Community health and human-animal contacts on the edges of Bwindi Impenetrable National Park, Uganda

Renata L. Muylaert[1&*], Ben Davidson[1&], Alex Ngabirano[2,3], Gladys Kalema-Zikusoka[2], Hayley MacGregor[4], James O. Lloyd-Smith[5], Ahmed Fayaz[1], Matthew A. Knox[1], David T. S. Hayman[1&]

[1]RLM: https://orcid.org/0000-0002-6466-6210, DH: https://orcid.org/0000-0003-0087-3015, MAK: https://orcid.org/0000-0001-6764-6568 Molecular Epidemiology and Public Health Laboratory, Hopkirk Research Institute, Massey University, Palmerston North, New Zealand

[2]https://orcid.org/0000-0003-3473-32052 Conservation Through Public Health, Plot 3 Mapera Lane, Uring Crescent, Entebbe, Uganda

[3]Bwindi Development Network, Buhoma, PO Box 109, Kanungu, Uganda

[4]http://orcid.org/0000-0002-9392-9331 Institute of Development Studies, University of Sussex and STEPS, Brighton BN1 9RE, United Kingdom

[5]https://orcid.org/0000-0001-7941-502X Department of Ecology and Evolutionary Biology, University of California Los Angeles, Los Angeles, CA, United States of America

[*]Corresponding author

E-mail: R.deLaraMuylaert@massey.ac.nz

[&]These authors contributed equally to this work

Abstract

Cross-species transmission of pathogens is intimately linked to human and environmental health. With limited healthcare and challenging living conditions, people living in poverty may be particularly susceptible to endemic and emerging diseases. Similarly, wildlife is impacted by human influences, including pathogen sharing, especially for species in close contact with people and domesticated animals. Here we investigate human and animal contacts and human health in a community living around the Bwindi Impenetrable National Park (BINP), Uganda. We used contact and health survey data to identify opportunities for cross-species pathogen transmission, focusing mostly on people and the endangered mountain gorilla. We conducted a survey with background questions and self-reported diaries to investigate 100 participants' health, such as symptoms and behaviours, and contact patterns, including direct contacts and sightings over a week. Contacts were revealed through networks, including humans, domestic, peri-domestic, and wild animals for 1) network of contacts seen in the week of background questionnaire completion, 2) network of contacts seen during the diary week. Participants frequently felt unwell during the study, reporting from one to 10 disease symptoms at different intensity levels (maximum of seven symptoms in one day), with severe symptoms comprising 6.4% of the diary records and tiredness and headaches the most common symptoms. Besides human-human contacts, direct contacts with livestock and peri-domestic animals were the most common. Wildlife contacts were the rarest, including one direct contact with gorilla with a concerning timeline of reported symptoms. The contact networks were moderately connected and revealing a preference in contacts within the same species or taxon and within their groups. Despite sightings of wildlife being much more common than touching, one participant declared direct contact with a mountain gorilla during the week. Gorillas were seen very close to six animal taxa (including themselves) considering all interaction types, mostly seen closer to other gorillas, but also people and domestic animals. Our findings reveal a local human population with recurrent symptoms of illness in a location with intense exposure to factors that can increase pathogen transmission, such as direct contact with domestic and wild animals and proximity among animal species. Despite significant biases

44 and study limitations, the information generated here can guide future studies, such as models for

45 disease spread and One Health interventions.

46 **Keywords:** disease ecology, close contact, self-reported survey, mountain gorilla, tropical forest,

47 human-animal interface, One Health, spillover

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Introduction

50   The COVID-19 pandemic, now the 'poster child' of the impact of an emerging infectious

51 disease, is suspected to have originated from a virus circulating in wild mammals [1]. Ebola virus

52 disease, HIV/AIDS, and SARS are all infamous emerging infectious diseases with origins in wildlife.

53 In fact, most human infections have their origins in wild or domestic animals. Therefore, despite

54 providing many benefits to health—such as overall well-being and services, including medicinal herbs

55 and provision of other natural resources [2–4]—green natural areas can also pose risks to human health,

56 especially when living in proximity to green areas is linked to social inequality and low-socio-economic

57 status.

58   In low to middle-income countries, and particularly in tropical regions, people also still suffer

59 from a high burden of numerous and treatable endemic diseases. These infections may be human-

60 adapted (e.g., malaria [5]) or zoonotic (e.g. leptospirosis [6]). Contacts between humans and other

61 animals can, therefore, pose hazards to human health, but the converse is also true [7]. Human behaviour

62 has contributed to species extinction rates much higher than pre-Anthropocene levels [8]. Habitat

63 destruction, climate change, pollution, species invasion, wildlife trade, and overharvesting [9–11] can

64 negatively impact ecosystems, leading to the declining health of many species [12]. In some cases, this

65 may be in the form of increased risk of pathogen transmission, with many examples where infectious

66 diseases have contributed to the decline of endangered wildlife species [13,14].

67   Disease risk is especially important in non-human great apes, such as the endangered

68 chimpanzees, bonobos (*Pan paniscus*), the Western lowland gorilla (*Gorilla gorilla gorilla*), Grauer's

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69   gorilla (*Gorilla beringei graueri*), and the mountain gorilla (*Gorilla beringei beringei*). They are all

70   endangered or critically endangered species [15] threatened by disease, poaching, and habitat loss. The

71   plight of non-human great apes is even more critical because their close relatedness to humans may

72   pose a higher risk for cross-species transmission of infections [16,17]. Human respiratory viruses can

73   be transmitted to gorilla populations from people, as in the case of Human Respiratory Syncytial Virus

74   [18].

75   Ebola virus disease (EVD) outbreaks in Central Africa have killed thousands of both people

76   and apes, with uncertain transmission pathways. These outbreaks have decimated the critically

77   endangered Eastern Lowland gorilla (*Gorilla beringei graueri*) population, reaching 90% mortality in

78   some areas [19]. Analyses of human EVD outbreaks suggest that land-use changes, particularly forest

79   fragmentation, may be increasing the risk of these outbreaks [20,21]. The human population density is

80   high in many African regions that share an interface with non-human great apes' habitat, such as in

81   Bwindi Impenetrable National Park (BINP) and the Virunga Volcanoes. Habitat degradation and human

82   encroachment—the land bordering BINP has an average population density of 300-400 people/km^2

83   [22], much higher than the average for Uganda (229 people/km^2, [23])—and ecotourism increase

84   human-wildlife contact.

85   Communities around BINP have had to deal with civil unrest, including after the displacement

86   of human populations by the creation of the park [24]. Precarious livelihoods are common around the

87   park. Yet, the area is an ecotourism destination with frequent visits to habituated groups of apes [25].

88   These factors, along with high inbreeding levels [26], probably increase the frequency and severity of

89   disease outbreaks in mountain gorillas [27,28] due to the increased susceptibility to and transmission

90   of infections via increasing contact rates.

91   More than 20 disease-causing pathogens are transmitted from humans to great apes [25]. These

92   pathogens include several viruses [18,29,30], bacteria, ectoparasites and endoparasites [31], leading to

93   diseases such as giardiasis and cryptosporidiosis [32]. Close contact, within a few meters of a coughing

94   or sneezing individual, would be enough for pathogen transmission from one species to another.

