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## COVID-19 in Ethiopia: A geospatial analysis of vulnerability to infection, case severity, and likelihood of death

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## 1 COVID-19 in Ethiopia: A geospatial analysis of vulnerability to infection, 2 case severity, and likelihood of death

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54 85 **Keywords:** Risk map, vulnerability, infection, severity, death, COVID-19, Ethiopia, geospatial  
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3 **88 Abstract**  
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6 **89 Background:** COVID-19 has caused a global public health crisis affecting most countries,  
7 including Ethiopia, in various ways. This study maps the vulnerability to infection, case  
8 severity, and likelihood of death from COVID-19 in Ethiopia.  
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10 **92 Methods:** Thirty-eight potential indicators of vulnerability to COVID-19 infection, case  
11 severity and likelihood of death, identified based on a literature review and the availability of  
12 nationally representative data at a low geographic scale, were assembled from multiple sources  
13 for geospatial analysis. Geospatial analysis techniques were applied to produce maps showing  
14 the vulnerability to infection, case severity, and likelihood of death in Ethiopia at a high level  
15 of resolution (1 km X 1 km).  
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24 **98 Results:** This study showed that vulnerability to COVID-19 infection is likely to be high  
25 across most parts of Ethiopia, particularly in the Somali, Afar, Amhara, Oromia, and Tigray  
26 regions. The number of severe cases of COVID-19 infection requiring hospitalisation and  
27 intensive care unit admission is likely to be high across Amhara, most parts of Oromia and  
28 some parts of the Southern Nations, Nationalities, and Peoples' Region. The risk of COVID-  
29 19-related death is high in the country's border regions, where public health preparedness for  
30 responding to COVID-19 is limited.  
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38 **105 Conclusion:** This study revealed geographical differences in vulnerability to infection, case  
39 severity, and likelihood of death from COVID-19 in Ethiopia. The study offers high-resolution  
40 maps that can guide the targeted interventions necessary to contain the spread of COVID-19 in  
41 Ethiopia.  
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### Strengths and limitations of this study

- This is the first study that maps vulnerability to COVID-19 infection, severe cases, and associated death in Ethiopia at a high level of resolution across the entire territory of Ethiopia.
- This is also the first study that has attempted to present the degree of service preparedness for COVID-19 across the country.
- The study incorporated a wide range of indicators from multiple sources and applied rigorous geospatial techniques to provide the best possible prediction maps.
- However, some important indicators such as psychosocial and clinical factors were not captured in our modelling due to the lack of geocoded data.

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## 128 **Introduction**

129 Coronavirus disease (COVID-19) has become one of the most serious global public health  
130 crises in modern times <sup>1</sup>. The disease was declared a pandemic on 11 March 2020 and has  
131 currently affected more than 216 countries and territories <sup>2</sup>. As of 3 August 2020, there were  
132 more than 17.6 million confirmed COVID-19 cases and over 680,000 associated deaths around  
133 the globe <sup>3</sup>. The highest numbers of cases and deaths have been reported from the USA, Brazil,  
134 India, and some European countries, such as Russia, the United Kingdom, Italy, and Spain <sup>3</sup>.  
135 African countries, including Ethiopia, have reported a low number of COVID-19, although the  
136 number of cases and deaths are currently on the rise <sup>4</sup>. In Ethiopia, the first case of COVID-19  
137 was reported on 13 March 2020, and the disease recently spread rapidly from the capital city,  
138 Addis Ababa, to other parts of the country, affecting almost all regions at various levels <sup>5</sup>.

139 COVID-19 has had severe health and economic consequences <sup>6</sup>. Multiple factors, such as  
140 socio-demographic, connectivity, behavioural, climatic, and comorbidity factors, are strong  
141 predictors of the differences in transmission, hospitalisation, and mortality rates among and  
142 within countries <sup>7,8</sup>. Studies conducted in Africa have provided limited information on the  
143 vulnerability of different areas to COVID-19 infection <sup>4,9</sup>. These studies have been conducted  
144 at the country level using a limited number of indicators <sup>4,9</sup>. Mapping the risks of COVID-19  
145 (infection, case severity, service preparedness and death) at a higher resolution (using the  
146 lowest administrative unit, such as the district) is important in many ways. First, the generated  
147 evidence can help the government and community better prepare and respond to the health-  
148 and non-health-related impacts of COVID-19 according to their contextual circumstances.  
149 Second, it can help the relevant bodies determine effective and efficient resource-mobilisation  
150 efforts, such as providing training for health care workers, supplying hospitals with necessary  
151 equipment, prioritising testing practices, and distributing hand sanitizer and protective  
152 facemasks. Third, the information can be utilised as a guide for designing targeted travel  
153 restrictions or applying full or partial lockdowns as needed. Fourth, the evidence can stimulate  
154 further study on COVID-19 in the country.

155 Given Ethiopia's large population size, variation in resources and vast geographic size, the risk  
156 of COVID-19 infection, case severity and likelihood of death are likely to differ across regions,  
157 zones, and districts, suggesting that local and context-specific interventions be implemented.  
158 Therefore, this study aimed to map the vulnerability to infection, case severity, and likelihood

159 of death from COVID-19 in Ethiopia at a higher geographic resolution (1 km X 1 km) over the  
160 whole territory of Ethiopia using rigorous state-of-the-art geospatial techniques.

## 161 **Methods**

### 162 **Study area**

163 This study focused on Ethiopia, the second-most populous country in Africa, with an estimated  
164 population size of more than 115 million <sup>10</sup>. Ethiopia has a total area of approximately 1.1  
165 million square kilometres, making it the 10<sup>th</sup> largest country in Africa and the 27<sup>th</sup> largest in  
166 the world. The country has a tiered administrative system consisting of regional states (first  
167 level), zones (second level), woredas or districts (third level), and kebeles or neighbourhoods  
168 (fourth level) <sup>11</sup>. There are nine administrative regional states in Ethiopia, including Tigray,  
169 Afar, Amhara, Oromia, Somali, Benishangul-Gumuz, Harari, Gambella, and the Southern  
170 Nations, Nationalities, and Peoples' Region (SNNPR), and two administrative cities (Addis  
171 Ababa and Direedawa). The four regional states (Afar, Somali, Benishangul-Gumuz, and  
172 Gambella) are categorised as developing regional states. The administrative units of Ethiopia  
173 (shapefiles) were obtained from the Database for Global Administrative Areas <sup>12</sup>.

### 174 **Data sources and variable selection**

175 The analysis data were assembled from multiple sources (Table 1). Potential indicators were  
176 selected based on evidence of association with COVID-19 infection, case severity, and death  
177 based on a literature review and the availability of country-wide representative data at a  
178 district geographic scale or lower (Figure 1). Table 2 presents the evidence for the association  
179 between indicators and COVID-19, as well as the rationale for selecting these indicators for  
180 the study.

181 The following area-level demographic and socio-economic indicators were used as indicators  
182 of COVID-19 infection and case severity: the average number of persons per household, the  
183 proportion of the population aged  $\geq 65$  years, the proportion of males, and the number of  
184 households in the lowest wealth quintile. All of these socio-economic and demographic  
185 indicators were obtained from the latest Ethiopia Demographic and Health Survey (EDHS) <sup>13</sup>.  
186 Population density, estimated as the number of people per grid, was obtained from WorldPop  
187 <sup>14</sup>.

188 Connectivity indicators, which measure the population-level vulnerability to infection, were  
189 also captured using distance and time-bounded markers. Specifically, average travel time  
190 (measured in minutes) to the nearest city with at least 50,000 people and proximity to

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3 191 international borders (measured in kilometres) were included to measure each area's level of  
4 192 susceptibility to infection. Data on travel time to the nearest city, obtained from the University  
5 193 of Oxford's Malaria Atlas Project (MAP), were used to quantify the accessibility of an area to  
6 194 high-density urban centres at a resolution of 1 km×1 km.<sup>15</sup> Data on proximity to international  
7 195 borders were obtained from the EDHS spatial data repository and were used to measure<sup>16</sup> the  
8 196 geodesic distance to the nearest international border in kilometres, indicating the risk of cross-  
9 197 border transmission and the spread of COVID-19. Infection rates and the spread of COVID-19  
10 198 were also positively correlated with the per capita public transportation use rate<sup>17</sup>. Thus, to  
11 199 determine the nearest cross-country road to each location on the map, we obtained and applied  
12 200 data for major roads from the World Bank<sup>18</sup>.

21 201 It is evident that inadequate knowledge about COVID-19 and a lack of awareness of prevention  
22 202 measures exacerbate the community transmission of the disease<sup>19</sup>. Therefore, we extracted  
23 203 data on the adult literacy rate, access to media (such as radio, television, and mobile phone  
24 204 messages) and knowledge about other infectious diseases (e.g., HIV) from the EDHS as proxies  
25 205 for knowledge of COVID-19 prevention measures in each area of the country<sup>13</sup>. According to  
26 206 the WHO, maintaining good hand hygiene through regular washing with soap and water is one  
27 207 of the most effective preventative measures for reducing the transmission of COVID-19<sup>20,21</sup>.  
28 208 Using the same data as above, we also assessed hand hygiene practices, access to water, and  
29 209 the availability of handwashing stations in a household.

37 210 Previous studies have shown that underlying chronic comorbidities and behavioural factors  
38 211 such as cigarette, alcohol and khat consumption were associated with more severe COVID-19  
39 212 infections<sup>22,23</sup>. Data on khat chewing and the alcohol consumption rate were obtained from the  
40 213 EDHS 2016<sup>13</sup>, and data on cigarette smoking were obtained from the Ethiopia Public Health  
41 214 Institute STEP wise approach to Surveillance (STEPS) study<sup>24</sup>. The STEP survey was also  
42 215 used to measure the prevalence of select non-communicable diseases (NCDs) such as  
43 216 hypertension, heart disease, and diabetes mellitus (DM).

50 217 The level of preparedness and readiness of health facilities to detect, manage, and control the  
51 218 COVID-19 pandemic at a given location was measured using data from the Service Availability  
52 219 and Readiness Assessment (SARA) survey<sup>25</sup>. For each geo-location, the obtained measures  
53 220 include the availability and readiness of facilities in terms of basic amenities and equipment,  
54 221 standard precautions, diagnostic capacities, and essential medicines. In addition, data on  
55 222 service readiness for specific diseases such as DM, chronic respiratory disease (CRD), and

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3 223 tuberculosis (TB), as well as the availability of intensive care units (ICUs) and laboratory  
4 224 facilities, were obtained from this same survey. To augment the health facility data, we  
5 225 extracted population-level indicators on health care access and barriers to care from EDHS  
6  
7 226 2016<sup>13</sup>.

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10 227 Finally, climatic data (temperature, precipitation, humidity, and sunlight exposure) were  
11 228 obtained from the WorldClim v2.0 Global Climate Database<sup>26</sup>. These data were extracted at a  
12 229 spatial resolution of 30 seconds or ~1 km<sup>2</sup> and were considered indicators of COVID-19  
13 230 infection in this study.

### 18 231 **Geospatial data processing**

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20 232 All data were georeferenced using a geographical information system, ArcGIS 10.6.1 software  
21 233 (ESRI Inc., Redlands CA, USA). A very small rectangular polygon (fishnet) with its centroid  
22 234 (fishnet centroid) covering the whole territory of Ethiopia was created using tools in ArcGIS  
23 235 (Figure 2). The fishnet centroid contained a unique identification number and was used as a  
24 236 common georeferenced system to process, join, and extract the raster and vector data collected  
25 237 from various sources. All vector data (point, polygon, and line) were converted to raster data  
26 238 using geostatistical methods<sup>27</sup>. Raster grids were then resampled to the common georeferenced  
27 239 system at a spatial resolution of 1 km x 1 km. Finally, a raster mask covering the entire country  
28 240 was created by clipping smaller spatial units from a large global raster data source.

### 35 241 **Statistical analyses**

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37 242 Geostatistical techniques such as spatial autocorrelation, kriging and semivariograms were  
38 243 applied to create a prediction grid surface from a scattered set of points<sup>28</sup>. Kriging assumes  
39 244 that the distance or direction between sample points reflects a spatial correlation that can be  
40 245 used to explain variation in the surface<sup>29</sup>. Since the variables had different units of  
41 246 measurement, the datasets were normalised using a min-max approach to a standard scale  
42 247 ranging from 0 (the lowest risk) to 100 (the highest risk)<sup>30</sup>. After normalisation, the indicators  
43 248 were averaged to create a vulnerability index, measuring the risk of COVID-19 for each geo-  
44 249 location<sup>31</sup>. The vulnerability indices were calculated separately for each domain, namely, the  
45 250 vulnerability to infection, case severity, and likelihood death from COVID-19. The three  
46 251 domains were then averaged to produce the overall COVID-19 vulnerability index. Given that  
47 252 COVID-19 is a new virus, there is a lack of evidence for assigning weights for each indicator.  
48 253 Hence, equal weight was given to all indicators when calculating the arithmetic mean for the  
49 254 aggregate vulnerability indices. We also used principal component analysis (PCA) and  
50 255 geometric means as alternative aggregation methods, producing broadly similar results

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3 256 (Supplemental Figure 1 and Supplemental Figure 2). The risk maps were then created  
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5 257 separately for infection, case severity, service preparedness, and death from the composite  
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7 258 index using geostatistical tools in ArcGIS. All data transformations and aggregations were  
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9 259 performed in R <sup>32</sup>.

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11 260 **Ethics aspects:** Ethical approval was not required for this study as it was based on publicly  
12  
13 261 available data.

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15 262 **Patient and public involvement:** This research was done without patient and public  
16  
17 263 involvement.

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## 23 265 **Results**

### 24 266 **Vulnerability to COVID-19 infection**

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27 267 Figure 3 shows the vulnerability map of COVID-19 infection in Ethiopia. The map highlights  
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29 268 that most parts of the country are likely to have a relatively high vulnerability and be at  
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31 269 substantial risk for COVID-19 infection. Most parts of the country are identified as vulnerable  
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33 270 to COVID-19 infection, with the exception of Addis Ababa and the north-western Somali  
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35 271 region. The peripheral areas of the country bordering Djibouti, Somalia, Eritrea, and South  
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37 272 Sudan appeared to be vulnerable to COVID-19 infection. These outlying areas are  
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39 273 characterised by a low level of geographical connectivity and low scores for disease  
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41 274 knowledge, hand hygiene and socio-economic indices (Supplemental Figure 3). They also have  
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43 275 certain climatic factors that were found to be important indicators of COVID-19 transmission.

### 44 276 **Vulnerability to severe cases of COVID-19 infection**

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46 277 Areas across the Amhara region and most parts of the Oromia region are likely to experience  
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48 278 severe forms of COVID-19 that require hospitalisation and ICU admission. Some parts of the  
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50 279 SNNPR are also expected to be at high risk of severe COVID-19 infections. The combination  
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52 280 of demographic (high proportion of older adults), comorbidity (high prevalence of  
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54 281 hypertension, DM, obesity, HIV, and TB), and behavioural and economic indicators (high  
55  
56 282 proportion of smokers and high level of alcohol and khat consumption, interior cooking, and  
57  
58 283 solid fuel use) renders these parts of the country at a higher risk of severe forms of COVID-19.  
59  
60 284 Figure 4 shows the levels of vulnerability to severe forms of COVID-19.

### 285 **Vulnerability to death from COVID-19**

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3 286 People living around border areas in Ethiopia are at a high risk for COVID-19-related death,  
4 as illustrated in Figure 5. Districts and zones in the Benishangul-Gumuz, Gambela, Afar,  
5 287 SNNPR, Dire Dawa, Southwest Somali, Northwest Amhara, Western Tigray, and Western and  
6 288 Eastern Oromia regions are at high risk for COVID-19-related death. The level of service  
7 289 preparedness and readiness to mitigate the health effects of COVID-19 appear to be very low  
8 290 in these regions (Figure 6). Ethiopia's border regions have inadequate ICU availability and  
9 291 laboratory capacity as well as limited health care access. They also have low general and  
10 292 laboratory capacity as well as limited health care access. They also have low general and  
11 293 service-specific readiness, as shown in Figure 6.

## 18 294 **Discussion**

20 295 This is the first study that maps vulnerability to COVID-19 infection, severe infection cases,  
21 296 and associated death in Ethiopia at a high resolution. This is also the first study that has  
22 297 attempted to present the degree of service preparedness for COVID-19 across the country.

23 298 We found that most parts of the country are vulnerable to COVID-19 infections, and the  
24 299 greatest burden might be outside of Addis Ababa. It is likely that compared to other regions, a  
25 300 higher proportion of people from the Amhara and Oromia regions, the two most populous  
26 301 regions of the country, will develop severe forms of COVID-19 leading to hospitalisation and  
27 302 ICU admission. Border areas of the country are also expected to face a higher risk of death than  
28 303 areas located in the central regions. The findings of this study are of paramount importance in  
29 304 preventing and controlling COVID-19 transmission and in designing targeted interventions,  
30 305 such as enacting travel restrictions, distributing preventative masks and determining which  
31 306 areas to prioritise if a COVID-19 vaccine becomes available. As some of these areas also have  
32 307 lower preparedness scores and low general and service-specific readiness scores, the findings  
33 308 have wider implications for allocating resources and strengthening the health care system after  
34 309 the COVID-19 pandemic.

