute and Tanzania Commission for Science and Technology (COSTECH permit No.2018–427-NA-2018-243) . Ethical clearance was obtained through the University of Glasgow College of Medical, Veterinary and Life Sciences Ethics Committee (Ref: 200180030).

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2021.107189.

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