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95   Moreover, pathogens spread by the faecal-oral route can be readily shared among species that overlap
96   spatially and share resources such as waterways. On the other hand, regarding the gorilla-human
97   interface, there are no reports of HIV transmission between humans and gorillas. However, HIV causes
98   immunosuppression in humans, leaving people susceptible to tuberculosis and other respiratory
99   diseases, which pose a threat to gorilla populations [25,33,34]. Nevertheless, there are
100   immunodeficiency viruses that had their ancestry in apes [35], such as SIVcpz from chimpanzees in
101   Cameroon [36], which is thought to be the ancestral group for the pandemic HIV-1 group M. Thus, it
102   is essential to investigate contact patterns between humans and other primates at the boundaries of
103   natural areas.

104   Interdisciplinary frameworks consider key ultimate and proximate components that drive cross-
105   species infection transmission to understand the process of disease emergence [37,38]. Studying and
106   addressing these components requires multidisciplinary teams comprising local community members,
107   ecologists, anthropologists, physicians, and more [39,40]. Ultimate drivers include broad
108   environmental, social and politico-economic drivers operating at different timescales and spatial scales
109   [38,41]. Living conditions and higher-level structural drivers, beyond the actions of individuals, may
110   have a large impact on people's livelihoods and the outcomes of the interactions between humans and
111   nature. Human communities in poor regions in proximity to natural areas frequently suffer from various
112   diseases and take the toll of inadequate health facilities, the precarity of livelihoods, food insecurity,
113   illiteracy, and concurrent proximity to livestock and wildlife, making them susceptible to cross-species
114   transmission. The proximate drivers comprise the 1) prevalence in the reservoir, which falls in the scope
115   of disease ecology; 2) contact rates, a prevalent knowledge gap for many systems; and 3) probability of
116   infection given exposure, which falls in the domain of microbial risk assessment.

117   Regarding contact rates, proximate driver 2, quantifying behaviour and contact patterns to
118   inform disease spread models can be challenging. Large projects attempting to measure demographics
119   and patterns of human-human contact have been conducted worldwide at small [42] and large scales
120   [43], with essential applications in epidemiological models [44]. While identifying human contact
121   patterns is important to predict onward disease spread, contact with wildlife and livestock is a crucial
122   factor allowing pathogen cross-species transmission to happen. However, data sets describing human-

123   animal contacts together with animal-animal contacts (such as Narat et al., in Central Africa [42]) are

124   rarely reported [45,46]. Contact data between numerous species can be cumbersome to gather by direct

125   observation but can be estimated from survey participants' perspectives, whereas self-declared

126   information can reveal relevant general contact patterns and health. Questionnaire research is hardly

127   ever objective [47]; nonetheless, self-declared information can be used as feedback to guide actions

128   most needed in small communities. Interventions like keeping distance from wildlife and handwashing

129   before preparing meals can greatly reduce the cross-over of disease-causing pathogens [48,49].

130   Initiatives to promote these types of needed actions have been made in the BINP, which economically

131   relies heavily on subsistence agriculture [50]. In this ecosystem, close relationships people have with

132   other people, their livestock and other animals can be explored through social science approaches and

133   measured by further focused enquiry informed by conceptual models of cross-species transmission

134   [37,39,40]. Understanding the potential contacts between humans and other animals and their network

135   structure can help inform the control measures required to manage and prevent future disease outbreaks.

136   This study used questionnaires to investigate people's health and potential risk factors for

137   infectious diseases investigating the contacts among humans, domestic, peri-domestic and wildlife, with

138   a particular focus on humans and the endangered mountain gorilla. We describe contact patterns in

139   humans and other animals living close to BINP through self-reported surveys for one week. We

140   analysed contact patterns for 1) human-human contacts, including the participants' social contacts and

141   their reported observations; 2) animal-human contacts, including direct contacts and sightings and 3)

142   their observation of animal-animal contacts in proximity to the animal-human interface. We expected

143   human contact patterns to follow patterns reported previously for southwestern Uganda [51]. We

144   expected wildlife sightings would be much more common than touching, with the existence of close

145   contact preferences within-taxon and within groups (domestic, peri-domestic, people, and wild

146   animals). Our questionnaire provides insights on community health and human-animal interface in two

147   villages near BINP.

Methods

Location and context

This study took place in Mukono parish at Bwindi Impenetrable National Park's Buhoma sector in Uganda, between June and August 2018. Questionnaires were completed by local villagers living next to the northwest border of BINP, Uganda. BINP covers an area of 331 km^2 in southwestern Uganda (Fig 1A, Fig 1B), and the villages are adjacent to BINP at the north-western edge of the park. This community was selected because it represents a scenario with risks of infection for both humans and wildlife where One Health initiatives have been put in practice [34]. People in the community generally have very low incomes, poor public health, and live in farmland areas adjacent to the highly biodiverse forests (Fig 1A) [34,52].

Figure 1. A. Hard border between the BINP forests and agricultural land. Photo credit: D. Hayman. **B. Study location around Bwindi National Park**, where questionnaires were applied to 100 people living in the Buhoma sector, Mukono Parish, Kanungu District, Southwestern Uganda. Source for shapefile: Mesa-IGAD geoportal http://mesa-geoportal.icpac.net/layers/geonode%3Abwindilulc2010 (accessed in July 2020).

Health around BINP

In Buhoma, the human lifetime fertility rate is five births per woman for 2020, with a median population age of 15.7 [53]. About 42% of people live in poverty in 2020 and the literacy rate is 77% (males 83%, females 71%, data from 2018 for 15+ year-old people [53]). The disease burden in the local human community is high with over 10% mortality in under 5-year-old children [54]. The population around Bwindi has a high prevalence of infectious diseases where malaria, respiratory diseases and diarrhoea are very common [55]. Moreover, the majority of the diagnoses from the local hospital are human diseases that can also pose a threat to great apes [56,57]. Limited access to clean water and soap are associated with poor hygiene in the local community, which can favour the spread

174 of diseases, such as COVID-19, typhoid and Hepatitis A [58]. Traditional healers practice in the

175 community alongside the nearest hospital providing basic medical care, just 2.8 km from the Buhoma

176 park headquarters, and a local store that sells antibiotics and other remedies off the shelf in the local

177 village.

Human-animal interface around BINP

179 BINP was a forest reserve until it was gazetted as National Park in 1991 [59,60]. The park is

180 home to around 120 mammal species with ten species of primates, including the endangered mountain

181 gorilla [61]. Other primates common to this area include chimpanzees, blue monkeys (*Cercopithecus*

182 *mitis,* hereafter monkeys), Colobus monkeys (*Colobus* spp., hereafter Colobus monkeys) and olive

183 baboons (*Papio anubis,* hereafter baboons). The formation of BINP led to local resentment due to

184 inadequate community consultation and concern about loss of access to resources. Agreements and

185 policy implementation plans (Integrated Conservation and Development) to ensure that the local

186 communities would benefit from the forest were made, such as tourism revenue sharing [50]. The shared

187 revenue is invested in infra-structure, health care, schools and livestock. Moreover, the creation of the

188 Bwindi and Mgahinga Conservation Trust intends to cover part of community development expenses.

189 However, there is still local concern regarding the distribution of the benefits to the community. The

190 economic activities in the area centre on subsistence farming (agriculture, cattle, goats, pigs, and

191 chicken [24,62]) and local living conditions are often inadequate (see S1 Fig and S2 Fig). The Bakiga—

192 the predominant ethnic group living adjacent to Bwindi Impenetrable BINP forests in Buhoma sector

193 [63]—are notably farmers, and traditionally the Batwa people lived in the interior of Bwindi

194 Impenetrable forest as hunter-gatherers. Both Batwa and Bakiga were prevented from using BINP land

195 in 1991; Bakiga could not open farming areas in BINP any longer and Batwa were forced to dwell

196 outside the forest edge because of the restricted land use policies [24,59,60]. Batwa livelihoods now

197 depend of exchanging labour for food, usually in other people's lands [62].