35 310 Despite the proportionally high infection rate in Addis Ababa at present, we found that the risk  
36 311 of COVID-19 infection is likely to become rather high in other regions. The high infection rate  
37 312 in Addis Ababa at this initial stage is expected, given that Addis Ababa is a major travel hub  
38 313 and Bole International Airport, located in the city, is one of the largest international airports in  
39 314 Africa. This exposes the city to a higher risk of imported cases and, subsequently, to an early  
40 315 surge of infections, leaving the areas outside the city at a higher risk of later infection. Second,  
41 316 we considered multifaceted risk factors (indicators) for COVID-19 infection in our geospatial

1  
2  
3 317 model. This means that although the city has a high degree of connectivity, it is also  
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5 318 characterised by higher scores for information penetration, knowledge of disease prevention  
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7 319 and hand hygiene practices that could help slow the rate of infection in the city<sup>13</sup>. Third, Addis  
8  
9 320 Ababa has relatively better and more consistent test-and-contact tracing practices than in other  
10  
11 321 parts of the country, which means that the chance of new infections being detected in the city  
12  
13 322 are much greater than in other parts of the country<sup>5</sup>. Future efforts to expand testing and tracing  
14  
15 323 practices in other areas of the county are likely to increase the extent of confirmed infections  
16  
17 324 in those other areas. Recent studies have demonstrated that effective social distancing and  
18  
19 325 contact tracing can significantly reduce the rate of infection<sup>33,34</sup>. These interventions should  
20  
21 326 be strengthened and expanded to areas identified as high risk in this study.

22  
23 327 Our study also showed that the risk for severe cases of COVID-19 infection is high in most  
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25 328 parts of the Amhara and Oromia regions. This may be due to the high prevalence of NCDs,  
26  
27 329 which are associated with severe cases of COVID-19. Previous studies have revealed that the  
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29 330 burden of NCDs, such as DM and hypertension, is high in these two regions<sup>24,35,36</sup>. With the  
30  
31 331 COVID-19 epidemic evolving rapidly in Ethiopia, fast-tracked public health education and  
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33 332 interventions to control and limit the spread of infection should be strengthened. In addition,  
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35 333 to address severe cases and potential mortality risks, strengthening and expanding tailored  
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37 334 health care services, including ICUs in high-risk areas, are crucial to prevent the exacerbation  
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39 335 of the COVID-19-induced public health crisis.

40  
41 336 Our study also revealed that peripheral areas sharing international borders are likely to see a  
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43 337 greater number of COVID-19-related deaths. The high risk of death along the border areas  
44  
45 338 might be attributed to low preparedness in case management and weak health care systems. In  
46  
47 339 contrast, although the Amhara and Oromia regions may have more severe cases, the  
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49 340 preparedness indicators show that the regions are better equipped to cope with these anticipated  
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51 341 severe cases. However, our study suggests that additional preparation and capacity  
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53 342 strengthening are needed mainly in the following areas: emergency response systems, case  
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55 343 detection and capacity to care for patients. It is also equally important that hospitals have  
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57 344 adequate supplies, health care personnel and life-saving medical intervention resources.  
58  
59 345 Despite encouraging efforts by the Ethiopian government and stakeholders to prepare the  
60  
346 health care system for the pandemic, the existing health care services in the country may face  
347 unprecedented challenges and crises due to the surge of patients that will require hospitalisation  
348 and ICU services at the same time. This can, however, be eased by implementing public health  
349 and social measures at the individual, community, and public authority levels to prevent

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3 350 infections and subsequent health, economic, and social consequences <sup>37</sup>. Studies have shown  
4  
5 351 that implementing non-pharmaceutical interventions, especially during the early stages of  
6  
7 352 infection, can reduce transmission and subsequent potential public health and economic crises  
8  
9 353 <sup>38</sup>.

10  
11 354 Further, we found notable regional disparities in health system preparedness and readiness  
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13 355 levels in the country. This is important because if the health care system is well equipped to  
14  
15 356 prevent and mitigate the spread of the pandemic, then the mortality rate from the disease can  
16  
17 357 be markedly reduced <sup>39</sup>. However, we observed that Ethiopia's border regions (i.e.,  
18  
19 358 Benishangul-Gumuz, Gambella, Afar, and Somali) have low preparedness levels.  
20  
21 359 Nevertheless, comparisons need to be treated with care because Ethiopia in general has very  
22  
23 360 low doctor-to-resident (1 doctor per 10,000 people) and hospital bed-to-population (3 hospital  
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25 361 beds per 10,000 people) ratios <sup>40</sup>. Several long-, medium- and short-term strategies, can be  
26  
27 362 implemented to mitigate these problems: (i) providing short-term training for potential actors  
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29 363 such as community leaders, students, and traditional and modern medical practitioners, (ii)  
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31 364 recruiting additional staff to work in COVID-19-related health care, (iii) establishing COVID-  
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33 365 19 clinics and changing outpatient rooms to emergency clinics, (iv) collaborating with private  
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35 366 hospitals ahead of surges so that they can be used in the case such surges occur, and (v)  
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37 367 establishing mobile clinics and temporary admission rooms in highly vulnerable areas.

## 368 **Policy implications**

38  
39 369 The findings of this study provide vital evidence that can inform policymakers in allocating  
40  
41 370 resources and guide health professionals in responding to and preventing COVID 19 infections.  
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43 371 With the limited resources that Ethiopia has, the measures implemented to limit the spread of  
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45 372 COVID-19 infection should be sustainable, should be tailored and should consider the national  
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47 373 and local contexts, such as varying socio-economic conditions. Strengthening the health care  
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49 374 system and improving the capacity of health extension workers (HEWs) needs to be top  
50  
51 375 priority. The national measures implemented in Ethiopia seem to be skewed towards  
52  
53 376 procurement-heavy interventions, such as establishing isolation facilities and obtaining  
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55 377 personal protective equipment and ventilators. While these interventions are critical,  
56  
57 378 community response should never be a secondary intervention. In this regard, the delayed  
58  
59 379 engagement of communities and HEWs hinders an effective outbreak response. Overall, it is  
60  
380 crucial that the Ethiopian government and all stakeholders strengthen their ongoing efforts to  
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prevent and slow the infection rate.



## 382 **Strength and Limitations**

383 This study has several strengths. First, the current study was conducted at a high level of  
384 resolution (1 km x 1 km) across the entire territory of Ethiopia. Second, it incorporated a wide  
385 range of indicators from multiple sources. Third, it applied rigorous geospatial techniques,  
386 including spatial autocorrelation, kriging and semivariograms, to provide the best possible  
387 prediction maps. Finally, we produced vulnerability mapping for infection or transmission,  
388 case severity, and associated death separately to assist with policy interventions related to each  
389 risk.

390 However, it is important to note some potential limitations of the study when interpreting the  
391 findings. First, the results need constant updating, as some of the time-varying variables used  
392 in the study can change when new interventions are introduced. Second, ongoing political  
393 turmoil in the country means that the dynamics of transmission may change depending on the  
394 location and severity of these incidents. Third, the calculation of the composite risk factor index  
395 was based on an unweighted average under the assumption that all indicators have equal  
396 importance, which may or may not be the case. Last, some important indicators, such as  
397 psychosocial and clinical factors, were not captured in our modelling due to the lack of  
398 geocoded data.

## 399 **Conclusions**

400 Although nearly three-quarters of the current COVID-19 cases reported in Ethiopia are  
401 concentrated in and around Addis Ababa, this study predicts that over time, the risk of COVID-  
402 19 infection will be higher across most other parts of the country. A higher proportion of people  
403 from the Amhara region, most of the Oromia region, and some parts of the SNNPR will develop  
404 severe cases of infection. Additionally, the risk of death will be higher in the regions of the  
405 country with low preparedness scores for COVID response. Hence, the preventative and  
406 control measures that are currently in place in the capital city should be strengthened and  
407 extended to regional areas, especially to high-risk areas, to prevent and mitigate the risk of  
408 COVID-19 infection, lower the number of severe cases, and limit the number of associated  
409 deaths in Ethiopia.

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## 413 Declaration

### 414 Authors' contributions

415 KAA, YAG, YK, DMF, DNK, YAM, HAG, MB, MDM, AAA, and BAD conceptualised the  
416 study. KAA designed and run the geospatial analysis. YAG involved in the data analysis. KAA,  
417 YAG, DMF, DNK, and YAM drafted the manuscript. HAG, MB, AAA<sub>1</sub>, MDM, BAD, SA,  
418 AA, AAA<sub>2</sub>, WMB, KTG, TG, ATG, LGG, AG, HTK, GDK, CTL, LBM, AAM, HM, HGT,  
419 AGT, FT, BLW, and YK Critically reviewed and revised the drafted manuscript. KAA, YK,  
420 and AHM were responsible for quality control of accuracy and integrity of data. All the authors  
421 interpreted the data. All authors contributed to the final draft and finally approved it to be  
422 published. All authors agreed to be accountable for all aspects of the work for any issue related  
423 to the accuracy or integrity of any part of the work. The corresponding author attests that all  
424 listed authors meet authorship criteria and that no others meeting the criteria have been omitted.

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426 **Competing interests:** None declared.

427 **Patient and public involvement:** This research was done without patient and public  
428 involvement.

429 **Data availability statement:** Extra data is available by emailing the corresponding author  
430 (KAA): kefyalew.alene@curtin.edu.au

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582 **Tables**

583 **Table 1:** Data sources and definitions of indicators for the vulnerability of COVID-19 in  
 584 Ethiopia.

Indicators	Data sources	Definitions
<b>Demographic indicators</b>		
Male sex	EDHS 2016	Total number of male populations divided by the total number of people participated in the survey
Older age	EDHS 2016	Total number of people with age $\geq 65$ years divided by the total number of people participated in the survey
<b>Socio-economic indicators</b>		
Population density	WorldPop	Number of people per square kilometre (grid)
Number of household members	EDHS 2016	Average number of people living in a house
Low wealth index	EDHS 2016	Number of people with low wealth index (poorer and poorest) divided by the total number of people participated in the survey
<b>Connectivity indicators</b>		
Travel times to cities	MAP	Travel time in minutes to the nearest city with a population of more than 50,000
Proximity to national borders	DHS Spatial Repository	The geodesic distance to the nearest international borders
Distance to major roads	World Bank	Distance in km to cross-country round
<b>Climatic indicators</b>		
Mean temperature	WorldClim	Annual mean environmental air temperature ( $^{\circ}\text{C}$ )
Mean precipitation	WorldClim	Annual mean rainfall (mm)
Wind speed	WorldClim	Annual mean wind speed ( $\text{m s}^{-1}$ )
Solar radiation	WorldClim	Annual mean solar radiation ( $\text{kJ m}^{-2} \text{day}^{-1}$ )
Water vapour pressure	WorldClim	Annual mean water vapour pressure (kPa), equivalent to absolute humidity.
<b>Behavioural indicators</b>		
Khat chewing	EDHS 2016	Total number of people chewing khat in the last one month prior to the survey divided by the total number of people participating in the survey
Alcohol drinking	EDHS 2016	Total number of people drinking alcohol in the month prior to the survey divided by the total number of people participating in the survey
Cigarette smoking	EPHI STEPS	Total number of people currently smoke cigarettes divided by the total number of people participating in the survey
Cooking inside the household	EDHS 2016	Total number of households where cooking takes place inside the house without a separate building or outdoors (i.e. exposure to smoke inside the home) divided by the total number of households in the survey
Use solid fuel for cooking	EDHS 2016	Number of households used some type of solid fuel (wood, dung, grass, crop) for cooking food divided by all households in the survey
<b>Disease prevention knowledge indicators</b>		
Adult illiteracy rate	EDHS 2016	Total number of adults (aged 15 years and above) who had not attended school or who cannot read and write divided by the total number of adults participated in the survey
Access to listen to the radio	EDHS 2016	Total number of people who had not access to listen to the radio divided by total survey participants
Access to watch TV	EDHS 2016	Total number of people have no access to watch television divided by total survey participants

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3 Mobile phone ownership	EDHS 2016	Total number of people have no access to mobile phone divide by the total number of survey participants
4 Knowledge toward HIV	EDHS 2016	Number of people with poor knowledge towards HIV divided by the total number of people participating in the survey
<b>Hand hygiene indicators</b>		
9 Travel time to water sources	EDHS 2016	Mean travel time in minutes to obtain water source (i.e. access to a water source)
11 Place for handwashing	EDHS 2016	Number of households have no fixed or mobile place for handwashing divided by total number of households in the survey
13 Soap or detergent availability for handwashing	EDHS 2016	Number of households have no essential handwashing agents (i.e. soap, and detergent) divided by total household in the survey
<b>Comorbidities indicators</b>		
17 HTN	EPHI STEPS	Total number of people with HTN divided by the total number of survey participants
19 DM	EPHI STEPS	Total number of people with DM divided by the total number of survey participants
21 BMI	EPHI STEPS	Mean body mass index
23 CVD	EPHI STEPS	Total number of people with heart disease divided by total number of people in the survey
25 Cholesterol	EPHI STEPS	Mean cholesterol level
26 HIV prevalence	EDHS 2016	Total number of people with HIV divided by survey participants
27 TB SMR	EMOH	Standardized morbidity ratio (SMR) as measured by observed number of TB cases divided by the expected number of TB cases
<b>Service availability and readiness indicators</b>		
30 Health care access problem	EDHS 2016	Difficulty of getting advice or treatment due to lack of money, or distance to a health facility
32 General service readiness and availability	EPHI SARA	Availability of equipment and supplies (i.e. basic amenities, equipment, standard precautions, diagnostic capacity, essential medicines) necessary to provide general health services
36 ICU availability	EPHI SARA	Availability of Critical Care Services (ICU) in hospitals
37 CRD readiness index	EPHI SARA	Availability of specific services for Chronic respiratory disease (CRD) diagnosis, management, and follow up
39 TB readiness index	EPHI SARA	Availability of specific services for tuberculosis diagnosis, management, and follow up
41 Diabetes readiness index	EPHI SARA	Availability of specific service for diabetes diagnosis and management and follow up
43 <i>G-Econ: Geographically based Economic data; EDHS: Ethiopia demographic and health survey; UN OCHA: United Nation Office for Coordination of Humanitarian Affairs; MAP: SRTM: Malaria Atlas Project; Shuttle Radar Topography Mission; EPHI: Ethiopia Public Health Institute; EMOH: Ethiopia Ministry of Health; SARA: Service Availability and Readiness Assessment</i>		

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598 **Table 2: Evidence for risk of COVID-19 infection, severity, and death**

Indicators	Risk factors	Evidence	References
<b>Demographic indicators</b>			
Male sex	Severity	Death from and severity of COVID-19 was strongly associated with being male (HR 1.99, 95%CI: 1.88-2.10)	Williamson E <sup>41</sup>
Older age	Severity	Older than 65 years were risk factors for disease progression in patients with COVID-19 (OR =6.06, 95% CI: 3.98, 9.22)	Zheng Z <sup>23</sup>
<b>Socio-economic indicators</b>			
Population density	Infection	High population density is a risk factor for COVID-19 infection	Ahmadi M <sup>42</sup>
Number of household members	Infection	Areas with a higher percentage of households with more than one person per room had a higher incidence of COVID-19	Ahmad K <sup>43</sup>
Low wealth index	Infection	Socio-economic deprivation (RR 1.26 per SD increase in Townsend Index) associated with COVID -19 infection	Ho FK <sup>44</sup>
<b>Connectivity indicators</b>			
Travel times to cities	Infection	The distance between Wuhan and other cities was inversely associated with the numbers of COVID-19 cases in that city	Zheng R <sup>45</sup>
Proximity to national borders	Infection	Cross country moment is a risk factor for COVID-19 transmission and importation	Chinazz M <sup>46</sup>
Distance to major roads	Infection	Spread of COVID-19 was correlated positively with public transportation per capita	Tian H <sup>47</sup>
<b>Climatic indicators</b>			
Mean temperature	Infection	Low ambient temperatures are associated with more rapid spread of COVID-19	Holtmann M <sup>48</sup>
Mean precipitation	Infection	Countries with higher rainfall measurements showed an increase in COVID-19 transmission	Sobral MFF <sup>49</sup>
Wind speed	Infection	Areas with low values of wind speed associated with a high rate of COVID-19 infection	Ahmadi M <sup>42</sup>
Solar radiation	Infection	Areas with low values of solar radiation exposure associated with a high rate of COVID-19 infection	Ahmadi M <sup>42</sup>
Water vapour pressure	Infection	High humidity reduces the transmission of COVID-19. Water vapour pressure negatively correctly with COVID-19 infection.	Wang J <sup>50</sup> , Li J <sup>51</sup>
<b>Behavioural indicators</b>			
Khat chewing	Severity	There is an association between khat chewing and chronic illness such as HIV infection, elevated diastolic blood pressure	Basker GV <sup>52</sup>
Alcohol drinking	Severity	Patients with alcohol use disorders at increased risk for COVID-19	Testino G <sup>22</sup>
Cigarette smoking	Severity	Current smoking was a risk factor for disease progression in patients with COVID-19 (OR =2.51, 95% CI: 1.39, 3.32)	Zheng Z <sup>23</sup>
Cooking inside the household	Severity	Areas with a higher percentage of incomplete kitchen facilities had a higher incidence of, and mortality associated with, COVID-19	Ahmad K <sup>43</sup>
Use solid fuel for cooking	Severity	Areas with a higher percentage of incomplete kitchen facilities had a higher incidence of, and mortality associated with, COVID-19	Ahmad K <sup>43</sup>
<b>Disease prevention knowledge indicators</b>			
Adult illiteracy rate	Infection	Adult learning education is a tool to contain the COVID-19 pandemics	Lopes H <sup>53</sup>
Access to listen to radio	Infection	Access to media is a crucial factor in public health responses to an outbreak	Ayedee N <sup>54</sup>
Access to watch TV	Infection	Media (Television) has a significant role in creating a positive atmosphere in COVID-19	Ayedee N <sup>54</sup>
Mobile phone ownership	Infection	Mobile phone calls and text messages help for the diagnosis, management, and control of infectious diseases	Wood S <sup>55</sup>
Knowledge towards HIV	Infection	Knowledge towards an infectious disease such as HIV can help to control the transmission of the diseases	Bertozzi S <sup>56</sup>
<b>Hand hygiene indicators</b>			