198 Most people living around BINP are primarily subsistence farmers, rearing livestock and

199 planting crops up to the forest edge (S2 Fig). This provides an active interface between the wildlife in

200 the park, the local villagers and their livestock, and it is at this interface where pathogens can cross

201 between humans, their domestic animals and wildlife [64]. With no buffer zone between the forest

202 habitat of the national park and the surrounding area (Fig 1A), wildlife from the national park frequently

203 enter the intensively cultivated farmland adjacent to the park to find food. A network of streams crosses

204 through the forest and farmland, creating a common source of drinking water—another potential route

205 of cross-contamination between people and animals. Moreover, despite the fact that hunting is illegal,

206 there is evidence of poaching in the Park's interior—for instance, 88 snares were destroyed in 2018 [65].

Community organizations

208   Several organisations work locally aiding conservation and social development. Conservation

209 Through Public Health (CTPH) is an organisation working at a community level and taking a

210 conservation medicine approach at the human-animal-environment interface, with an overall focus on

211 mountain gorilla conservation. CTPH works closely with local health providers (Bwindi Community

212 Hospital) and the community, as well as with Uganda Wildlife Authority. CTPH promotes a One Health

213 approach and supports the communities with guidance on family planning, hygiene, sanitation,

214 infectious disease prevention and control, nutrition and sustainable agriculture. CTPH has a strong focus

215 on education on the topics of forest conservation, risks of disease transmission among humans, gorillas

216 and domestic animals, and monitoring homes visited by gorillas [52]. The Mountain Gorilla Veterinary

217 Project, started by Diane Fossey in 1970, now the Gorilla Doctors, also runs a gorilla health program in

218 the Virunga Volcanos and BINP [66]. Prior to the many collective efforts of these organisations and the

219 application of active conservation strategies, the mountain gorilla population had dwindled to less than

220 250 animals. Now, decades later, the mountain gorilla population is over 1000 and the species was

221 recently reclassified as endangered from critically endangered [15].

Questionnaires

223   Questionnaires were designed by our multidisciplinary team, where the key information

224 required included human-human, human-animal and animal-animal contacts. The questions were

225 written in a manner appropriate to the local community and included pictures to provide clarity and to

226 be as easy as possible to complete. Interviewees were recruited by AN, from CTPH, who is a local

227 community member who has worked for CTPH since 2005. Small field trials were performed by DH

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228   and AN and the questions were refined and tested to ensure the data collected would be in a useable

229   form and culturally acceptable. All further community engagement was by CTPH alone, led by AN. By

230   asking the same question in different ways unreliable answers could be identified and these were

231   excluded from the final analysis.

232   Participants were recruited through community meetings and visiting homes. Participant

233   selection was through convenience sampling and based in part on participants' willingness or perceived

234   ability to complete the questionnaire. Only participants who gave their informed consent were included

235   in this study, all older than 18 years. The participants' answer sheets were identified by unique

236   identification numbers and their identity was not known to the authors, except AN.

237   Two types of questionnaire were used: first, interview-type questions (S1 File) and, second, a

238   seven-day questionnaire diary (S2 File); both were completed between June and July 2018. The

239   questionnaire and diaries were introduced to the study participants in community meetings led by AN.

240   During the meetings, AN would speak in English and Rukiga as necessary. The completed questionnaire

241   sheets were returned to the CTPH centre and stored in a locked room. In August 2018 data was entered

242   into a Microsoft® Access database by DH and BD, keeping the identity of interviewees anonymous. If

243   clarifications were required these were performed by AN.

Background questionnaire

245   The background questionnaire consisted of 29 questions, most of which could be answered by

246   ticking an appropriate box (S1 Data File). Information collected was about age, gender, ethnicity,

247   education, number of people living in the household, marital status and the number of children.

248   Questions including the types and number of latrines used, number of mosquito nets, and any ill health

249   and associated symptoms experienced were also asked. Symptom severity was indicated as mild ('*does*

250   *not interfere with your day too much'*), moderate ('*interferes a lot with your life, but you can be*

251   *independent'*) or severe ('*you were unable to behave normally and needed substantial help*'). A request

252   for the vaccination history of each participant and their family members, as per their vaccination

253   records, was included. The final question asked the study participants to identify any animals from a

10

254   list that they had seen, touched or got close to. The background information was confirmed in a follow-

255   up meeting, which was useful to get the participants ready for completing the diary.

Diaries

257   The diary included 49 questions, 48 of which were in a checklist format, allowing participants

258   to answer with a tick (S2 Data File). People were asked to record questions relating to hygiene, such as

259   toileting frequency and location, as well as details around handwashing and food preparation.

260   Behaviours associated with an increased risk of zoonotic pathogen transmission, such as contact with

261   animal faeces or blood, handling raw meat, or being bitten or scratched were included. Questions on

262   daily eating habits included the number of daily meals, food types, treatment of leftovers, and washing

263   of hands and utensils. These questions were designed to capture habits that might lead to increased

264   pathogen exposure as well as nutritional status, that might impact infection susceptibility. Disease

265   symptoms were recorded, including the severity of the symptoms experienced by the participant or of

266   anyone else in the household. Visits to a doctor or traditional healer and details about any medicines

267   taken were recorded.

268   Participants were also asked if they touched other people, saw other people touching each other,

269   or attended any group meetings that day. The final question asked participants to identify any animal-

270   to-animal contact that they had observed with this question: *"Today have you seen the following touch*

271   *or got very close (e.g. be together in the same field, trees or plantation)"*. This was done by drawing

272   lines (links) between two identical lists of animals to form an interaction network. Each line then

273   represented that the animals were observed to have close contact (were together in the same field, trees

274   or plantation). Each animal was a node in a pictorial network. The list included 22 taxa: humans, eight

275   domestic (cow, goat, sheep, pig, cat, dog, chicken, rabbit), two peri-domestic considered as one taxa

276   (mouse and rat were summed altogether for the sake of comparison as data from the diary did not

277   include mouse), and twelve wild animal taxa (gorilla, monkey, baboon, bushpig, civet, chimpanzee,

278   elephant, colobus, porcupine, duiker, bushbuck, and squirrel). Questions relating to topics of a sensitive

279   nature such as HIV infection and illegal activities, such as hunting wildlife for food and entering the

280   national park to use its resources, were not asked.

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Ethics approval

Ethics approval was given by the Massey University Human Ethics Committee (Permit number #SOA 17/12, DH), the Royal Dick School of Veterinary Science Human Research Ethical Review Committee (HERC, BD), and Mbarara University of Science and Technology Research Ethics Committee (CTPH, GKZ). No wild, domestic or peri-domestic animals were handled in this study. All participants in the study provided informed consent, and no children under 18 took part in the study.

Data analyses

Demography and health

A descriptive analysis and summary statistics were performed on the data captured from the background questions and the diaries associated with the general health of the community, focusing on reported symptoms and the contacts between species. To check potential correlation between symptoms felt when participants were unwell between background questionnaire week and the diary week we performed a simple Spearman's correlation test. Then, we present the information on participants who declared contact with gorillas plus timespan of a particular event of direct contact and information relevant for cross-species pathogen transmission.