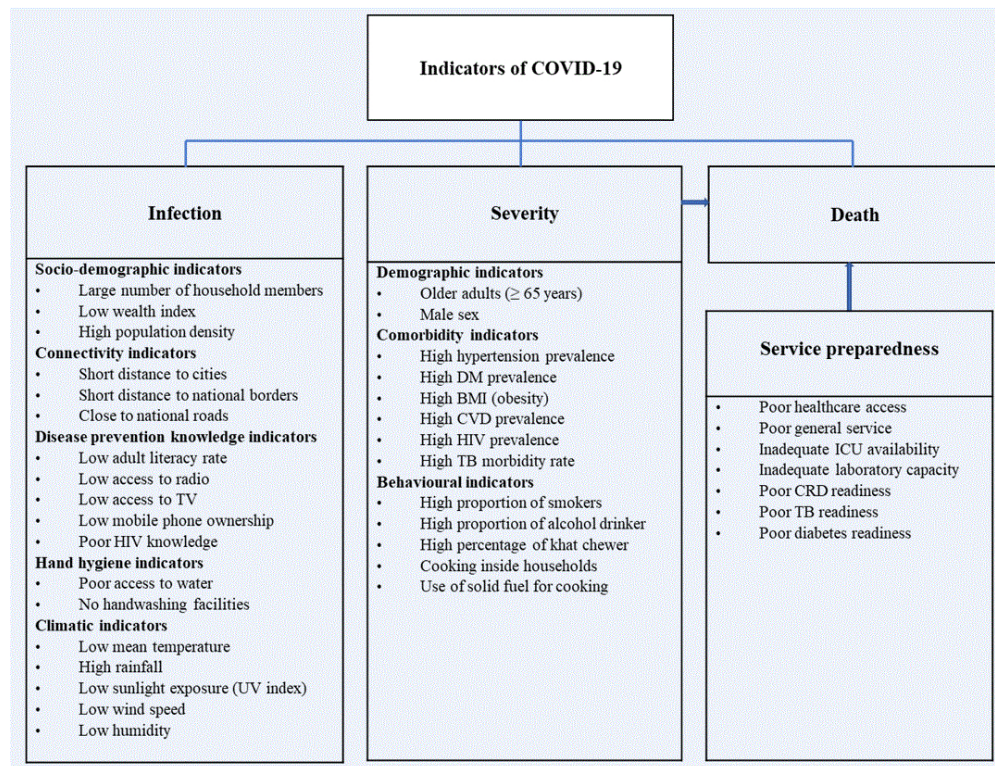


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3 4 5 6 7 8 9 10	Travel time to water sources	Infection	Adequate water supply is essential for the control of COVID-19 infection	WHO <sup>57</sup>
11 12 13 14 15 16 17 18 19 20 21 22	Place for handwashing	Infection	Hand washing is recommended by WHO for the control of COVID-19 infection	WHO <sup>58</sup>
23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40	Soap or detergent availability for handwashing	Infection	Availability of soap or detergent is essential to keep hand hygiene for the prevention of COVID-19 infection	WHO <sup>58</sup>
<b>Comorbidities indicators</b>				
11 12 13 14 15 16 17 18 19 20 21 22	HTN	Severity	Hypertension was statistically significant with a higher rate of severity and death (OR = 2.72, 95% CI: 1.60, 4.64)	Zheng Z <sup>23</sup>
23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40	DM	Severity	Death from COVID-19 was associated with DM (HR 1.50, 95%CI: 1.40-1.60) 1.50	Williamson E <sup>41</sup>
11 12 13 14 15 16 17 18 19 20 21 22	BMI	Severity	Death from COVID-19 was associated with higher BMI (HR 1.27, 95%CI: 1.18-1.36)	Williamson E <sup>41</sup>
23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40	CVD	Severity	Cardiovascular disease was significantly associated with higher COVID-19 severity and death (OR = 5.19, 95% CI: 3.25, 8.29)	Zheng Z <sup>23</sup>
11 12 13 14 15 16 17 18 19 20 21 22	HIV prevalence	Severity	Mortality from COVID-19 was associated with immunosuppression (HR 1.69, 95%CI: 1.21-1.34)	Williamson E <sup>41</sup>
23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40	BB SMR	Severity	respiratory diseases were significantly associated with COVID-19 death and severity (OR = 5.15, 95% CI: 2.51, 10.57)	Zheng Z <sup>23</sup>
<b>Service availability and readiness indicators</b>				
11 12 13 14 15 16 17 18 19 20 21 22	Health care access problem	Death	Healthcare resource availability is associated with COVID-19 mortality	Ji Y <sup>7</sup>
23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40	General service readiness	Death	General health service preparedness is essential for combating the COVID-19 pandemic	WHO <sup>59</sup>
11 12 13 14 15 16 17 18 19 20 21 22	ICU availability	Death	Lack of critical care unite increase the risk of death from COVID-19	Murthy S <sup>60</sup>
23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40	CRD readiness	Death	Cardiorespiratory disease (CRD) is a risk factor for COVID-19 related death	Zheng Z <sup>23</sup>
11 12 13 14 15 16 17 18 19 20 21 22	TB readiness	Death	TB determinants outcomes of patients with COVID-19	Tadolini M <sup>61</sup>
23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40	Diabetes readiness	Death	Diabetes affects the prognosis of patients with COVID-19	Zheng Z <sup>23</sup>
<p><i>G-Econ: Geographically based Economic data; EDHS: Ethiopia demographic and health survey; UN OCHA: United Nation Office for Coordination of Humanitarian Affairs; MAP: SRTM: Malaria Atlas Project; Shuttle Radar Topography Mission; EPHI: Ethiopia Public Health Institute; EMOH: Ethiopia Ministry of Health; SARA: Service Availability and Readiness Assessment</i></p>				

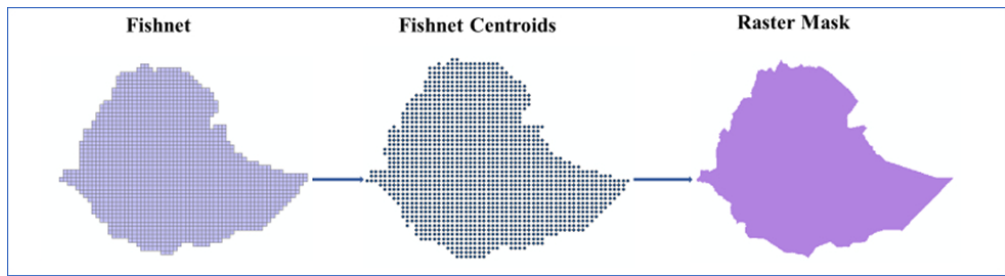
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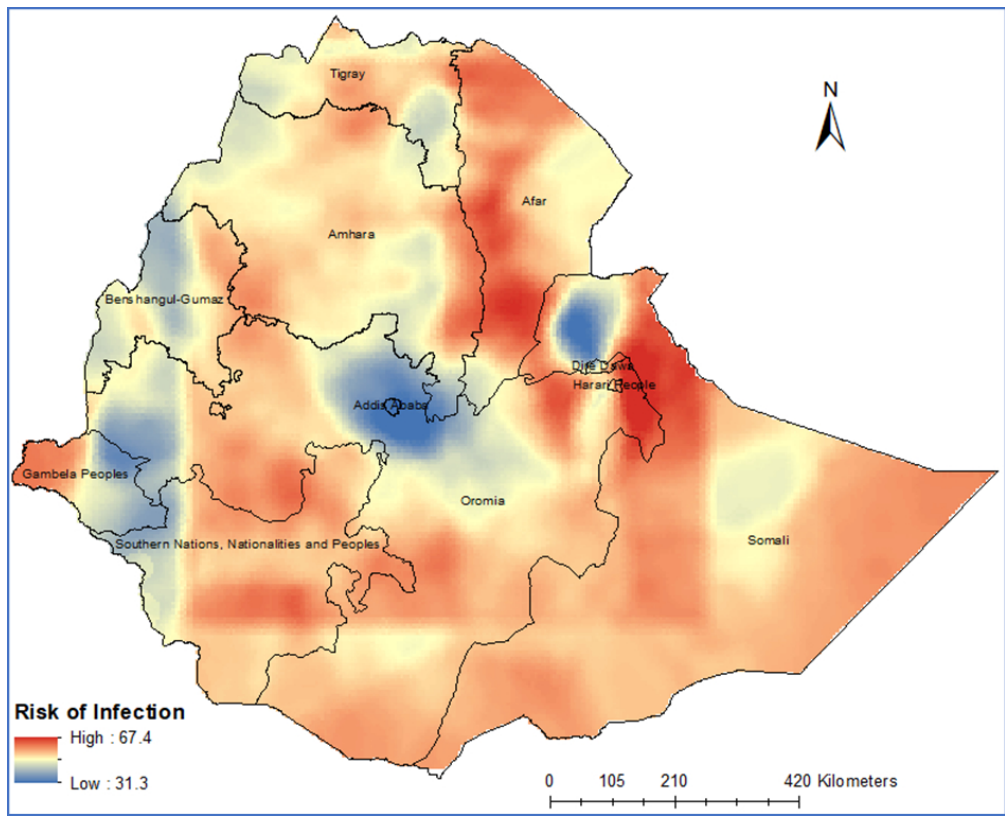
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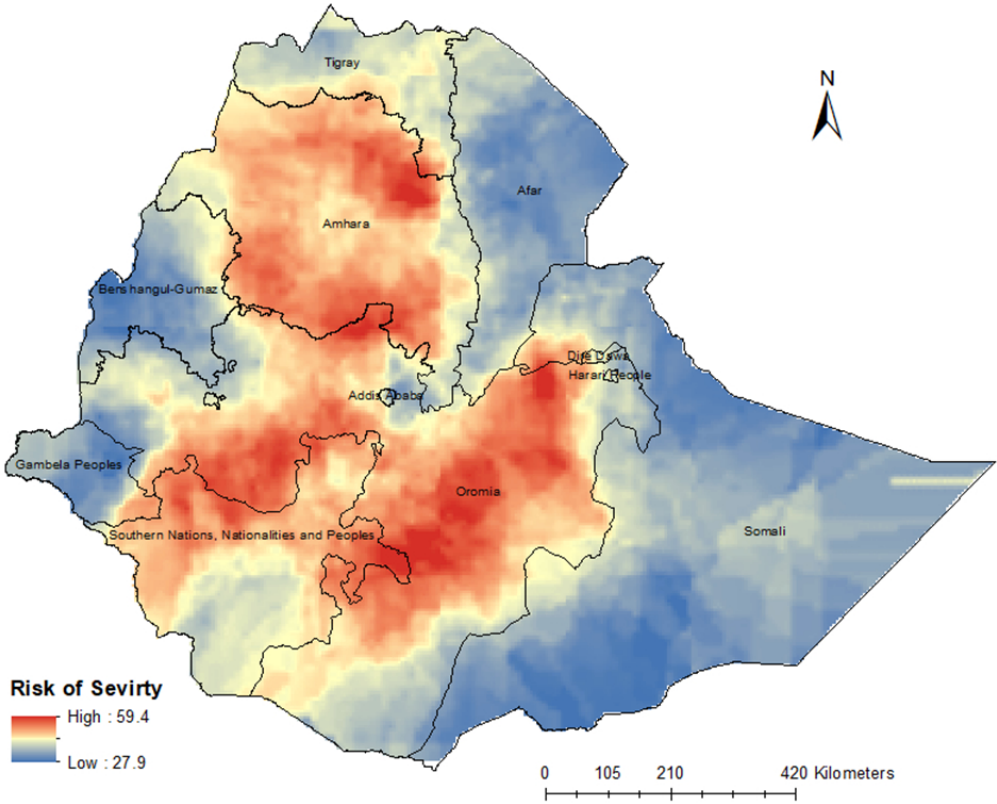
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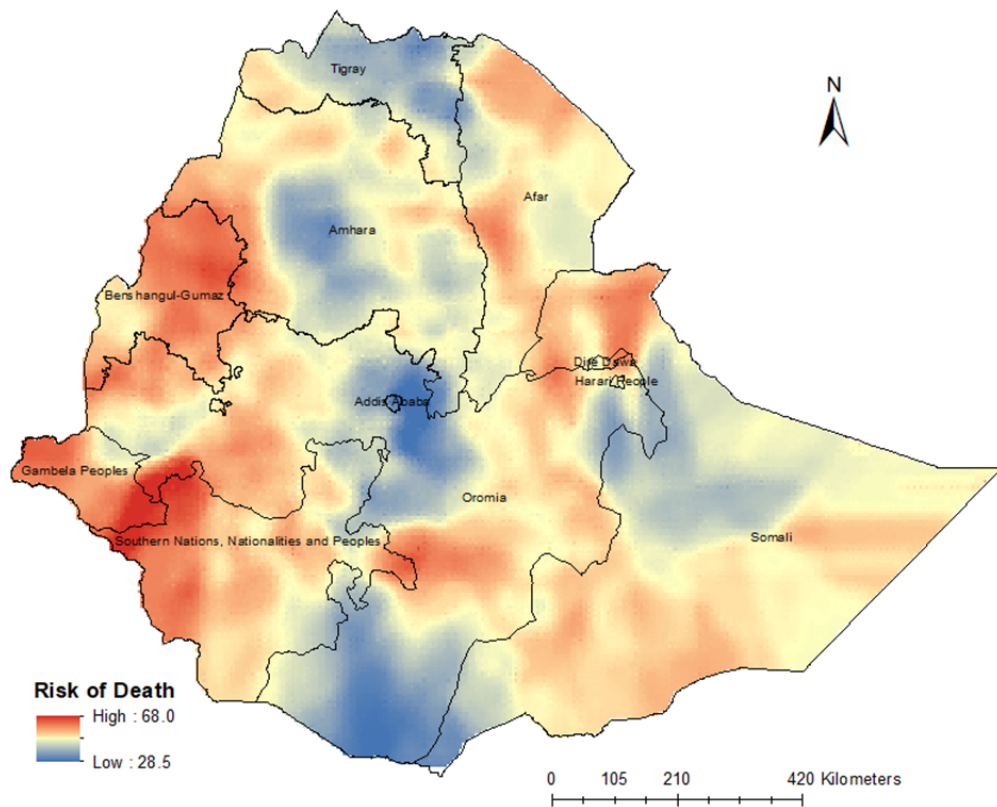
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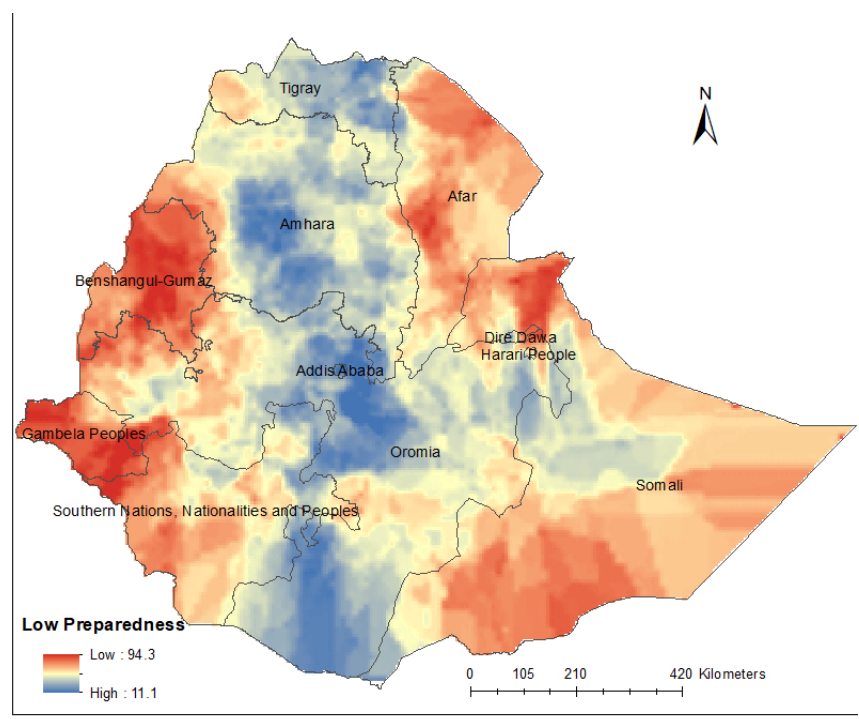
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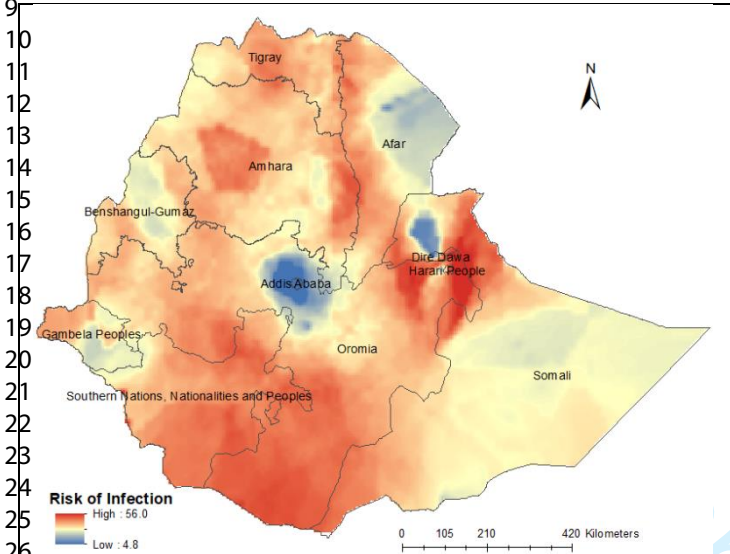
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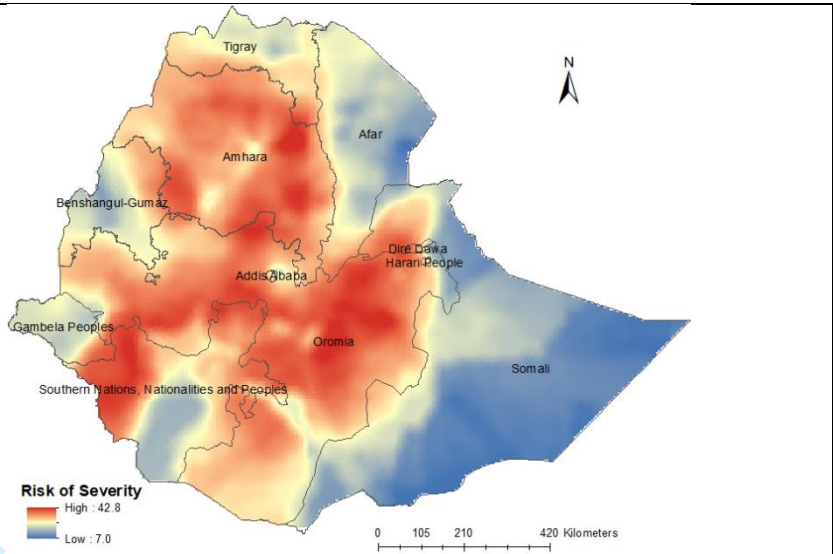
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**Supplemental Information**

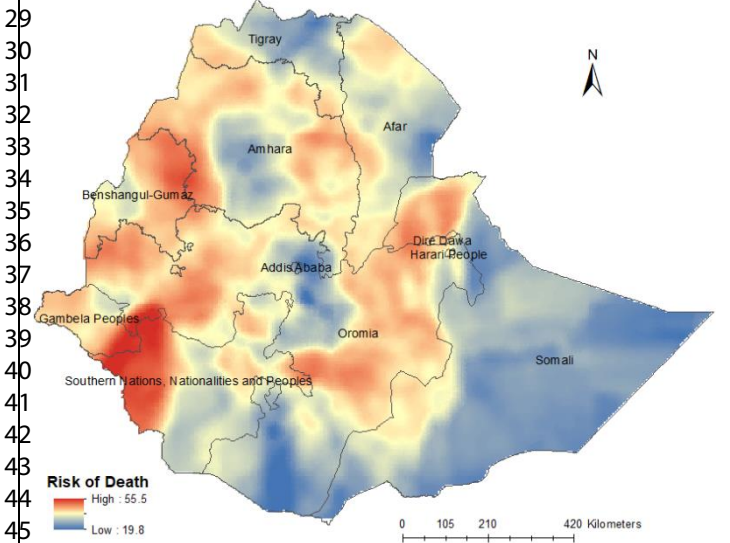
**Supplemental Figure 1:** Vulnerability maps of COVID-19 infection, severity, preparedness, and death in Ethiopia, created based on a geometric mean as alternative aggregation method.



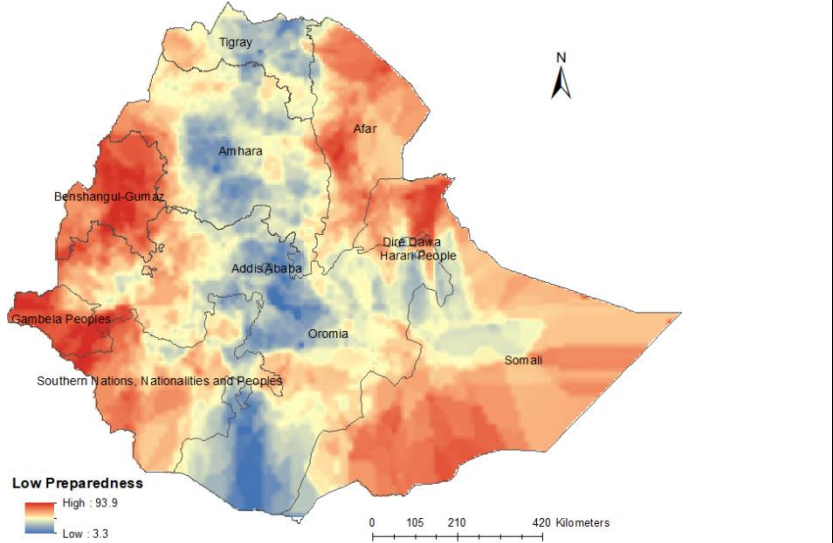
S Figure 1a. COVID-19 infection risk map in Ethiopia, created based on a geometric mean



S Figure 1b. COVID-19 severity risk map in Ethiopia, created based on a geometric mean



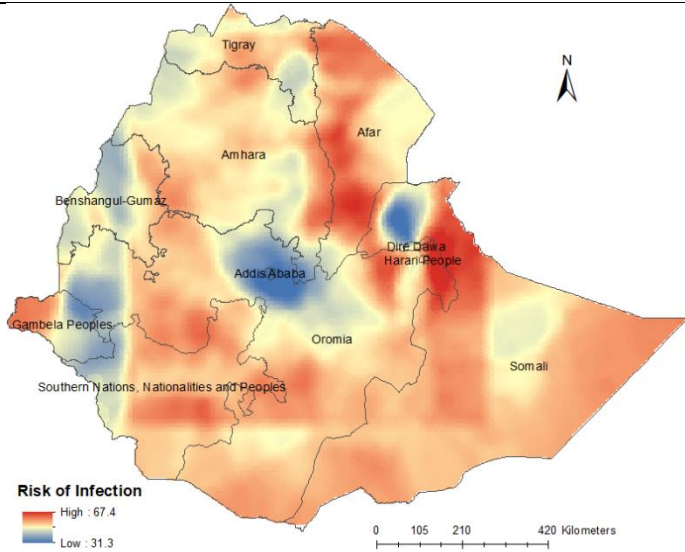
S Figure 2c. Death risk map of COVID-19 in Ethiopia, created based on a geometric mean



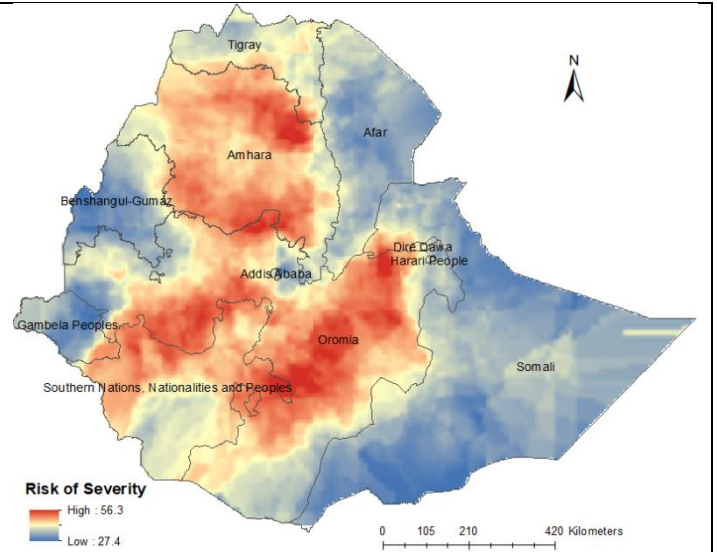
S Figure 3d. Service preparedness map of COVID-19 in Ethiopia, created based on a geometric mean



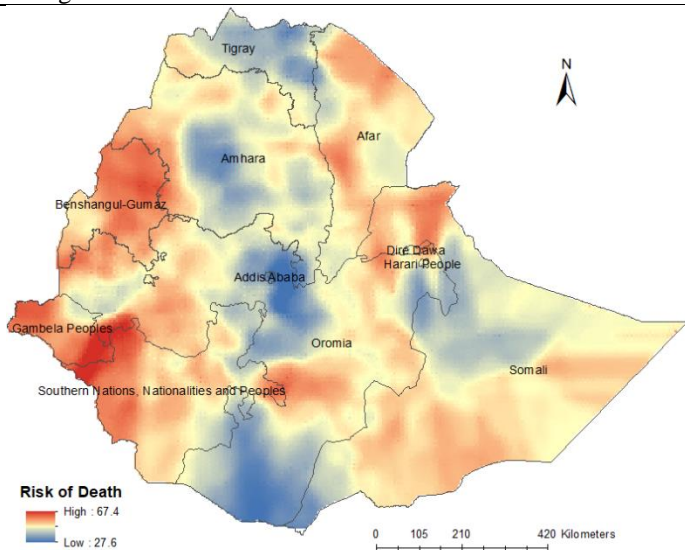
**Supplemental Figure 2: Vulnerability maps of COVID-19 infection, severity, preparedness, and death in Ethiopia, created based on a principal component analysis (PCA) as alternative aggregation method.**



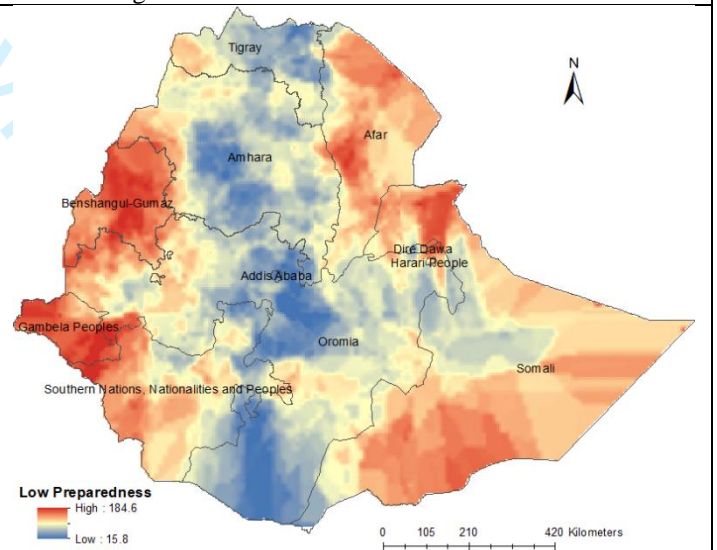
S Figure 2a. COVID-19 infection risk map in Ethiopia, created based on a geometric mean



S Figure 2b. COVID-19 severity risk map in Ethiopia, created based on a geometric mean



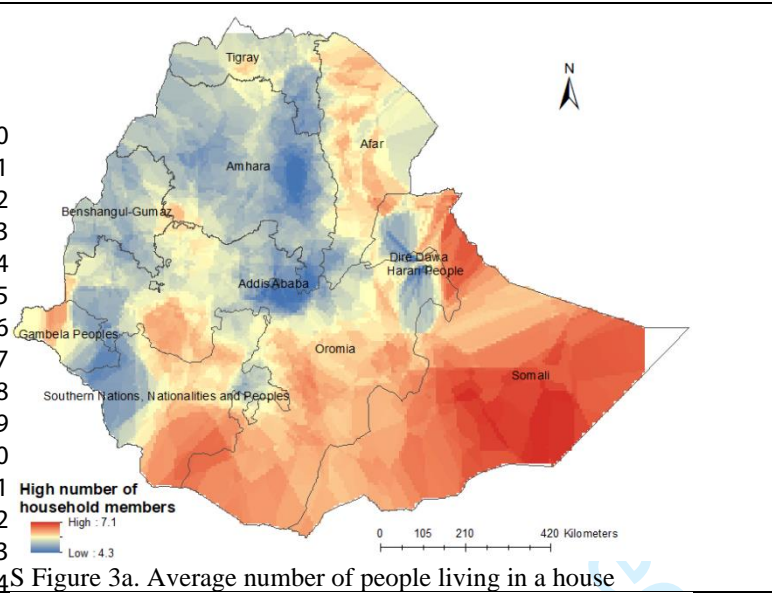
S Figure 2c. Death risk map of COVID-19 in Ethiopia, created based on a geometric mean



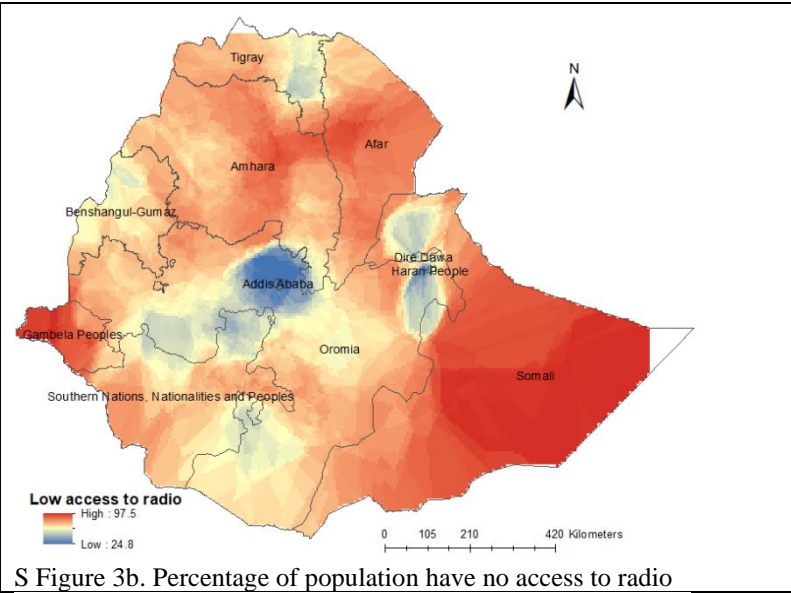
S Figure 2d. Service preparedness map of COVID-19 in Ethiopia, created based on a geometric mean

**Supplemental Figure 3:** Selected indicators showing the risk of COVID-19 infection in Ethiopia

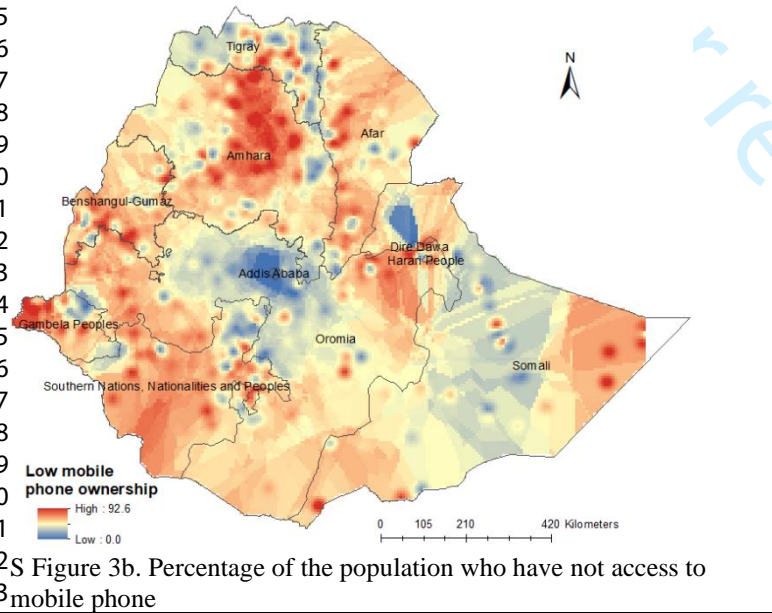
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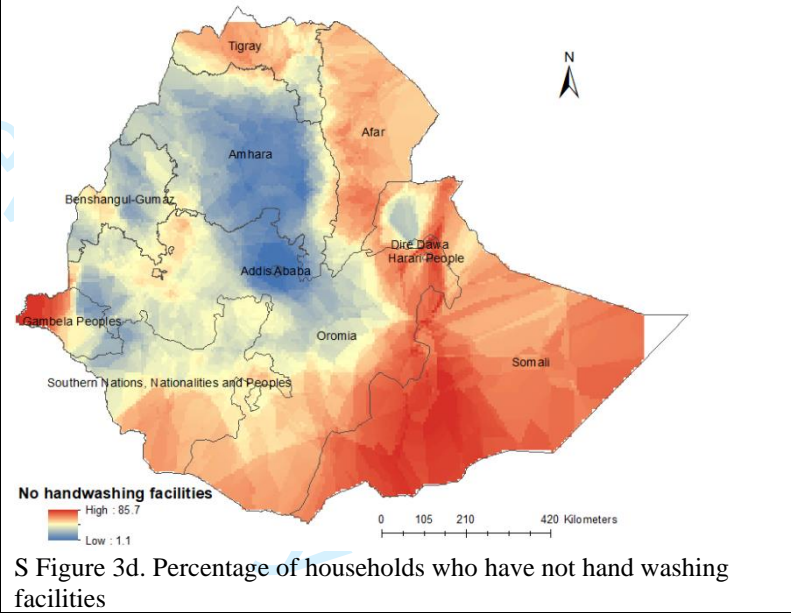
S Figure 3a. Average number of people living in a house



S Figure 3b. Percentage of population have no access to radio



S Figure 3b. Percentage of the population who have not access to mobile phone



S Figure 3d. Percentage of households who have not hand washing facilities

# BMJ Open

## COVID-19 in Ethiopia: A geospatial analysis of vulnerability to infection, case severity, and death

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<b>&lt;b&gt;Primary Subject Heading&lt;/b&gt;:</b>	Epidemiology
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## 1 COVID-19 in Ethiopia: A geospatial analysis of vulnerability to infection, 2 case severity, and death

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54 85 **Keywords:** Risk map, vulnerability, infection, severity, death, COVID-19, Ethiopia, geospatial  
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3 88 **Abstract**  
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6 89 **Background:** COVID-19 has caused a global public health crisis affecting most countries,  
7  
8 90 including Ethiopia, in various ways. This study maps the vulnerability to infection, case  
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10 91 severity, and likelihood of death from COVID-19 in Ethiopia.  
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13 92 **Methods:** Thirty-eight potential indicators of vulnerability to COVID-19 infection, case  
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15 93 severity and likelihood of death, identified based on a literature review and the availability of  
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17 94 nationally representative data at a low geographic scale, were assembled from multiple sources  
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19 95 for geospatial analysis. Geospatial analysis techniques were applied to produce maps showing  
20  
21 96 the vulnerability to infection, case severity, and likelihood of death in Ethiopia at a spatial  
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23 97 resolution of 1 km X 1 km.  
24

25 98 **Results:** This study showed that vulnerability to COVID-19 infection is likely to be high  
26  
27 99 across most parts of Ethiopia, particularly in the Somali, Afar, Amhara, Oromia, and Tigray  
28  
29 100 regions. The number of severe cases of COVID-19 infection requiring hospitalisation and  
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31 101 intensive care unit admission is likely to be high across Amhara, most parts of Oromia and  
32  
33 102 some parts of the Southern Nations, Nationalities, and Peoples' Region. The risk of COVID-  
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35 103 19-related death is high in the country's border regions, where public health preparedness for  
36  
37 104 responding to COVID-19 is limited.  
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39 105 **Conclusion:** This study revealed geographical differences in vulnerability to infection, case  
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41 106 severity, and likelihood of death from COVID-19 in Ethiopia. The study offers maps that can  
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43 107 guide the targeted interventions necessary to contain the spread of COVID-19 in Ethiopia.  
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5**Strengths and limitations of this study**

- This is the first study that maps vulnerability to COVID-19 infection, severe cases, and associated death in Ethiopia at a high level of resolution across the entire territory of Ethiopia.
- This is also the first study that has attempted to present the degree of service preparedness for COVID-19 across the country.
- The study incorporated a wide range of indicators from multiple sources and applied rigorous geospatial techniques to provide the best possible prediction maps.
- However, some important indicators such as psychosocial and clinical factors were not captured in our modelling due to the lack of geocoded data.