Human social contact data

For direct social contacts, data was collected in age classes and the frequency (0-5 and above contacts per day) for each pairwise interaction. Frequency histograms for contacts between all age class combinations were created. We calculated all human-human direct contacts (counts) and their non-parametric 95% confidence intervals based on a bootstrap procedure with 1000 interactions per unique pair of age classes, containing the interviewee and their direct number of contacts. Then, observed contact rates were calculated as the number of days on which the interaction between age classes was seen (presence or absence) over seven days. While children were not included as participants in our study, we believe asking for observed contacts goes some distance to collect unbiased data about their contact patterns. This means the calculation for observed contact rates (sum of days on which the

306   interaction between age classes were seen for all individuals, separated by age class) is different from

307   the self-declared direct contacts (sum of contacts on for each interaction for all individuals, separated

308   by age class).

Human-animal interface

310   First, data were gathered for each participant, tabulating how many times they had close contact

311   with animals over the week. Then, timeline plots were produced to illustrate the number of self-reported

312   direct contacts (touching) or sightings of animals or their faeces per individual over the week.

313
314   Human-animal interface networks were produced from the observations of contacts from two

315   sources: 1) Contacts from the background questionnaire week (link weight = number of participants

316   reporting that contact), 2) Sum of all contacts along the week (link weight = sum of the contacts seen

317   along the week/7). To explore contact information consistency, we correlated the link weights between

318   the background questionnaire week and diary week with Spearman's correlation test. We believe this

319   approach helps to complement the actual contacts each participant had with contacts that happened in

320   the background questionnaire week and give a broad picture of the local context of contacts. We

321   calculated the animal-animal contact network structure using a network science approach, where a node

322   is a taxon (a species or group of species in several cases, like duiker).and the links between each pair of

323   taxa have weights given by the total number of events along the week when the participants have seen

324   a direct contact or a close contact (be together in the same field, trees or plantation). Where appropriate

325   for network analyses, we converted the edges to binary (present or absent).

326   To measure how connected the two networks of contacts were we calculated two descriptors:

327   connectance and assortativity. Connectance measures the proportion of binary links observed in a

328   network in relation to the number of potential links it could maximally have. We also quantified the

329   relative frequency of interactions within versus between particular species or groups, using the nominal

330   assortativity metric "r" [67]. We calculated the metric r for two levels: node-node assortativity and

331   assortativity based on broader groups (domestic, peri-domestic, human, wild). This metric is positive

332   when there is a pattern of more contacts with that same node (or group) than with other nodes (groups),

13

333   and negative when the network presents a disassortative pattern, i.e. when a node (group) has more

334   contacts with other nodes (groups) than with the same. Networks were built in R 4.0.3 [68]; the

335   calculation of metrics and network drawing were performed with the packages *igraph* and *ggplot2*

336   [69,70].

Results

Demography and health

Background information

340   All the participants recruited for this study completed the background questions (S1 Data File)

341   and the diaries (S2 Data File), except participant 83, who did not complete the background information.

342   In a small proportion of the questionnaires, individuals did not declare their age (N=2), village (N=1),

343   ethnicity (N=2) or gender (N=1). All participants filled the diaries, but there was variation in the number

344   of days completed: one participant completed the diaries for two days, two people completed them for

345   five days, ten people completed them for six days, 78 participants completed them for seven days, seven

346   participants completed them for eight days, one person completed them for nine days, and one person

347   completed them for ten days. These answers add up to 700 days of daily data for 100 participants.

348   The sample comprised 81% male to 19% female participants, from 19 to 70 years old (median

349   = 35 years old, S3 Fig). Seventy-five percent of the participants were married, with their age at marriage

350   ranging from 14 years to 30 years with a mean of 21 years (Table 1). Of the 98 respondents that recorded

351   their ethnicity, 93 were from the Bakiga tribe, two from the Banyankole tribe and one each from the

352   Basonga, Batwa and Mukonzo tribes. Half of the respondents resided in Mukono and half in Nkwenda

353   villages. The median number of people living in the same household with each participant was 2,

354   varying from one to 10 people, and the number of children varied with age class of participant (S4 Fig).

355   The background questionnaire included a question that sought to identify diseases that any of the

356   participants had ever suffered from, but unfortunately this question was generally misunderstood, since

357   many identified diseases that they had been previously vaccinated against. Because of that, the answers

14

358 were not included in the analysis. Most interviewees used pit latrines (98%; 73% had covered pit

359 latrines) and had at least one bed net in the house (Table 1). The mean number of bed nets per household

360 was three. Regarding healthcare behaviour, over half (N=51) of the participants reported feeling unwell

361 in in the week preceding diary completion, reporting at least one symptom (S5 Fig). Thirty participants

362 went to the hospital or health centre to get treatment. Regarding treatment, 9 reported symptoms but did

363 not seek treatment, 10 participants sought self-treatment, and 6 sought traditional treatment with the

364 local healers.

365

366 **Table 1. Background information on Participants in Mukono Parish, Uganda**. These questions

367 were answered before the collection of information on diaries, in the previous week. We retrieved

368 information for 99 participants for the background data and 100 participants for the diary data.

Background information	Value
Age (mean ±SD)	37.9 ± 12.6
Marital Status	
Married	77
Not married	22
Age when married (mean ±SD)	20.7 ± 3.7
Education Level	
Primary complete	52
Secondary complete	40
University or College	20
Gender	
Male	80
Female	19
Ethnicity	
Bakiga	93
Banyankole	2
Basonga	1
Batwa	1
Mukonzo	1
Not declared	1
Village	
Mukono	50

Nkwenda	49
Unwell in the last week	
Yes	51
No	48
Bed Net	
Yes	99
Visited health worker last week	
No	69
Yes	30
Visited hospital last week	
No	79
Yes	29
Self-treatment last week	
No	65
Yes	34
Visited traditional healer last week	
No	93
Yes	6

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Diary information

372   Regarding meat preparation, 58 of the participants reported in their diaries that they had handled

373   raw meat (N= 101 entries for handling raw meat), 14 had been bitten or scratched by an animal (N=22

374   entries) and 41 participants had come into contact with the blood of an animal (N=66 entries for

375   touching blood) at least once along the week. All participants reported washing their hands before eating

376   at least once during the week, but did not always use soap to wash their hands, which was done 72% of

377   the time (N=700 entries for all days, N=504 answered "yes" to wash hands with soap before meals).

378   Participants who reported having washed hands with soap before meals and also washed hands with

379   soap after going to the toilet at least once a week summed 94, and using soap for both situations (used

380   soap before meals and after toilet) happened 63% of the time. Regarding nutrition, it was more likely

381   that people would report eating two meals a day (42.3%) than one meal (25.8%) or three meals (25.5%).

382   The staple diet consisted mainly of posho, beans, matooke and porridge with 97.3% of all meals

16

383 recorded consisting of one or more these carbohydrates. Meals containing animal protein were recorded

384 in 10.7% of all recorded entries.

385 In the diary, people reported feeling unwell on 281 of the 700 total days recorded (40%) with

386 11.6% of these records indicating moderate symptoms and 6.4% reflecting severe symptoms. Most

387 participants reported feeling at least one symptom along the week (N=75). In contrast, 48 participants

388 did not report any symptoms during the background survey week. Nevertheless, the number of

389 symptoms felt during the background survey week was positively correlated with the sum of felt

390 symptoms during the diary week (Spearman's correlation test rho=0.70, p<0.0001). Only 23 participants

391 did not declare any symptom at any point in both data sources (background survey week and diary

392 week).

393 Of the syndromes reported, headaches and tiredness were the most common (Fig 2). Pain and

394 coughing were reported often (8.7% and 9.5% of the time, respectively), while diarrhoea and fever were

395 less common (2.4% and 4.5% of the time, respectively); itching and skin rashes were reported the least.