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## 128 **Introduction**

129 Coronavirus disease (COVID-19) has become one of the most serious global public health  
130 crises in modern times <sup>1</sup>. The disease was declared a pandemic on 11 March 2020 and has  
131 currently affected more than 216 countries and territories <sup>2</sup>. As of 3 August 2020, there were  
132 more than 17.6 million confirmed COVID-19 cases and over 680,000 associated deaths around  
133 the globe <sup>3</sup>. The highest numbers of cases and deaths have been reported from the USA, Brazil,  
134 India, and some European countries, such as Russia, the United Kingdom, Italy, and Spain <sup>3</sup>.  
135 African countries, including Ethiopia, have reported a low number of COVID-19, although the  
136 number of cases and deaths are currently on the rise <sup>4</sup>. In Ethiopia, the first case of COVID-19  
137 was reported on 13 March 2020 in Addis Ababa, but at the time of this study almost all regions  
138 of the country were affected at varying levels <sup>5</sup>. However, number of cases in the country are  
139 still very low due to limited testing capacity and delays in reporting confirmed cases.

140 Multiple factors, such as socio-demographic, connectivity, behavioural, climatic, and  
141 comorbidity factors, are strong predictors of the differences in transmission, hospitalisation,  
142 and mortality rates among and within countries <sup>6,7</sup>. Studies conducted in Africa have provided  
143 limited information on the vulnerability of different areas to COVID-19 infection <sup>4,8</sup>. These  
144 studies have been conducted at the country level using a limited number of indicators <sup>4,8</sup>.  
145 Mapping the risks of COVID-19 (infection, case severity, service preparedness and death) at  
146 the lowest administrative unit, such as the district is important in many ways. First, the  
147 generated evidence can help the government and community better prepare and respond to the  
148 health- and non-health-related impacts of COVID-19 according to their contextual  
149 circumstances. Second, it can help the relevant bodies determine effective and efficient  
150 resource-mobilisation efforts, such as providing training for health care workers, supplying  
151 hospitals with necessary equipment, prioritising testing practices, and distributing hand  
152 sanitizer and protective facemasks. Third, the information can be utilised as a guide for  
153 designing targeted travel restrictions or applying full or partial lockdowns as needed. Fourth,  
154 the evidence can stimulate further study on COVID-19 in the country.

155 Given Ethiopia's large population size, variation in resources and vast geographic size, the risk  
156 of COVID-19 infection, case severity and likelihood of death are likely to differ across regions,  
157 zones, and districts, suggesting that local and context-specific interventions be implemented.  
158 Therefore, this study aimed to map the vulnerability to infection, case severity, and likelihood  
159 of death from COVID-19 in Ethiopia using rigorous state-of-the-art geospatial techniques.

## 160 **Methods**

### 161 **Study area**

162 This study focused on Ethiopia, the second-most populous country in Africa, with an estimated  
163 population size of more than 115 million <sup>9</sup>. Ethiopia has a total area of approximately 1.1  
164 million square kilometres, making it the 10<sup>th</sup> largest country in Africa and the 27<sup>th</sup> largest in  
165 the world. The country has a tiered administrative system consisting of regional states (first  
166 level), zones (second level), woredas or districts (third level), and kebeles or neighbourhoods  
167 (fourth level) <sup>10</sup>. There are nine administrative regional states in Ethiopia, including Tigray,  
168 Afar, Amhara, Oromia, Somali, Benishangul-Gumuz, Harari, Gambella, and the Southern  
169 Nations, Nationalities, and Peoples' Region (SNNPR), and two administrative cities (Addis  
170 Ababa and Diredawa). Four of these regional states (namely, Afar, Somali, Benishangul-  
171 Gumuz, and Gambella) are relatively less developed, and categorised as developing regional  
172 states. They lag behind the rest of the country in all indicators related to human development  
173 and disease prevention and control programs. The administrative units of Ethiopia (shapefiles)  
174 were obtained from the Database for Global Administrative Areas <sup>11</sup>.

### 175 **Data sources and variable selection**

176 The data for this study were assembled from multiple sources (Table 1). Potential indicators  
177 were selected based on evidence of association with COVID-19 infection, case severity, and  
178 death based on a literature review and the availability of country-wide representative data at a  
179 district geographic scale or lower (Figure 1). Table 2 presents the evidence for the association  
180 between indicators and COVID-19, as well as the rationale for selecting these indicators for  
181 the study.

182 The following area-level demographic and socio-economic indicators were used as indicators  
183 of COVID-19 infection and case severity: the average number of persons per household, the  
184 proportion of the population aged  $\geq 65$  years, the proportion of males, and the number of  
185 households in the lowest wealth quintile. All of these socio-economic and demographic  
186 indicators were obtained from the latest Ethiopia Demographic and Health Survey (EDHS) <sup>12</sup>.  
187 A map showing the distribution of EDHS datapoints are available as supplementary  
188 information (Supplemental Figure 1). Population density, estimated as the number of people  
189 per grid, was obtained from WorldPop <sup>13</sup>.

190 Connectivity indicators, which measure the population-level vulnerability to infection, were  
191 also captured using distance and time-bounded markers. Specifically, average travel time

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3 192 (measured in minutes) to the nearest city and proximity to international borders (measured in  
4 193 kilometres) were included to measure each area's level of susceptibility to infection. Data on  
5 194 travel time to the nearest city, obtained from the University of Oxford's Malaria Atlas Project  
6 195 (MAP), were used to quantify the accessibility of an area to high-density urban centres at a  
7 196 resolution of 1 km×1 km<sup>14</sup>. Data on proximity to international borders were obtained from the  
8 197 EDHS spatial data repository and were used to measure<sup>15</sup> the geodesic distance to the nearest  
9 198 international border in kilometres, indicating the risk of cross-border transmission and the  
10 199 spread of COVID-19. Infection rates and the spread of COVID-19 were also positively  
11 200 correlated with the per capita public transportation use rate<sup>16</sup>. Thus, to determine the nearest  
12 201 cross-country road to each location on the map, we obtained and applied data for major roads  
13 202 from the World Bank<sup>17</sup>.

23 203 It is evident that inadequate knowledge about COVID-19 and a lack of awareness of prevention  
24 204 measures exacerbate community transmission of the disease<sup>18</sup>. Therefore, we extracted data  
25 205 on adult literacy rate, access to media (such as radio, television, and mobile phone messages)  
26 206 and knowledge about other infectious diseases (e.g., HIV) from the EDHS as proxies for  
27 207 knowledge of COVID-19 prevention measures in each area of the country<sup>12</sup>. According to the  
28 208 WHO, maintaining good hand hygiene through regular washing with soap and water is one of  
29 209 the most effective preventative measures for reducing the transmission of COVID-19<sup>19,20</sup>.  
30 210 Using the same data as above, we also assessed hand hygiene practices, access to water, and  
31 211 the availability of handwashing stations in a household.

39 212 Previous studies have shown that underlying chronic comorbidities and behavioural factors  
40 213 such as cigarette, alcohol and khat consumption were associated with more severe COVID-19  
41 214 infections<sup>21,22</sup>. Data on khat chewing and the alcohol consumption rate were obtained from the  
42 215 EDHS 2016<sup>12</sup>, and data on cigarette smoking were obtained from the Ethiopia Public Health  
43 216 Institute STEP wise approach to Surveillance (STEPS) study<sup>23</sup>. The STEP survey was also  
44 217 used to measure the prevalence of selected non-communicable diseases (NCDs) such as  
45 218 hypertension, heart disease, and diabetes mellitus (DM).

52 219 The level of preparedness and readiness of health facilities to detect, manage, and control the  
53 220 COVID-19 pandemic at a given location was measured using data from the Service Availability  
54 221 and Readiness Assessment (SARA) survey<sup>24</sup>. For each geo-location, the obtained measures  
55 222 include the availability and readiness of facilities in terms of basic amenities and equipment,  
56 223 standard precautions, diagnostic capacities, and essential medicines. In addition, data on  
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224 service readiness for specific diseases such as DM, chronic respiratory disease (CRD), and  
225 tuberculosis (TB), as well as the availability of intensive care units (ICUs) and laboratory  
226 facilities, were obtained from this same survey. To augment the health facility data, we  
227 extracted population-level indicators on health care access and barriers to care from EDHS  
228 2016 <sup>12</sup>.

229 Finally, climatic data (temperature, precipitation, humidity, and sunlight exposure) were  
230 obtained from the WorldClim v2.0 Global Climate Database <sup>25</sup>. These data were extracted at a  
231 spatial resolution of 30 seconds or ~1 km<sup>2</sup> and were considered indicators of COVID-19  
232 infection in this study.

### 233 **Geospatial data processing**

234 All data were georeferenced using a geographical information system, ArcGIS 10.6.1 software  
235 (ESRI Inc., Redlands CA, USA). The ideal resolution for spatial analysis was a latitude and  
236 longitude point that represented the location of the data cluster (point-level data), but when  
237 these were not available, we geolocated the available data to the smallest geographical areal  
238 unit, typically representing an administrative unit such as village or districts. In instances when  
239 the latitude and longitude coordinates of the village or district were not available in the dataset,  
240 centroids of the village or districts were also identified using Google Maps. A very small  
241 rectangular polygon (fishnet) with its centroid (fishnet centroid) covering the whole territory  
242 of Ethiopia was created using a sampling tool under the data management tools in the  
243 ArcToolbox (Figure 2). The fishnet centroid contained a unique identification number and was  
244 used as a common georeferenced system to process, join, and extract the raster and vector data  
245 collected from various sources. All vector data (point, polygon, and line) were converted to  
246 raster data using geostatistical methods <sup>26</sup>. Raster grids were then resampled to the common  
247 georeferenced system at a spatial resolution of 1 km x 1 km. Finally, a raster mask covering  
248 the entire country was created by clipping smaller spatial units from a large global raster data  
249 source.

### 250 **Statistical analyses**

251 Geostatistical techniques such as spatial autocorrelation, kriging and semivariograms were  
252 applied to create a prediction grid surface from a scattered set of points <sup>27</sup>. Kriging assumes  
253 that the distance or direction between sample points reflects a spatial correlation that can be  
254 used to explain variation in the surface <sup>28</sup>. Since the variables had different units of  
255 measurement, the datasets were normalised using a min-max approach to a standard scale  
256 ranging from 0 (the lowest risk) to 100 (the highest risk) <sup>29</sup>. After normalisation, the indicators

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3 257 were averaged to create a vulnerability index, measuring the risk of COVID-19 for each geo-  
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5 258 location<sup>30</sup>. The vulnerability indices were calculated separately for each domain, namely, the  
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7 259 vulnerability to infection, case severity, and likelihood of death from COVID-19. The three  
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9 260 domains were then averaged to produce the overall COVID-19 vulnerability index. Given that  
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11 261 COVID-19 is a new virus, there is a lack of evidence for assigning weights for each indicator.  
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13 262 Hence, equal weight was given to all indicators when calculating the arithmetic mean for the  
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15 263 vulnerability indices. However, we also used principal component analysis (PCA) and  
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17 264 geometric mean methods, which produced broadly similar results (Supplemental Figure 2 and  
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19 265 Supplemental Figure 3). The risk maps were then created separately for infection, case severity,  
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21 266 service preparedness, and death from the composite index using geostatistical tools in ArcGIS.  
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23 267 All data transformations were performed in R<sup>31</sup>. All items included in this study are available  
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25 268 in the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology)  
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27 269 Statement checklist (Supplemental Table 1).

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27 270 **Ethics aspects:** Ethical approval was not required for this study as it was based on publicly  
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29 271 available data.

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31 272 **Patient and public involvement:** This research was done without patient and public  
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33 273 involvement.

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35 274 **Funding:** There was no funding source for this study.

## 36 37 38 275 **Results**

### 39 40 276 **Vulnerability to COVID-19 infection**

41  
42 277 Figure 3 shows the vulnerability map of COVID-19 infection in Ethiopia. The map highlights  
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44 278 that most parts of the country are likely to have a relatively high vulnerability and be at  
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46 279 substantial risk for COVID-19 infection. Most parts of the country are identified as vulnerable  
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48 280 to COVID-19 infection, with the exception of Addis Ababa and the north-western Somali  
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50 281 region. The peripheral areas of the country bordering Djibouti, Somalia, Eritrea, and South  
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52 282 Sudan appeared to be vulnerable to COVID-19 infection. These outlying areas are  
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54 283 characterised by a low level of geographical connectivity and low scores for disease  
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56 284 knowledge, hand hygiene and socio-economic indices (Supplemental Figure 4). They also have  
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58 285 certain climatic factors that were found to be important indicators of COVID-19 transmission.

### 58 59 286 **Vulnerability to severe cases of COVID-19 infection**

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287 Areas across the Amhara region and most parts of the Oromia region are likely to experience  
288 severe forms of COVID-19 that require hospitalisation and ICU admission. Some parts of the  
289 SNNPR are also expected to be at high risk of severe COVID-19 infections. The combination  
290 of demographic (high proportion of older adults), comorbidity (high prevalence of  
291 hypertension, DM, obesity, HIV, and TB), and behavioural and economic indicators (high  
292 proportion of smokers and high level of alcohol and khat consumption, interior cooking, and  
293 solid fuel use) renders these parts of the country at a higher risk of severe forms of COVID-19.  
294 Figure 4 shows the levels of vulnerability to severe forms of COVID-19.

### 295 **Vulnerability to death from COVID-19**

296 People living around border areas in Ethiopia are at a high risk for COVID-19-related death,  
297 as illustrated in Figure 5. Districts and zones in the Benishangul-Gumuz, Gambela, Afar,  
298 SNNPR, Dire Dawa, Southwest Somali, Northwest Amhara, Western Tigray, and Western and  
299 Eastern Oromia regions are at high risk for COVID-19-related death. The level of service  
300 preparedness and readiness to mitigate the health effects of COVID-19 appear to be very low  
301 in these regions (Figure 6). Ethiopia's border regions have inadequate ICU availability and  
302 laboratory capacity as well as limited health care access. They also have low general and  
303 service-specific readiness, as shown in Figure 6.

## 304 **Discussion**

305 This is the first study that maps vulnerability to COVID-19 infection, severe cases, and  
306 associated death in Ethiopia at a high resolution. This is also the first study that has attempted  
307 to present the degree of service preparedness for COVID-19 across the country.

308 We found that most parts of the country are vulnerable to COVID-19 infections, and the  
309 greatest burden might be outside of Addis Ababa. It is likely that compared to other regions, a  
310 higher proportion of people from the Amhara and Oromia regions, the two most populous  
311 regions of the country, will develop severe forms of COVID-19 leading to hospitalisation and  
312 ICU admission. Border areas of the country are also expected to face a higher risk of death than  
313 areas located in the central regions. The findings of this study are of paramount importance in  
314 preventing and controlling COVID-19 transmission and in designing targeted interventions,  
315 such as enacting travel restrictions, distributing preventative masks and determining which  
316 areas to prioritise if a COVID-19 vaccine becomes available. As some of these areas also have  
317 lower preparedness scores and low general and service-specific readiness scores, the findings

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3 318 have wider implications for allocating resources and strengthening the health care system after  
4 319 the COVID-19 pandemic.

7 320 Despite the disproportionately high infection rate in Addis Ababa at present (Supplemental  
8 321 Figure 5), we found that the risk of COVID-19 infection is likely to become rather high in other  
9 322 regions. The high infection rate in Addis Ababa at this initial stage is expected, given that Addis  
10 323 Ababa is a major travel hub and Bole International Airport, located in the city, is one of the  
11 324 largest international airports in Africa. This exposes the city to a higher risk of imported cases  
12 325 and, subsequently, to an early surge of infections, leaving the areas outside the city at a higher  
13 326 risk of later infection. Second, we considered multifaceted risk factors (indicators) for COVID-  
14 327 19 infection in our geospatial model. This means that although the city has a high degree of  
15 328 connectivity, it is also characterised by higher scores for information penetration, knowledge  
16 329 of disease prevention and hand hygiene practices that could help slow the rate of infection in  
17 330 the city<sup>12</sup>. Third, Addis Ababa has relatively better and more consistent test-and-contact tracing  
18 331 practices than in other parts of the country, which means that the chance of new infections  
19 332 being detected in the city are much greater than in other parts of the country<sup>5</sup>. Future efforts to  
20 333 expand testing and tracing practices in other areas of the county are likely to increase the extent  
21 334 of confirmed infections in those other areas. Recent studies have demonstrated that effective  
22 335 social distancing and contact tracing can significantly reduce the rate of infection<sup>32,33</sup>. These  
23 336 interventions should be strengthened and expanded to areas identified as high risk in this study.

24 337 Our study also showed that the risk for severe cases of COVID-19 infection is high in most  
25 338 parts of the Amhara and Oromia regions. This may be due to the high prevalence of NCDs,  
26 339 which are associated with severe cases of COVID-19. Previous studies have revealed that the  
27 340 burden of NCDs, such as DM and hypertension, is high in these two regions<sup>23,34,35</sup>.