396 Two individuals reported seven symptoms on a single day. A person was more likely to feel unwell for

397 one, two or three days (20.2%, 12.9% and 5.1% respectively), compared to four or more days (less than

398 1%). The average number of symptoms reported was 1.7 per person (min=0, max=7 symptoms per day),

399 where it was most common to report no symptom (59.8%), or 1 symptom per day (20% of entries).

400 People were more likely to pass a bowel movement more than twice in a day compared to once

401 a day (73.3% versus 26.7%), which may reflect a high incidence of gastrointestinal disease in the human

402 population. Despite the frequent number of bowel movements reported per day (mean=2.05, median=2,

403 max=5), people only acknowledged having diarrhoea in 17 entries of the diary reported by nine

404 participants. The diary information showed that forty-six people sought medical help from a clinic and

405 took medication with a further 14 people seeking advice and treatments from a traditional healer along

406 the week, varying from one to seven visits along the week. From the people who visited traditional

407 healer, 10 ended up taking medicine from the traditional healer; 23 participants reported taking medicine

408 they prepared at home along the week.

409

410   **Figure 2.** For a week, symptoms and their severity were reported in participants diaries in Buhoma,

411   southwestern Uganda (2018).

Human social contact data

413   We report self-reported close contacts (touching) for 100 individuals (Table 1, Fig 3).

414   Participants reported a total of 5777 direct contacts, but 113 contacts from 2 participants were removed

415   because we could not retrieve the participants' ages. Thus, we ended up with 5664 human-human direct

416   interactions. Moreover, participants reported 2491 observations of interactions between other people

417   from various ages (when they saw people touching other people), adding up to a total of 8155 human-

418   human interactions in our study. Age classes with highest observed contacts were interviewees of age

419   class 41 or more who interacted with people aged 21-40 (S6 Fig). Self-reported direct social contacts

420   varied from an average of 0.76 to 2.30 contacts per person per day for any age class (Fig 3, S1 Table).

421   Observed contacts varied from an average of 0.65 to 3.53 (mean= 1.66 average number of days of

422   contact per age class, S6 Fig).

423

424   **Figure 3. Frequency histograms with self-reported direct human-human (N= 5664) contacts**

425   **around BNP.** Data represents age classes for 98 individuals (there was no age information for two

426   individuals) and the number of people they touched along one week in a self-reported diary. No children

427   participated in the questionnaire.

Human-animal interface

429   From the diary questions, where participants were asked if they had seen a certain type of animal

430   or their faeces that week, the domestic animals such as chickens, goats, cows and pigs were reported as

431   the most common animals seen compared to wild animals. Peri-domestic animals were also frequently

432   seen. Seeing was more common than touching, and wild animals were rarely reported to be touched

433   (Fig 4). The animals that were reported to be touched most frequently were goats, chicken, pigs and

434   cows, cats and dogs. However, there were very rare records of touching wild animals. One person

435   reported to touch a civet and a monkey at the same day. One participant reported to have touched a

436   duiker, and there were two events of touching a squirrel. Moreover, 4 participants reported having

437   touched a monkey, with one participant reporting having touched a monkey twice in a week (S3 Table).

438   Contact with animal faeces/dung—only reported for domestic and peri-domestic animals, since their

439   faeces are more easily recognizable—are reported in S7 Fig. Contact with the faeces of different animals

440   followed the trend for direct contacts reported, with sightings being more common than direct

441   contacts—touching the dung of chicken, goats, cow and pigs were the most common direct contacts

442   reported.

443

444   **Figure 4. Sightings and direct contacts between participants, wildlife, domestic and peri domestic**

445   **animals reported by ordered participants along a week by self-reported dairies in Buhoma,**

446   **Uganda**. A. Sightings in dark gray B. Touching directly the animal in dark gray.

447

448   Over the seven-day period that the diaries were recorded 20 participants reported seeing

449   mountain gorilla at 40 occasions. On 21 of those occasions, the participants ate two or less meals the

450   day of sighting, in 29 cases they had more than one bowel movement in a day, with 2 individuals

451   reaching 4 bowel movements in a day, and in 10 of the 40 occasions of gorilla sightings, the participants

452   drank unboiled water from sources. From the 20 individuals who declared seeing a gorilla at 40

453   occasions, a majority of people felt unwell (31/40 occasions), and there were 23 occasions when they

454   reported that others in the same household were unwell on the same day the participant saw a gorilla.

455   The average number of symptoms of people who saw a gorilla reported was 1.52 (median=1, min=0,

456   max=6), slightly higher than the average number of symptoms per person along the week was 1.36

457   (median=1, min=0, max=7). The average number of symptoms per person for those occasions when the

458   participants did not see a gorilla was 1.25 (median=1, min=0, max=7). The most common symptom of

459   those who saw a gorilla was tiredness and headaches but coughing and fever were reported too. In one

460   occasion, a participant reported a severe cough on the same day of a gorilla sighting. Respondents

461   recorded between one and five gorilla sightings over the week. Nine people reported multiple gorilla

462   sightings over the week. On one occasion there was physical contact between gorilla and a human (S8

19

463   Figure). At the same day of this physical contact, the participant touched other animals (cow, chicken,

464   goat) and saw several other animals, including monkeys and baboons. This participant also had four

465   bowel movements that day and declared having respiratory symptoms (coughing) two days before

466   touching the gorilla and mild pain at the day of contact. This individual reported coughing and headache

467   symptoms in members of his household three days after the day of contact.

468   The contact networks illustrate that people involved in this study had regular contact or had

469   been in close proximity to both domestic animals and wildlife (Fig 5). Both networks were moderately

470   connected; The connectance value for the human-animal contact network using the diary data (divided

471   by 7) was 0.31, and 0.26 for the background questionnaire week network. The observations of contacts

472   revealed many close contacts between groups of humans, domestic, peri-domestic and wildlife.

473   Regarding assortativity (preferential links) in the network, taxa tended to contact their similar taxa over

474   other taxa (r=0.24 for diary network, r=0.29 for the background questionnaire week network). In

475   addition, the same group (groups = domestic, human, peri-domestic or wildlife) also tended to contact

476   the same group over contacting other groups (r=0.40 for diary network, r=0.32 for background

477   questionnaire week network). The complete interaction list for the contact networks considering

478   background questionnaire week interactions and summed diary interactions is available in S3 Table.

479   From the close contact networks, the most common interaction observed between groups were cow-

480   person (S3 Table), followed by goat-person, chicken (domestic)-person, followed by pig-person.

481   Person-person contacts made up for the highest number of interactions, followed by goat-goat, cow-

482   cow and chicken-chicken. Peri-domestic contacts were the 12th most common interaction, while the

483   wildlife species with most reported interaction events were primates. The most reported interaction

484   between wildlife taxa in close contact with humans were baboons, then gorillas, then monkeys. Most

485   common wildlife-wildlife in-taxon contacts were gorilla-gorilla (N=56) and monkey-monkey (N=56).

486   Wildlife-domestic close contacts were rarely seen, such as squirrel-rabbit, gorilla-cow, chimpanzee-

487   dog, or elephant-dog. Person-gorilla contacts were the 36th most common observed interaction in the

488   network. The complete list containing the number of taxa each animal interacted with (including

489   themselves) is available in S4 Table.

20

490   During the diary completion week, humans interacted with 18 taxa, followed by dogs and cows,

491   which were seen in close contact with 13 and 10 taxa. The wild taxon in close contact with the smallest

492   number of other taxa was the civet (1 taxa), followed by duiker and porcupines (all interacting 2 taxa

493   or less, including themselves). Gorillas had rarely been observed in close proximity or were seen

494   touching domestic animals (dogs and cows) and wildlife (baboon and monkey).

495

496   **Figure 5. Local close contact networks reported in Buhoma, Uganda (2018).** Data was collected

497   from self-reported surveys. Node size and link line width are proportional to number of interactions at

498   taxa-level (number of taxa the node interacted with) and link-level (value of self-reported and observed

499   contacts summed), respectively. Colours illustrate people in yellow, wildlife in red, peri-domestics in

500   green, and domestic animals in purple. Animal-to-animal data comes from observations of people who

501   reported seeing an animal touching or getting very close to another animal. A. Seen last week

502   (background questionnaire week), B. Seen during the week of Diary completion. C. Correlation

503   between matching pairwise interactions. Labels in gray represent interaction of nodes from different

504   groups.

505

Discussion

507   Our study reveals that the human population of the Buhoma sector around BINP is generally

508   suffering from poor health and lives at the interface of substantial domestic, peri-domestic, and wild

509   animal interactions, with important implications for the risk of cross-species pathogen transmission

510   events. Examining contact patterns and community health is important to understand those risks and

511   contribute to initiatives that increase human and ecological health. Over half of the participants reported

512   symptoms of disease within the previous week with varying levels of severity. Contacts with domestic

513   and peri-domestic animals were very common, and human-human contacts were the most common

514   contacts reported, as expected. Seeing wild animals was much more common than touching them, with

515   only nine directly reported events of touching a wild animal, and one case of person touching a gorilla.

516   These numbers make up much less than 1% of total animal-person direct self-reported contacts

21

517   (N=1424), with most direct human-animal contacts being with domestic or peri-domestic animals.

518   However, people's perceptions of close contacts along the week revealed hundreds of close contacts

519   between humans and 20 animal species considered in the survey (S3 Table, S4 Table). Below we discuss

520   the self-reported health patterns, focusing on the interaction between people and mountain gorillas, the

521   local context, social contact patterns and the broad human-animal interface. Then, we discuss caveats

522   of this study and future directions.

Demography and health

524   People declared feeling unwell, feeling at least one symptom 40% of the time along the week,

525   an indicator of poor health, with headaches and tiredness being the most reported symptoms. These

526   could be related to the general lack of good nutrition, inadequate intake of water or other fluids, or may

527   reflect underlying disease—both of which could result in a compromised immune system. The frequent

528   number of daily bowel motions of study participants could indicate underlying gastrointestinal disease.

529   With a local human prevalence of intestinal parasitism ranging from 25% to 57% and the prevalence of

530   other enteric pathogens at 49%, including *Giardia* and *Cryptosporidium* [71], it is possible that

531   diarrhoea was under-reported in this study (17 cases in 700 entries, 2.4%), given that people reported

532   passing a bowel motion up to five times in a day without reporting diarrhoea. In addition, over a quarter

533   of the participants reported drinking un-boiled water, potentially exposing them to water-borne disease

534   risk.

535   Regarding disease symptoms, although guidance was given in the questionnaire regarding

536   severity levels, all information gathered was self-reported and therefore subjective. Moreover, if the

537   'normal' state for an individual is feeling constantly tired with headaches (Fig 2), possibly due to poor

538   nutrition, heat and dehydration, the individual may not report these as symptoms. This may also be the

539   case for individuals suffering from chronic diseases who have lived with the symptoms for many years

540   and have learnt to tolerate them. This may mean that the symptoms' severity could be under-reported

541   so these results should be interpreted with caution, such as the difference between reported diarrhoea

542   and the frequency of defecation reported. It is common for people in this community to only eat two

543   meals a day, with a diet that is high in carbohydrates, low in protein, and generally of low nutritive

544   value, suggesting that most of the local population is likely to be malnourished. Food insecurity in the

545   area was beyond the focus of this study and should be assessed in depth using survey methods designed

546   for that purpose (e.g., [72]).

547   Considering risk factors for disease exposure, 68% of people reported handling raw meat and

548   animal blood, and 28 people indicated that they had cuts on their hands during the week. Eleven

549   participants had contact with animal blood and had cuts on their hands on the same day. These events

550   are associated with an increased risk of the transmission of zoonotic diseases. Several studies in the area

551   surrounding BINP and other parks have demonstrated the sharing of pathogens between the local human

552   population, domestic livestock and wild animals, many of which could be transmitted by these high-

553   risk activities [73–77]. The use of pit latrines also increases the risk of disease [78,79]. Together, these

554   findings may explain the high level of disease symptoms reported in this study. All participants provided

555   stool samples that may reveal underlying disease and will be analysed in future studies. A community

556   with limited access to health care of good quality and with a high density of malnourished and

557   immunocompromised people can act as a potential reservoir for pathogens that could be transmitted to

558   non-human great apes such as the endangered mountain gorilla. Although many people reported seeking

559   medical help, the quality of care they received is unknown. The relatively high level of handwashing

560   reported by the participants is likely due to the regular workshops run by CTPH throughout the local

561   communities using a network of Village Health and Conservation Teams (VHCTs), community health

562   workers also trained to promote biodiversity conservation. A focus on preventative human health care,

563   like the CTPH workshops, immunisation programs and surveillance should be prioritised for the local

564   communities bordering the BINP. Commonly reported diseases for this region and other rural parts of

565   Uganda include malaria, measles, intestinal parasites, typhoid and skin disease [80]. For those, fever,

566   coughing and respiratory distress the most reported symptoms, whereas the symptoms reported in our

567   survey could be associated with malaria and the other diseases mentioned. Moreover, several zoonoses

568   including leptospirosis, Q fever and rickettsial fevers occur locally [6,81]. For privacy reasons, people

569   were not asked about their HIV status. However, it could be assumed to be around the values of

570   prevalence for southwestern Uganda (7.9%, [82]).

23

Human social contact data

Data on human contact patterns are scarce in Uganda [51], and gathering sufficient data about social contacts can help understand the spread of infectious diseases. Our results show that reported contacts among humans were numerous—the participants declared to be interacting with five people or more (regardless of age class) in 71% of the days, with a mean of at least 8 contacts per day and a median of seven contacts per day. This pattern of numerous interactions per individual per day was reported in another study recently conducted in southwestern Uganda [51], which reported an average routine contact of 7.2 individuals per participant. It is interesting to see this convergence of results between self-reported assessments guided through workshops in our study and a study based on interviews under a similar social context and region [51]. Self-reported contacts were restricted to individuals of 18 years old or more, and thus are limited by the age groupings. With the contact data is biased towards adults, this allows only limited inferences about child contacts and older adults due to how the data for age classes were divided, aggregating all ages from 41 years or older. Observations of contacts, reported in the diaries, also pointed to more contact events for the ages of 21 and older. However, these data give more insights into contacts for children and teenagers because, while participants were always older than 18 years old, they could observe the presence of a variety of age classes interacting during their daily routine (S6 Figure).

Human-animal interface

Systematic data on contact between humans and animals and between different animal taxa are relatively rare but can be valuable for understanding the complex process of how pathogens spread from contact with other animals or their environment [38]. As expected, most reported and observed contacts occurred between people and domestic animals, emphasizing the importance of livestock in the area and how they are deeply associated with social and economic relationships [40]. Contact (and thus pathogen transmission) is likely to be more frequent between domestic mammals and their wild relatives than between humans and wild primates [83]. The potential of pathogen transmission through taxa and their environment should be a priority in future studies in this area. For instance, in this area, a recent

24

597 study detected *Giardia* in 5.5% of livestock in this area that has an active human-livestock-wildlife

598 interface [84].