28 341 Our study also revealed that peripheral areas sharing international borders are likely to see a  
29 342 greater number of COVID-19-related deaths. The high risk of death along the border areas  
30 343 might be attributed to low preparedness in case management and weak health care systems. In  
31 344 contrast, although the Amhara and Oromia regions may have more severe cases, the  
32 345 preparedness indicators show that the regions are better equipped to cope with these anticipated  
33 346 severe cases. However, our study suggests that additional preparation and capacity  
34 347 strengthening are needed mainly in the following areas: emergency response systems, case  
35 348 detection and capacity to care for patients. It is also equally important that hospitals have  
36 349 adequate supplies, health care personnel and life-saving medical intervention resources.



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3 350 Despite encouraging efforts by the Ethiopian government and stakeholders to prepare the  
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5 351 health care system for the pandemic, the existing health care services in the country may face  
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7 352 unprecedented challenges and crises due to the surge of patients that will require hospitalisation  
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9 353 and ICU services at the same time. This can, however, be eased by implementing public health  
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11 354 and social measures at the individual, community, and public authority levels to prevent  
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13 355 infections and subsequent health, economic, and social consequences <sup>36</sup>. Studies have shown  
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15 356 that implementing non-pharmaceutical interventions such as physical distancing, mask use, and  
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17 357 closure of schools, especially during the early stages of infection, can reduce transmission and  
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19 358 subsequent potential public health and economic crises <sup>37</sup>.

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21 359 Further, we found notable regional disparities in health system preparedness and readiness  
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23 360 levels in the country. This is important because if the health care system is well equipped to  
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25 361 prevent and mitigate the spread of the pandemic, then the mortality rate from the disease can  
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27 362 be markedly reduced <sup>38</sup>. However, we observed that Ethiopia's border regions (i.e.,  
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29 363 Benishangul-Gumuz, Gambella, Afar, and Somali) have low preparedness levels.  
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31 364 Nevertheless, comparisons between the border regions and other regions of the country need  
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33 365 to be treated with care because Ethiopia in general has very low doctor-to-resident (1 doctor  
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35 366 per 10,000 people) and hospital bed-to-population (3 hospital beds per 10,000 people) ratios  
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37 367 <sup>39</sup>. Several long-, medium- and short-term strategies, can be implemented to mitigate these  
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39 368 problems: (i) providing short-term training for potential actors such as community leaders,  
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41 369 students, and traditional and modern medical practitioners, (ii) recruiting additional staff to  
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43 370 work in COVID-19-related health care, (iii) establishing COVID-19 clinics and changing  
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45 371 outpatient rooms to emergency clinics, (iv) collaborating with private hospitals ahead of surges  
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47 372 so that they can be used in the case such surges occur, and (v) establishing mobile clinics and  
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49 373 temporary admission rooms in highly vulnerable areas.

#### 46 374 **Strength and Limitations**

48 375 This study has several strengths. First, the current study was conducted at a spatial resolution  
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50 376 of 1 km x 1 km across the entire territory of Ethiopia. Second, it incorporated a wide range of  
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52 377 indicators from multiple sources. Third, it applied rigorous geospatial techniques, including  
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54 378 spatial autocorrelation, kriging and semivariograms, to provide the best possible prediction  
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56 379 maps. Finally, we produced vulnerability mapping for infection or transmission, case severity,  
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58 380 and associated death separately to assist with policy interventions related to each risk.

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3 381 However, it is important to note some potential limitations of the study when interpreting the  
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5 382 findings. First, the results need constant updating, as some of the variables used in the study  
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7 383 may change overtime. Second, the data used in this study were not collected in the same year  
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9 384 and the results might be changed if recently available data used in the analysis. However, many  
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11 385 of the variables used in this study were static and may not change over time. Moreover, we  
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13 386 used the most recently available data for non-static variables such as EDHS data. Third,  
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15 387 ongoing political turmoil in the country means that the dynamics of transmission may change  
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17 388 depending on the location and severity of these incidents. For example, in areas of low security  
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19 389 resulting from active conflict, the local health systems might be ill-prepared to prevent and  
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21 390 control COVID-19. Insecurity also may generate unpredictable population movements, and  
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23 391 this in turn could exacerbate infection dynamics in the country. Fourth, the calculation of the  
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25 392 composite risk factor index was based on an unweighted average under the assumption that all  
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27 393 indicators have equal importance, which may or may not be the case. Some of the variables  
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29 394 included in our score may have greater effects on vulnerability to infection, case severity, and  
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31 395 likelihood of death than others. Giving equal weight for all these variables may influence the  
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33 396 findings of our study, but the exact effect is hard to tell. However, we have calculated a  
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35 397 weighted index using PCA as an alternative method, which produced broadly similar results  
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37 398 (Supplemental Figure 2 and Supplemental Figure 3). Last, some important indicators, such as  
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39 399 psychosocial and clinical factors (e.g., mental illness, quality of life, and social support), were  
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41 400 not captured in our modelling due to the lack of geocoded data.

## 401 **Conclusions**

402 Although nearly three-quarters of the current COVID-19 cases reported in Ethiopia are  
403 concentrated in and around Addis Ababa, this study predicts that over time, the risk of COVID-  
404 19 infection will be higher across most other parts of the country. A higher proportion of people  
405 from the Amhara region, most of the Oromia region, and some parts of the SNNPR will develop  
406 severe cases of infection. Additionally, the risk of death will be higher in the regions of the  
407 country with low preparedness scores for COVID response. Hence, the preventative and  
408 control measures that are currently in place in the capital city should be strengthened and  
409 extended to regional areas, especially to high-risk areas, to prevent and mitigate the risk of  
410 COVID-19 infection, lower the number of severe cases, and limit the number of associated  
411 deaths in Ethiopia.

## 412 **Declaration**

## 413 **Authors' contributions**

414 KAA, YAG, YK, DMF, DNK, YAM, HAG, MB, MDM, AAA, and BAD conceptualised the  
415 study. KAA designed and run the geospatial analysis. YAG involved in the data analysis. KAA,  
416 YAG, DMF, DNK, and YAM drafted the manuscript. HAG, MB, AAA<sub>1</sub>, MDM, BAD, SA,  
417 AA, AAA<sub>2</sub>, WMB, KTG, TG, ATG, LGG, AG, HTK, GDK, CTL, LBM, AAM, HM, HGT,  
418 AGT, FT, BLW, and YK Critically reviewed and revised the drafted manuscript. KAA, YK,  
419 and AHM were responsible for quality control of accuracy and integrity of data. All the authors  
420 interpreted the data. All authors contributed to the final draft and finally approved it to be  
421 published. All authors agreed to be accountable for all aspects of the work for any issue related  
422 to the accuracy or integrity of any part of the work. The corresponding author attests that all  
423 listed authors meet authorship criteria and that no others meeting the criteria have been omitted.

424 **Funding:** There is no funding source for this study.

425 **Competing interests:** None declared.

426 **Patient and public involvement:** This research was done without patient and public  
427 involvement.

428 **Data availability statement:** Extra data is available by emailing the corresponding author  
429 (KAA): kefyalew.alene@curtin.edu.au

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## Tables

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**Table 1:** Data sources and definitions of indicators for the vulnerability of COVID-19 in

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Ethiopia.

Indicators	Data sources	Spatial resolution	Definitions
<b>Demographic indicators</b>			
Male sex	EDHS 2016	Latitude and longitude point	Total number of male populations divided by the total number of people participated in the survey
Older age	EDHS 2016	Latitude and longitude point	Total number of people with age $\geq 65$ years divided by the total number of people participated in the survey
<b>Socio-economic indicators</b>			
Population density	WorldPop	1 km X 1 km	Number of people per square kilometre (grid)
Number of household members	EDHS 2016	Latitude and longitude point	Average number of people living in a house
Low wealth index	EDHS 2016	Latitude and longitude point	Number of people with low wealth index (poorer and poorest) divided by the total number of people participated in the survey
<b>Connectivity indicators</b>			
Travel times to cities	MAP	1 km $\times$ 1 km	Travel time in minutes to the nearest city with a population of more than 50,000
Proximity to national borders	DHS Spatial Repository	Latitude and longitude point	The geodesic distance to the nearest international borders
Distance to major roads	World Bank	District	Distance in km to cross-country round
<b>Climatic indicators</b>			
Mean temperature	WorldClim	1 km $\times$ 1 km	Annual mean environmental air temperature ( $^{\circ}$ C)
Mean precipitation	WorldClim	1 km $\times$ 1 km	Annual mean rainfall (mm)
Wind speed	WorldClim	1 km $\times$ 1 km	Annual mean wind speed ( $m\ s^{-1}$ )
Solar radiation	WorldClim	1 km $\times$ 1 km	Annual mean solar radiation ( $kJ\ m^{-2}\ day^{-1}$ )
Water vapour pressure	WorldClim	1 km $\times$ 1 km	Annual mean water vapour pressure (kPa), equivalent to absolute humidity.
<b>Behavioural indicators</b>			
Khat chewing	EDHS 2016	Latitude and longitude point	Total number of people chewing khat in the last one month prior to the survey divided by the total number of people participating in the survey
Alcohol drinking	EDHS 2016	Latitude and longitude point	Total number of people drinking alcohol in the month prior to the survey divided by the total number of people participating in the survey
Cigarette smoking	EPHI STEPS	Latitude and longitude point	Total number of people currently smoke cigarettes divided by the total number of people participating in the survey
Cooking inside the household	EDHS 2016	Latitude and longitude point	Total number of households where cooking takes place inside the house without a separate building or outdoors (i.e. exposure to smoke inside the home) divided by the total number of households in the survey

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3 Use solid fuel for 4 cooking	EDHS 2016	Latitude and longitude point	Number of households used some type of solid fuel (wood, dung, grass, crop) for cooking food divided by all households in the survey
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#### 6 Disease prevention knowledge indicators

7 Adult illiteracy rate	EDHS 2016	Latitude and longitude point	Total number of adults (aged 15 years and above) who had not attended school or who cannot read and write divided by the total number of adults participated in the survey
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12 Access to listen to the 13 radio	EDHS 2016	Latitude and longitude point	Total number of people who had not access to listen to the radio divided by total survey participants
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15 Access to watch TV	EDHS 2016	Latitude and longitude point	Total number of people have no access to watch television divided by total survey participants
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18 Mobile phone 19 ownership	EDHS 2016	Latitude and longitude point	Total number of people have no access to mobile phone divide by the total number of survey participants
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21 Knowledge toward 22 HIV	EDHS 2016	Latitude and longitude point	Number of people with poor knowledge towards HIV divided by the total number of people participating in the survey
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#### 24 Hand hygiene indicators

26 Travel time to water 27 sources	EDHS 2016	Latitude and longitude point	Mean travel time in minutes to obtain water source (i.e. access to a water source)
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29 Place for handwashing	EDHS 2016	Latitude and longitude point	Number of households have no fixed or mobile place for handwashing divided by total number of households in the survey
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32 Soap or detergent 33 availability for 34 handwashing	EDHS 2016	Latitude and longitude point	Number of households have no essential handwashing agents (i.e. soap, and detergent) divided by total household in the survey
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#### 35 Comorbidities indicators

36 HTN	EPHI STEPS	Latitude and longitude point	Total number of people with HTN divided by the total number of survey participants
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40 DM	EPHI STEPS	Latitude and longitude point	Total number of people with DM divided by the total number of survey participants
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43 BMI	EPHI STEPS	Latitude and longitude point	Mean body mass index
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46 CVD	EPHI STEPS	Latitude and longitude point	Total number of people with heart disease divided by total number of people in the survey
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49 Cholesterol	EPHI STEPS	Latitude and longitude point	Mean cholesterol level
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52 HIV prevalence	EDHS 2016	Latitude and longitude point	Total number of people with HIV divided by survey participants
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56 TB SMR	EMOH	District	Standardized morbidity ratio (SMR) as measured by observed number of TB cases divided by the expected number of TB cases
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#### 59 Service availability and readiness indicators

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Health care access problem	EDHS 2016	Latitude and longitude point	Difficulty of getting advice or treatment due to lack of money, or distance to a health facility
General service readiness and availability	EPHI SARA	Latitude and longitude point	Availability of equipment and supplies (i.e. basic amenities, equipment, standard precautions, diagnostic capacity, essential medicines) necessary to provide general health services
ICU availability	EPHI SARA	Latitude and longitude point	Availability of Critical Care Services (ICU) in hospitals
CRD readiness index	EPHI SARA	Latitude and longitude point	Availability of specific services for Chronic respiratory disease (CRD) diagnosis, management, and follow up
TB readiness index	EPHI SARA	Latitude and longitude point	Availability of specific services for tuberculosis diagnosis, management, and follow up
Diabetes readiness index	EPHI SARA	Latitude and longitude point	Availability of specific service for diabetes diagnosis and management and follow up
<p><i>G-Econ: Geographically based Economic data; EDHS: Ethiopia demographic and health survey; UN OCHA: United Nation Office for Coordination of Humanitarian Affairs; MAP: SRTM: Malaria Atlas Project; Shuttle Radar Topography Mission; EPHI: Ethiopia Public Health Institute; EMOH: Ethiopia Ministry of Health; SARA: Service Availability and Readiness Assessment</i></p>			

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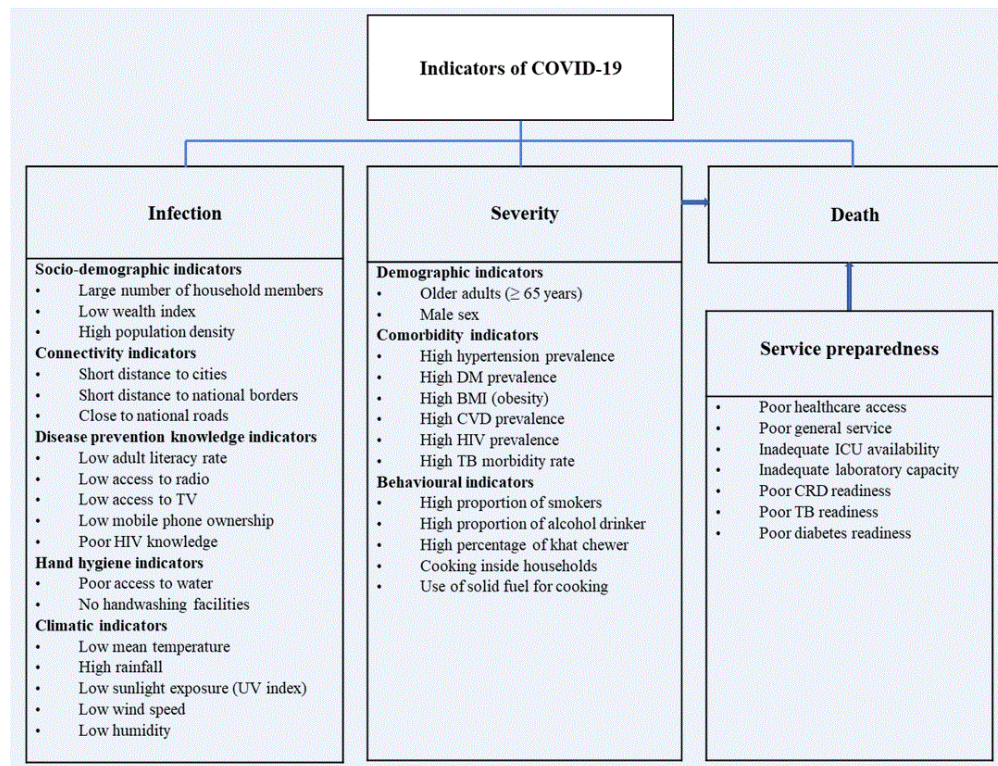
**Table 2: Evidence for risk of COVID-19 infection, severity, and death**

Indicators	Risk factors	Evidence	References
<b>Demographic indicators</b>			
Male sex	Severity	Death from and severity of COVID-19 was strongly associated with being male (HR 1.99, 95%CI: 1.88-2.10)	Williamson E <sup>40</sup>
Older age	Severity	Older than 65 years were risk factors for disease progression in patients with COVID-19 (OR =6.06, 95% CI: 3.98, 9.22)	Zheng Z <sup>22</sup>
<b>Socio-economic indicators</b>			
Population density	Infection	High population density is a risk factor for COVID-19 infection	Ahmadi M <sup>41</sup>
Number of household members	Infection	Areas with a higher percentage of households with more than one person per room had a higher incidence of COVID-19	Ahmad K <sup>42</sup>
Low wealth index	Infection	Socio-economic deprivation (RR 1.26 per SD increase in Townsend Index) associated with COVID -19 infection	Ho FK <sup>43</sup>
<b>Connectivity indicators</b>			
Travel times to cities	Infection	The distance between Wuhan and other cities was inversely associated with the numbers of COVID-19 cases in that city	Zheng R <sup>44</sup>
Proximity to national borders	Infection	Cross country moment is a risk factor for COVID-19 transmission and importation	Chinazz M <sup>45</sup>
Distance to major roads	Infection	Spread of COVID-19 was correlated positively with public transportation per capita	Ayeneu B <sup>16</sup> .
<b>Climatic indicators</b>			
Mean temperature	Infection	Low ambient temperatures are associated with more rapid spread of COVID-19	Holtmann M <sup>46</sup>
Mean precipitation	Infection	Countries with higher rainfall measurements showed an increase in COVID-19 transmission	Sobral MFF <sup>47</sup>
Wind speed	Infection	Areas with low values of wind speed associated with a high rate of COVID-19 infection	Ahmadi M <sup>41</sup>
Solar radiation	Infection	Areas with low values of solar radiation exposure associated with a high rate of COVID-19 infection	Ahmadi M <sup>41</sup>
Water vapour pressure	Infection	High humidity reduces the transmission of COVID-19. Water vapour pressure negatively correctly with COVID-19 infection.	Wang J <sup>48</sup> , Li J <sup>49</sup>
<b>Behavioural indicators</b>			
Khat chewing	Severity	There is an association between khat chewing and chronic illness such as HIV infection, elevated diastolic blood pressure	Basker GV <sup>50</sup>
Alcohol drinking	Severity	Patients with alcohol use disorders at increased risk for COVID-19	Testino G <sup>21</sup>
Cigarette smoking	Severity	Current smoking was a risk factor for disease progression in patients with COVID-19 (OR =2.51, 95% CI: 1.39, 3.32)	Zheng Z <sup>22</sup>
Cooking inside the household	Severity	Areas with a higher percentage of incomplete kitchen facilities had a higher incidence of, and mortality associated with, COVID-19	Ahmad K <sup>42</sup>
Use solid fuel for cooking	Severity	Areas with a higher percentage of incomplete kitchen facilities had a higher incidence of, and mortality associated with, COVID-19	Ahmad K <sup>42</sup>
<b>Disease prevention knowledge indicators</b>			
Adult illiteracy rate	Infection	Adult learning education is a tool to contain the COVID-19 pandemics	Lopes H <sup>51</sup>
Access to listen to radio	Infection	Access to media is a crucial factor in public health responses to an outbreak	Ayedee N <sup>52</sup>
Access to watch TV	Infection	Media (Television) has a significant role in creating a positive atmosphere in COVID-19	Ayedee N <sup>52</sup>
Mobile phone ownership	Infection	Mobile phone calls and text messages help for the diagnosis, management, and control of infectious diseases	Wood S <sup>53</sup>