599   The networks of close contacts plus direct reports of contacts revealed hundreds of interaction

600 events, with a positive correlation (Spearman's correlation test rho=0.67, p<0.0001) between the

601 interactions reported for the background questionnaire week and the interactions occurring during the

602 diary week (Fig 5). From those, despite rare events, wild animals were mentioned to be having close

603 contacts with humans, for instance, gorillas, baboons, squirrel, monkey, and duiker (S3 Table, S4

604 Table). One of the participants declared direct contact with a civet, and one participant declared having

605 direct contact with a gorilla. The participant who touched a gorilla was male, Bakiga, and had cuts on

606 his hands before and after the day of contact, in addition to symptoms of concern. He had contact with

607 people on the same day of the contact with a gorilla (day 4). He declared to have touched chicken, cow,

608 and goats on the same day, and also touched the dung of chicken, cow, goat, pig, and rat at the same

609 day he touched a gorilla. At that time, he was part of the human-gorilla conflict resolution teams

610 (HUGOs) and declared having headache and respiratory symptoms (coughing) on day 7 in his

611 household members three days after touching a gorilla. The participant declared a visit to the clinic on

612 day 2 of the diary. Nevertheless, of concern are the respiratory symptoms of coughing and breathing

613 difficulty, given that respiratory viruses can cause severe disease and lead to fatalities in gorilla

614 populations [7,18,85]. This participant reported coughing symptoms two days before the contact. Given

615 how contagious COVID-19 is and having spread from an asymptomatic keeper to eight captive gorillas

616 in San Diego Zoo Safari Park [86], this study provides useful information to minimise human and gorilla

617 disease transmission during the pandemic.

618   Gorilla sightings appear to be frequent as over half the respondents had ever seen a gorilla, and

619 nine of these reporting multiple gorilla sightings over the week, which is similar to the results of a

620 previous study in this area [71]. Several of these respondents also reported seeing other wildlife such

621 as monkeys and baboons, which may indicate a group of people that may work near the park. A group

622 likely to report a high number of gorilla sightings are the human and gorilla conflict resolution

623 volunteers (gorilla guardians or HUGOs). HUGOs should be prioritized for preventive health measures

624   in the region; it would be interesting to measure contacts more intensively for this group, composed of

625   people responsible for moving mountain gorillas who have ventured onto agricultural land backing onto

626   the forest. Moreover, there were 1.57 reported gorilla-person contacts/day reported (and 3 reports for

627   background questionnaire week) and 5.57 gorilla-gorilla contacts/day (10 records for the background

628   questionnaire week network), which brings an interesting perspective on observer bias and on how

629   frequent this contact is. When a person gets close to a gorilla, it is highly likely that this person also

630   sees a gorilla in close contact with other gorillas.

631   This study has revealed species within the Bwindi Impenetrable Forest ecosystem that are in

632   close contact. As other studies have indicated, humans have cross-species contacts [58] with gorillas,

633   which are to be expected given the local mountain gorilla conservation programs and tourism. Also,

634   some gorilla families have home ranges close to the park's perimeter, and that move out of the forest,

635   spending a considerable amount of time close to cultivated agricultural areas [64]. This may explain the

636   rare events of sightings of cows and gorillas (0.14 contacts/day, zero for the background questionnaire

637   week) and dogs and gorillas (also 0.14 contacts/day and zero for the background questionnaire week,

638   S3 Table) reported. We need to gain a better understanding of where this interface may be most

639   frequently active. This will help determine the strategies that could be used to minimise the risk of

640   disease transmission at this interface, in the absence of wider change in ultimate drivers. Goats have

641   free range close to the border of the forest, and this hard edge is probably where goats and gorillas are

642   more likely to spatially overlap and to share waterways and grazing areas. Cows are more likely to be

643   tethered at night but like the goats are walked to new grazing areas each day.

644   Although humans and great apes are more distantly related to domestic animals, this does not

645   preclude the transmission of pathogens, particularly those that can infect multiple hosts, from goats and

646   cattle to humans or wild great apes [83]. Monkeys and baboons were reported as seen near the gorillas,

647   a finding reported previously [87]. Baboons and gorillas share several intestinal parasites including

648   *Cryptosporidium*, *Giardia*, *Trichuris* and *Strongyloides* species [87]. It is likely that gorillas and

649   monkeys have pathogens in common due to their spatial overlap and shared habitat. Respiratory viruses

650   with possible transmission between humans and baboons [88] and humans and New World monkeys

26

651   [89] have been observed. In our network, baboons, monkeys and gorillas had similar interactions among

652   themselves (Figure 5, S3 Table). As well as being potential victims of disease, this highlights the

653   possible risk of monkeys or baboons acting as reservoirs or intermediate hosts for diseases that affect

654   both humans and gorillas.

655   Despite intense action of different actors in the region to promote conservation and public

656   health, including a One Health national agenda [90], empirical studies need to quantify these

657   relationships between human beings and wildlife more thoroughly. Though we specifically did not ask

658   the nature of any contacts, our study is limited to what participants were comfortable reporting.

659   Activities related to the collection of resources in the park are regulated via permits for multiple use

660   zones in parishes bordering the park, and outside of these areas, law enforcement can be applied.

661   Pressures on living conditions and cultural practices still lead to unauthorized access to the park's

662   resources, such as collecting herbs, honey, and wood. We acknowledge that hunting and illegal

663   poaching still happens in the region, including recent cases of gorilla killings [91], which is negative

664   from a biological conservation perspective, but also a complex issue that needs to be further addressed

665   since there is a high subsistence demand in the region [92,93].

Limitations of Study

667   This study has significant limitations, such as recall bias, typically associated with diary-based

668   research [94]. However, filling diaries for a short period tends to minimize recall bias due to the small-

669   time lag between an event occurring and being recorded compared to a questionnaire [95]. Another

670   bias is the non-random nature of the recruitment of participants since their selection was based on

671   literacy and age. Although the questionnaire and diary questions asked about the health of all household

672   members, the ages of any unwell members were not captured. Because of these limitations, it is possible

673   that the frequency of disease symptoms reported in the diaries in this study underrepresents the actual

674   disease in the community. Moreover, literacy can be associated with the tasks that a person might do in

675   their day-to-day lives, with low literacy levels associated with more prolonged episodes of sickness

676   [96]. More literate adults are more likely to work outside of the home in occupations such as teaching,

677   nursing, or running their own business, whereas nonliterate individuals are more likely to be doing

678   manual work at home and working with animals and crops [3]. The latter activities present a higher risk

679   for human contact with livestock (which is the most common type of cross-species contact, see S3

680   Table) or wildlife and associated pathogen transmission. We will investigate community activities in

681   future works but note that most activities in the area point to subsistence farming [92,97], which is

682   noticeable in our results showing the frequent contacts with livestock.

683   Furthermore, male participants were overrepresented in this study (81% males, 19% females).

684   This disparity in the selection of study recruits may partly reflect convenience, but partly because of

685   gender biases and patriarchal systems, meaning more men volunteer as our community member who

686   administered the questionnaires (AN) was male. As different genders can perform different activities,

687   the diseases associated with these tasks can be gender-sensitive [98]. An example of this is the gender-

688   specific division of labour, which is a feature of the Bakiga tribe, with men responsible for hunting and

689   building houses and women collecting firewood and fetching water [99]. Future analysis should be

690   more representative of the population in terms of participants' gender, literacy level and ethnicity. This

691   is especially important for marginalised groups, such as the Batwa (only 1 participant in our study),

692   who were traditionally hunter-gatherers and forest dwellers and who have a low literacy level [100].