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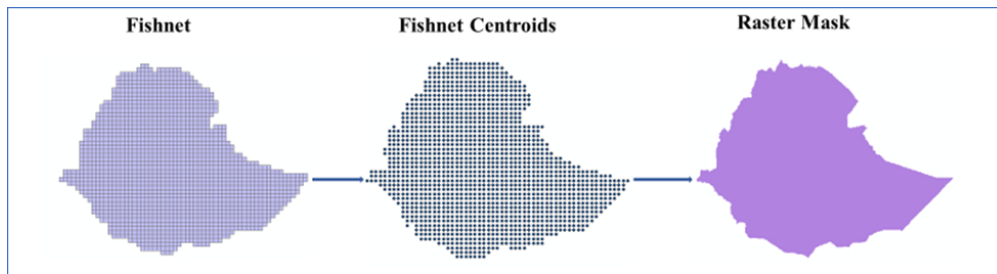
3 4 5	Knowledge towards HIV	Infection	Knowledge towards an infectious disease such as HIV can help to control the transmission of the diseases	Bertozzi S <sup>54</sup>
<b>Hand hygiene indicators</b>				
6 7 8	Travel time to water sources	Infection	Adequate water supply is essential for the control of COVID-19 infection	WHO <sup>55</sup>
9 10	Place for handwashing	Infection	Hand washing is recommended by WHO for the control of COVID-19 infection	WHO <sup>56</sup>
11 12	Soap or detergent availability for handwashing	Infection	Availability of soap or detergent is essential to keep hand hygiene for the prevention of COVID-19 infection	WHO <sup>56</sup>
<b>Comorbidities indicators</b>				
13 14 15 16	HTN	Severity	Hypertension was statistically significant with a higher rate of servery and death (OR = 2.72, 95% CI: 1.60,4.64)	Zheng Z <sup>22</sup>
17 18 19	DM	Severity	Death from COVID-19 was associated with DM (HR 1.50, 95%CI: 1.40-1.60) 1.50	Williamson E <sup>40</sup>
20 21	BMI	Severity	Death from COVID-19 was associated with higher BMI (HR 1.27, 95%CI: 1.18-1.36)	Williamson E <sup>40</sup>
22 23	CVD	Severity	Cardiovascular disease was significantly associated with higher COVID-19 servility and death (OR = 5.19, 95% CI: 3.25, 8.29)	Zheng Z <sup>22</sup>
24 25	HIV prevalence	Severity	Mortality from COVID-19 was associated with immunosuppression (HR 1.69, 95%CI: 1.21-1.34)	Williamson E <sup>40</sup>
26 27	SB SMR	Severity	respiratory diseases were significantly associated with COVID-19 death and severity (OR = 5.15, 95% CI: 2.51, 10.57)	Zheng Z <sup>22</sup>
<b>Service availability and readiness indicators</b>				
28 29	Health care access problem	Death	Healthcare resource availability is associated with COVID-19 mortality	Ji Y <sup>6</sup>
30 31	General service readiness	Death	General health service preparedness is essential for combating the COVID-19 pandemic	WHO <sup>57</sup>
32 33	ICU availability	Death	Lack of critical care unite increase the risk of death from COVID-19	Murthy S <sup>58</sup>
34 35 36	CRD readiness	Death	Cardiorespiratory disease (CRD) is a risk factor for COVID-19 related death	Zheng Z <sup>22</sup>
37 38	TB readiness	Death	TB determinants outcomes of patients with COVID-19	Tadolini M <sup>59</sup>
39 40	Diabetes readiness	Death	Diabetes affects the prognosis of patients with COVID-19	Zheng Z <sup>22</sup>
41-43 <i>Econ: Geographically based Economic data; EDHS: Ethiopia demographic and health survey; UN OCHA: United Nation Office for Coordination of Humanitarian Affairs; MAP: SRTM: Malaria Atlas Project; Shuttle Radar Topography Mission; EPHI: Ethiopia Public Health Institute; EMOH: Ethiopia Ministry of Health; SARA: Service Availability and Readiness Assessment</i>				

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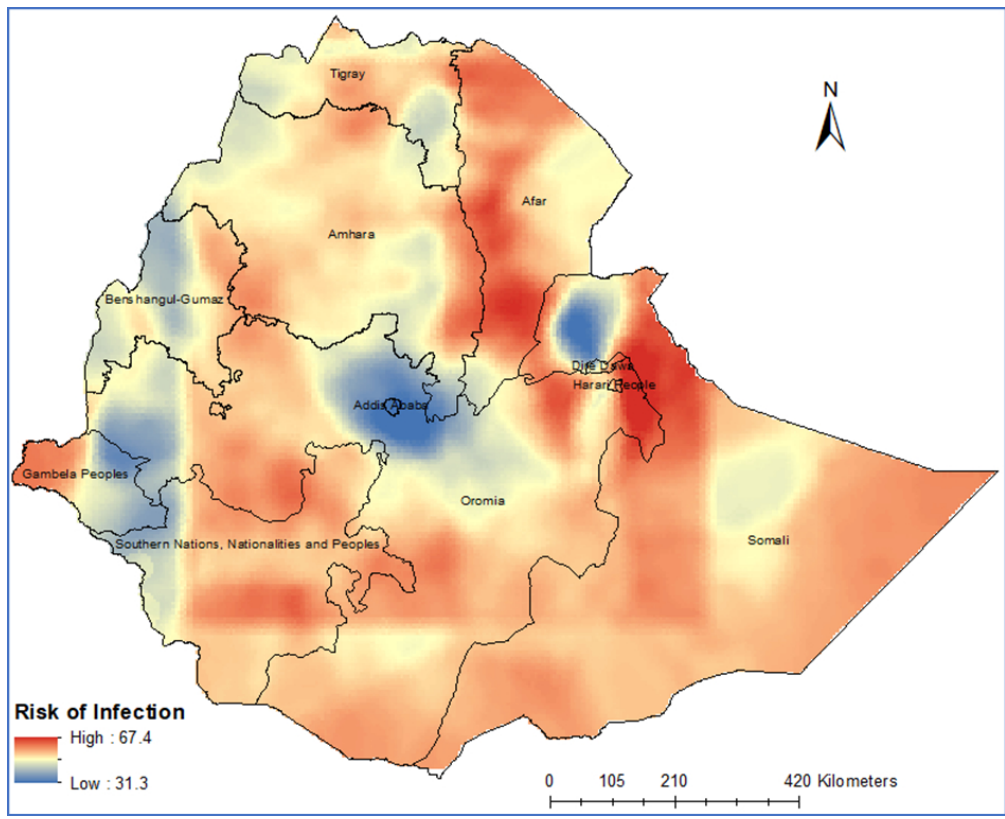
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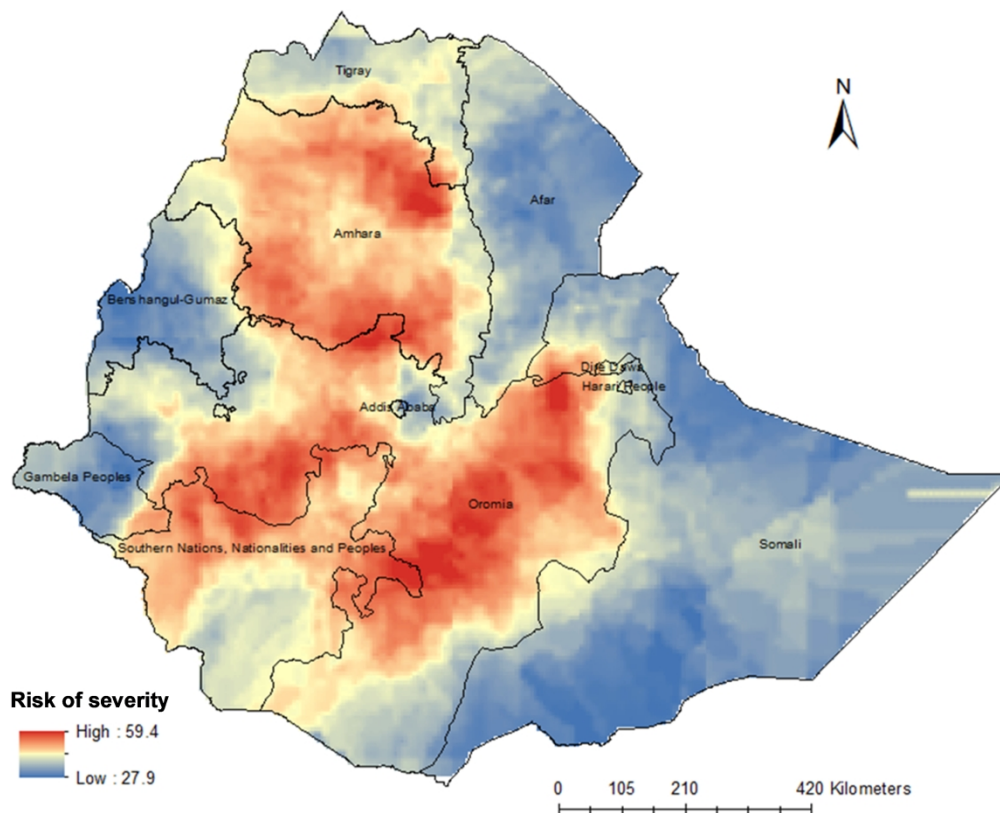
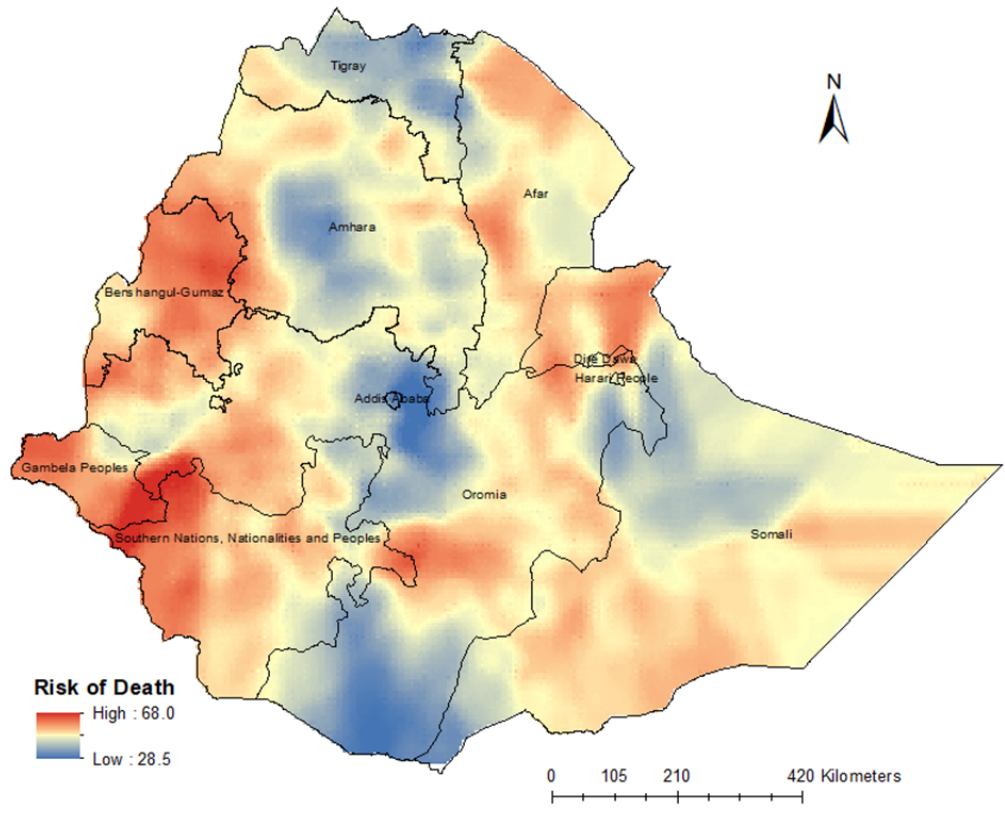


Figure 4

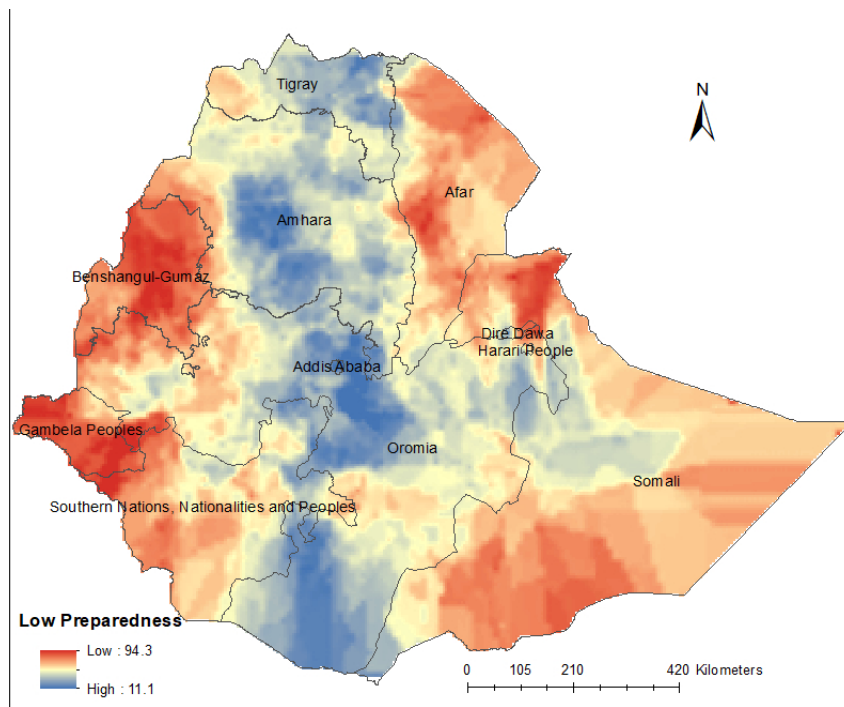
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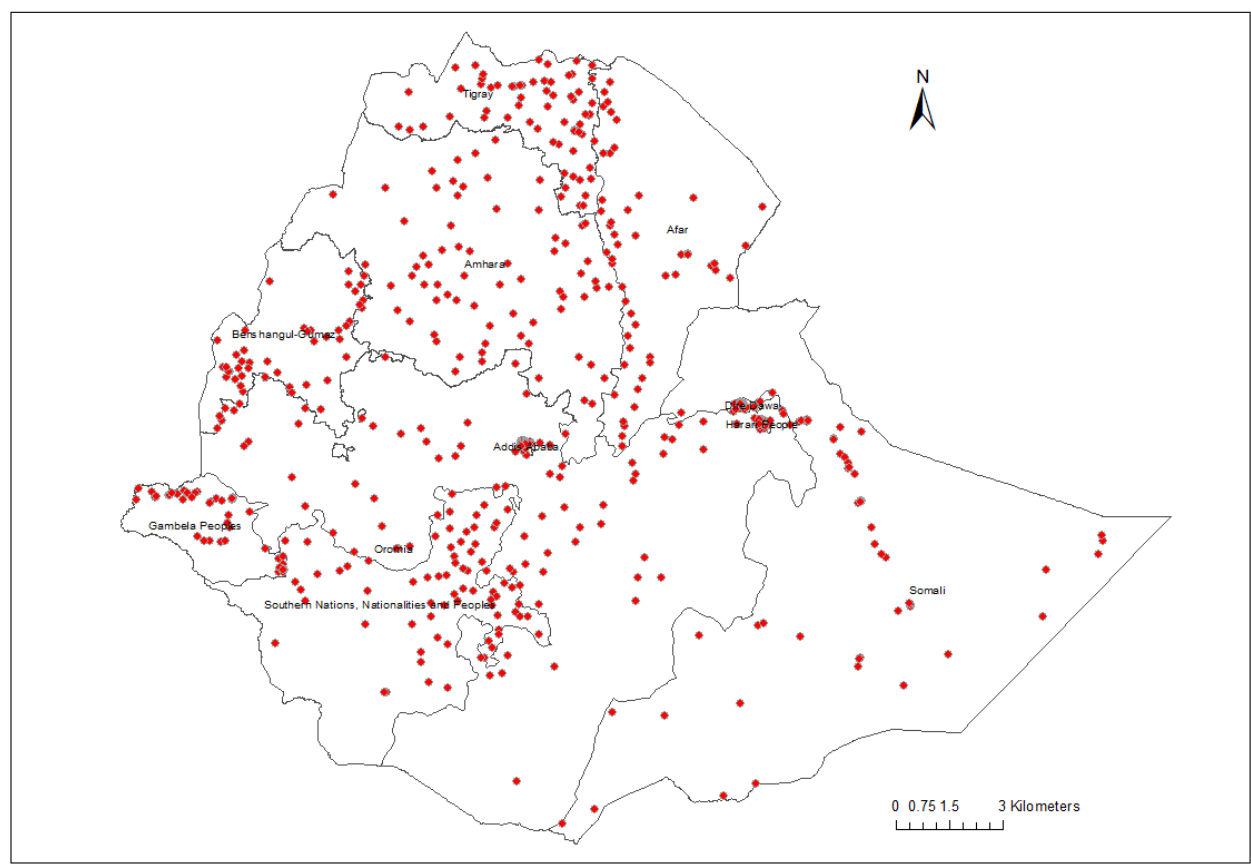