693   The Batwa were resettled from within BINP when the park was established, and they have been defined

694   as refugees in the villages at the forest margins [24], with privatised land surrounding the forest largely

695   owned by the Bakiga people (the majority of participants, N=93). Despite local actions of NGOs and

696   institutional initiatives, the edge-dwellers' situation remains critical in terms of living conditions and

697   well-being [101], and the survival of the Batwa in the future is threatened. Furthermore, many Batwa

698   living in extreme poverty are forced to use public land resources, thus increasing their exposure to

699   diseases from polluted groundwater and latrines [24]. Strategies, such as poverty alleviation, addressing

700   crop raiding and illegal access to the park, improving revenue sharing, and local governance are

701   envisioned for this area at governmental levels [102]. This region demands long-term efforts to combat

702   poverty, discrimination against minorities, and tailoring of interventions to their needs.

Future studies for managing disease risk

Acknowledging the complexity of the interactions between humans and animals and human behaviour are essential steps for understanding systems, including developing infectious disease dynamic models and for meaningful interventions to reduce disease risk [38,103]. Human and animal dimensions are entangled in the Buhoma sector, where people's livelihoods are connected with BINP due to the proximity to the park. Concurrent research from our group investigates infection prevalence and cross-species transmission events, using next-generation sequencing metagenomic studies from faeces collected from cattle, goats, humans, and gorillas in the BINP region. The results from these studies will assist with informing future work measuring relevant components for cross-species transmission. To manage the risk of disease transmission in the region, further detail is needed regarding non-human great apes that are in close contact with humans and domestic species. Future studies may look at the spatial and temporal overlap of all these species, as well as specific activities associated with a high risk of pathogen transmission. Detailed mapping of people and animal movements can reveal spatial or temporal overlaps between species. A thorough medical survey, including biological sampling of individuals who are in regular contact with the gorilla groups, may highlight subgroups that present a higher risk of disease transmission. These subgroups include visiting tourists, researchers, gorilla trackers, children, park rangers, ethnic groups, and the HUGOs. In addition, future studies could do more in-depth interviews and participant observation with the people that reported regular sightings of wildlife to gain more insights into the high-risk activities and social determinants that could lead to the transmission of pathogens and to an understanding of the wider political economy and livelihood challenges regionally. A preventative health program to manage intestinal parasites and manage livestock to reduce contamination of shared waterways should be considered in goat flocks and cattle herds close to BINP. Preventative health programs and disease surveillance of the local human and gorilla populations should continue to prioritize improving livelihoods and conservation in the area. Moreover, disease surveillance of tourists entering the park could further inform the disease risks within the local ecosystem. The One Health Initiative organized by CTPH, with support from the Uganda Ministry of Health and other organizations, led to an increase in family-planning users, support for

730 conservation, and reduction in incidence of gorilla disease, including giardiasis and scabies since the

731 creation of CTPH in 2003 [34,84].

Conclusion

733   This study highlights a local human population that is generally unwell and may act as a

734 reservoir for pathogens. Humans and domestic animals form a tightly coupled system that may act as a

735 reservoir for infectious diseases that could spill over to endangered wildlife, including the mountain

736 gorilla. Despite having several caveats, our findings are relevant to inform local community workers

737 and stakeholders of the overall health condition and contact patterns of the local community around

738 BINP. Several behaviours that may increase zoonotic disease transmission risk were identified for

739 Mukono and Nkwenda villages in the Buhoma sector. With fewer than 1000 mountain gorilla mature

740 individuals remaining in their natural habitat [15], it is a matter of urgency that we gain the knowledge

741 that will allow us to best mitigate the risks and prevent the transmission of infectious diseases to this

742 endangered species. More broadly, the improvement of healthcare and living conditions in the region

743 is of utmost importance to reduce the burden of pathogens in humans and wildlife. In this case study,

744 we provide evidence of an active interface between humans and other species, including cattle, goats,

745 baboons, and the endangered mountain gorilla around the BINP. We offer the first characterization of

746 the human-animal contact network around BINP based on survey data and report frequent interactions

747 indicating strong potential for pathogen cross-species transmission among various animal species.

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Supporting Information

S1 File. "File Background questions.pdf" Virtual version of the questionnaire that was printed to the participants in Buhoma, Uganda (2018).

S2 File. "S2 File Diary questions.pdf". Virtual version of the dairy that was printed to the participants in Buhoma, Uganda (2018).

S1 Data file. "Data_File_S1_Survey.xlsx". Relevant data from the questionnaire containing the answers from to the participants in Buhoma, Uganda (2018).

S2 Data file. "Data_File_S2_Daily.xlsx". Relevant data from the dairy containing the answers from to the participants in Buhoma, Uganda (2018).

S1 Figure: Photos from Buhoma, Uganda, showing elements that are part of the local living conditions around Bwindi Impenetrable National Park. A. Set for washing hands and water usage outside a house. B. Water supply in plastic containers. C. Water supply from artesian well. D. Local butchery entrance. D. and E. goats very close to the Park border. F. Cooking area in one of the village's houses. Photos: D. Hayman.

S2 Figure. Pictures from Buhoma, Uganda, showing parts of the village. A. Panoramic view of the street. B. View of the village close to the Bwindi Impenetrable National Park and livestock in the background. C. Closer view of one of the local houses. Photos: D. Hayman.

S3 Figure. Gender and age distribution of the participants. Gender bias in our sampling is a significant study limitation.

S4 Figure. Average number of children per participant age group. The average number of children per age group of participants varied from no children older than six years old for younger participants (between 16-20 years old) to more than three children for participants above 30 years old.

1101 **S5 Fig. Health care behaviours in Buhoma during a self-reported survey conducted in 2018.**

1102 Treatment choices of those who declared to be unwell or seek treatment (abbreviated as "treat.") during

1103 the week before diary completion.

1104 **S6 Figure. Self-reported observed human-human contacts around BNP.** Observed contacts were

1105 collected along one week in a self-reported diary per age class.

1106 **S7 Figure. Self-reported direct contacts between humans and animal faeces around BNP.** Contacts

1107 were collected along one week in a self-reported diary. A. Sightings of dung in gray. B. Direct contact

1108 with dung in gray.

1109 **S8 Figure. Summary of self-reported information for the participant who declared to have**

1110 **touched a gorilla.** Timeline with symptoms reported for a participant who reported touching a

1111 mountain gorilla. Sources for the gorilla and hand sillhouettes: Creazilla (CC BY 4.0):

1112 https://creativecommons.org/licenses/by/4.0/deed.pt; https://creazilla.com/nodes/832270-two-hands-

1113 reaching-silhouette

1114 **S1 Table. Age classes of self-reported direct contacts (n=98) with the people they touched along**

1115 **seven days in Buhoma, Uganda.** Two individuals from the total sample (n=100) did not declare their

1116 age and were removed from the analysis.

1117 **S2 Table. Self-reported events of actual touching certain animals or their dung the previous week**

1118 **in Buhoma, Uganda (2018), according to 100 participants.** Values for all species in the questionnaire

1119 are shown from highest to lowest.

1120 **S3 Table. Link list containing the events of perception of local close contacts during a one-week**

1121 **survey in Buhoma, Uganda (2018).** The number of contact events is in decrescent order based on the

1122 diary week sum of events divided by seven days.

1123 **S4 Table. Taxon-level metrics reported in Buhoma according to the participant's observations of**

1124 **human and animal close contacts**. Data is arranged in ascending order of the number of species a node

1125 interacted with, including the node itself.