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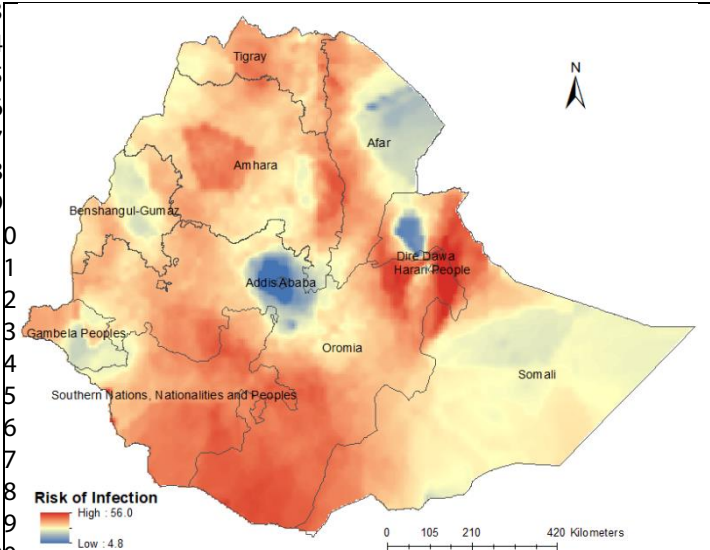
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Supplemental Information

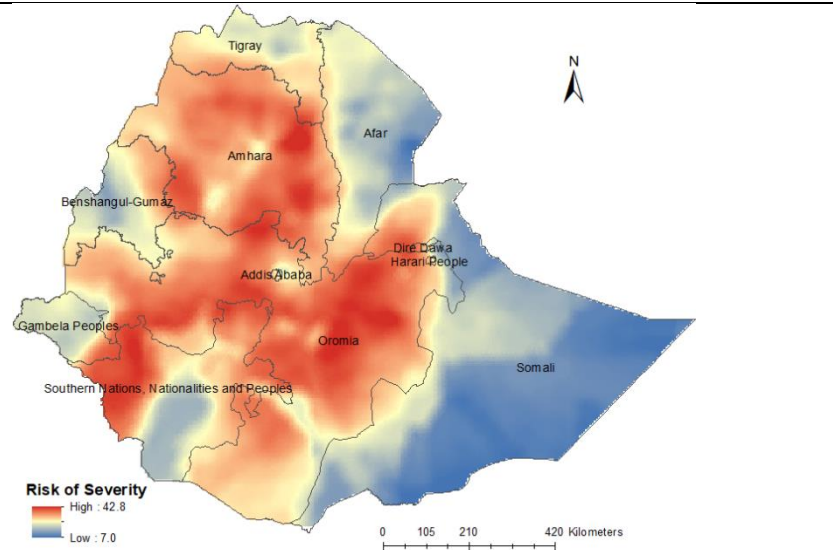


Supplemental Figure 1: A map showing the distribution of the Ethiopia Demographic and Health Survey (EDHS 2016) datapoints.

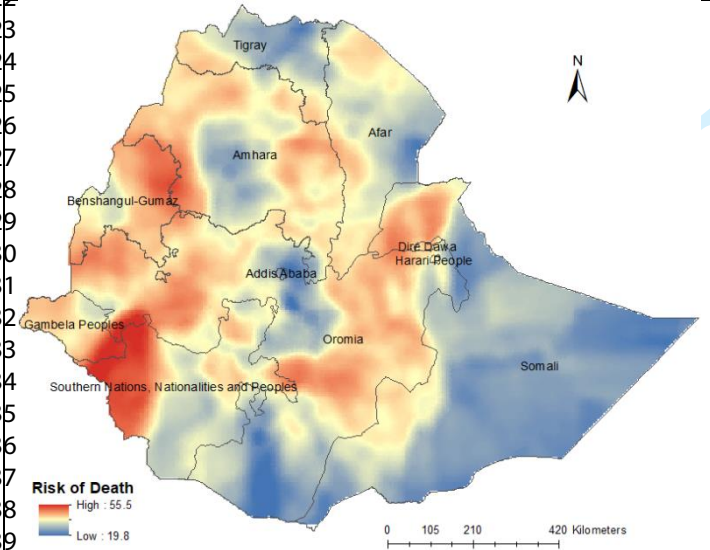
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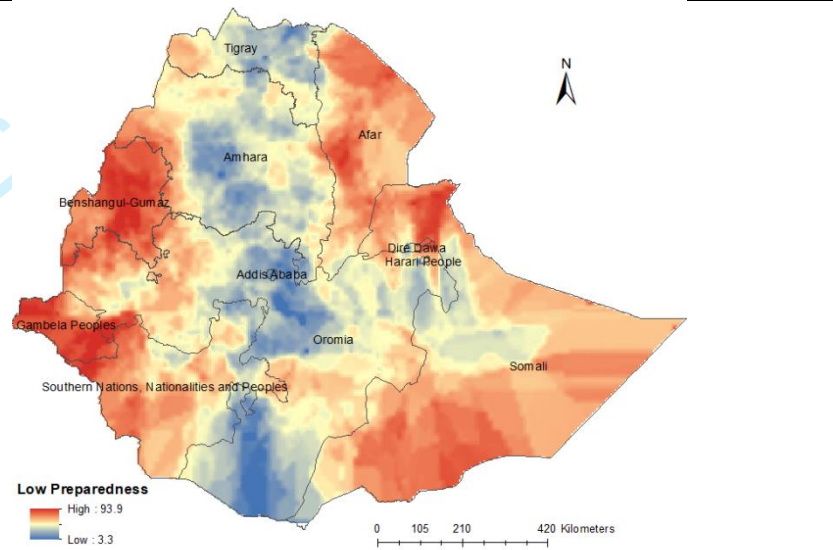
S Figure 2a. COVID-19 infection risk map in Ethiopia, created based on a geometric mean



S Figure 2b. COVID-19 severity risk map in Ethiopia, created based on a geometric mean

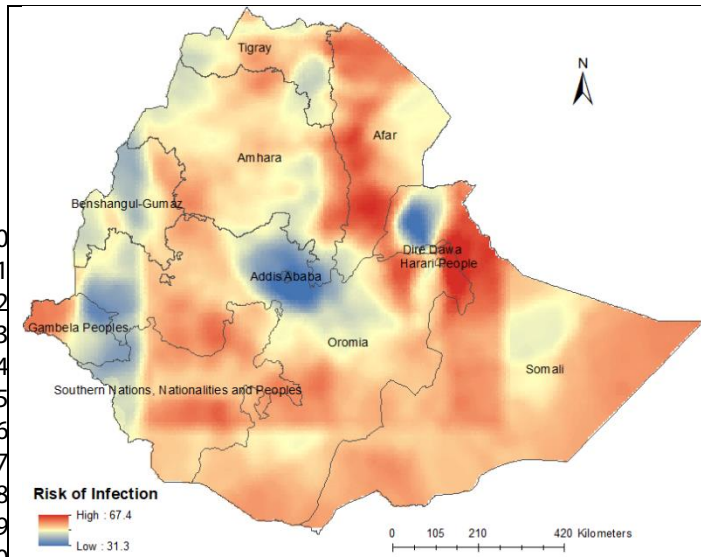


S Figure 2c. Death risk map of COVID-19 in Ethiopia, created based on a geometric mean

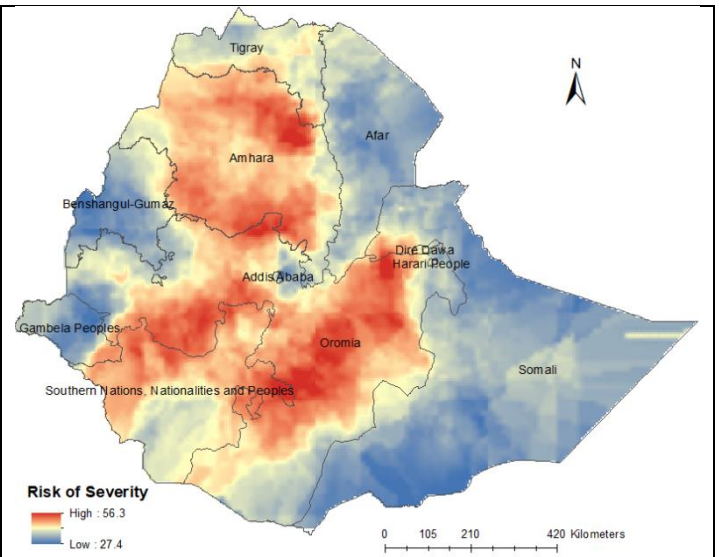


S Figure 2d. Service preparedness map of COVID-19 in Ethiopia, created based on a geometric mean

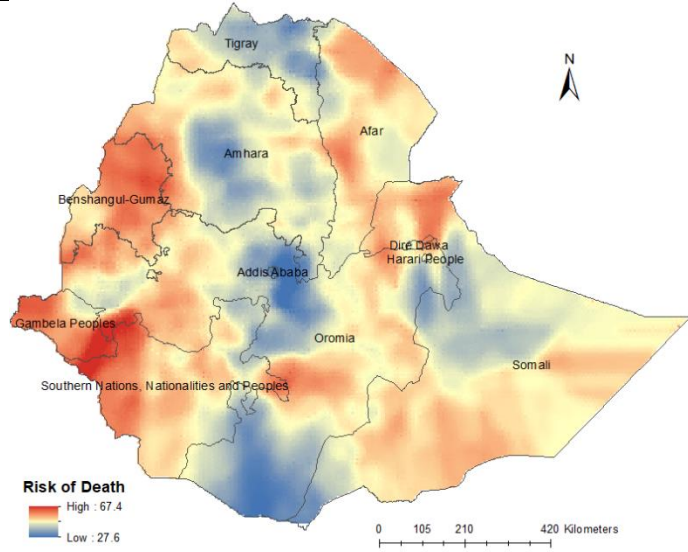
**Supplemental Figure 2: Vulnerability maps of COVID-19 infection, severity, preparedness, and death in Ethiopia, created based on a geometric mean as alternative aggregation method.**



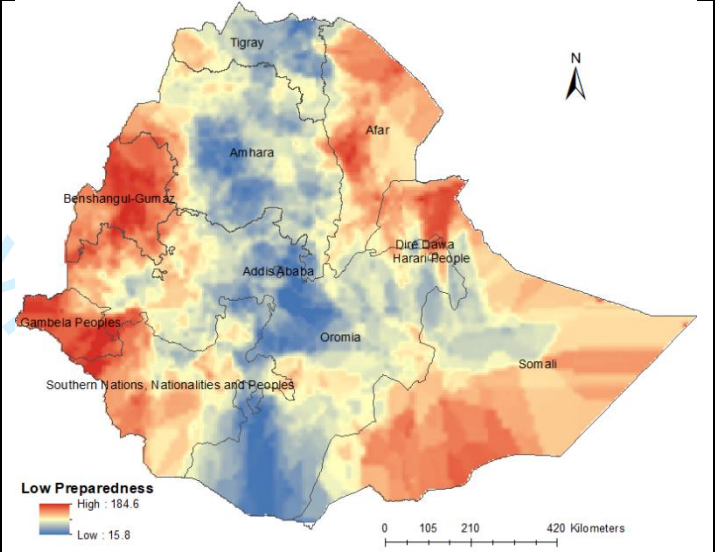
S Figure 3a. COVID-19 infection risk map in Ethiopia, created based on a geometric mean



S Figure 3b. COVID-19 severity risk map in Ethiopia, created based on a geometric mean



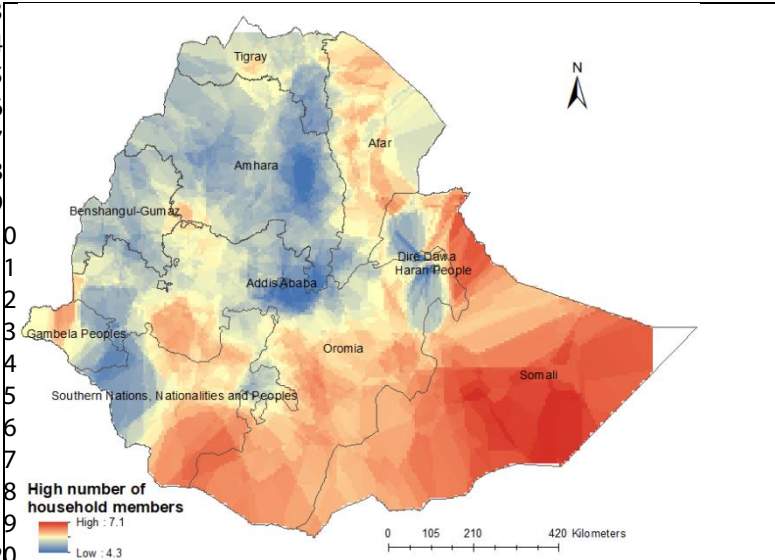
S Figure 3c. Death risk map of COVID-19 in Ethiopia, created based on a geometric mean



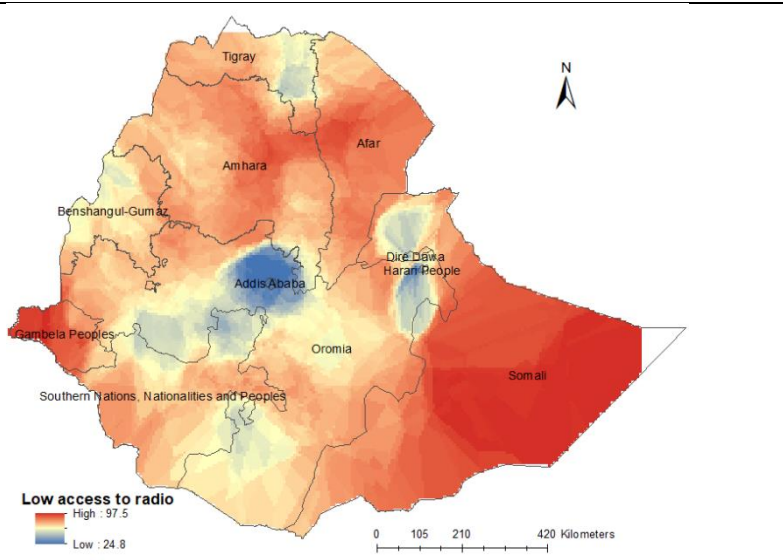
S Figure 3d. Service preparedness map of COVID-19 in Ethiopia, created based on a geometric mean

**Supplemental Figure 3:** Vulnerability maps of COVID-19 infection, severity, preparedness, and death in Ethiopia, created based on a principal component analysis (PCA) as alternative aggregation method.

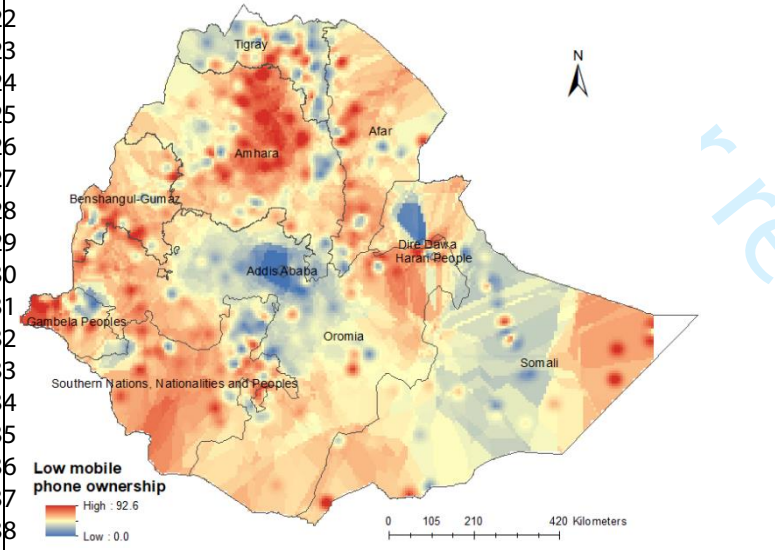
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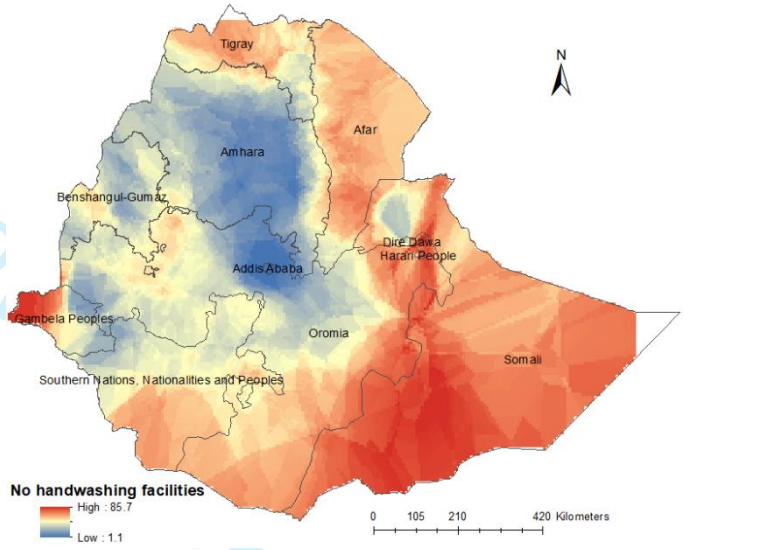
S Figure 4a. Average number of people living in a house



S Figure 4b. Percentage of population have no access to radio



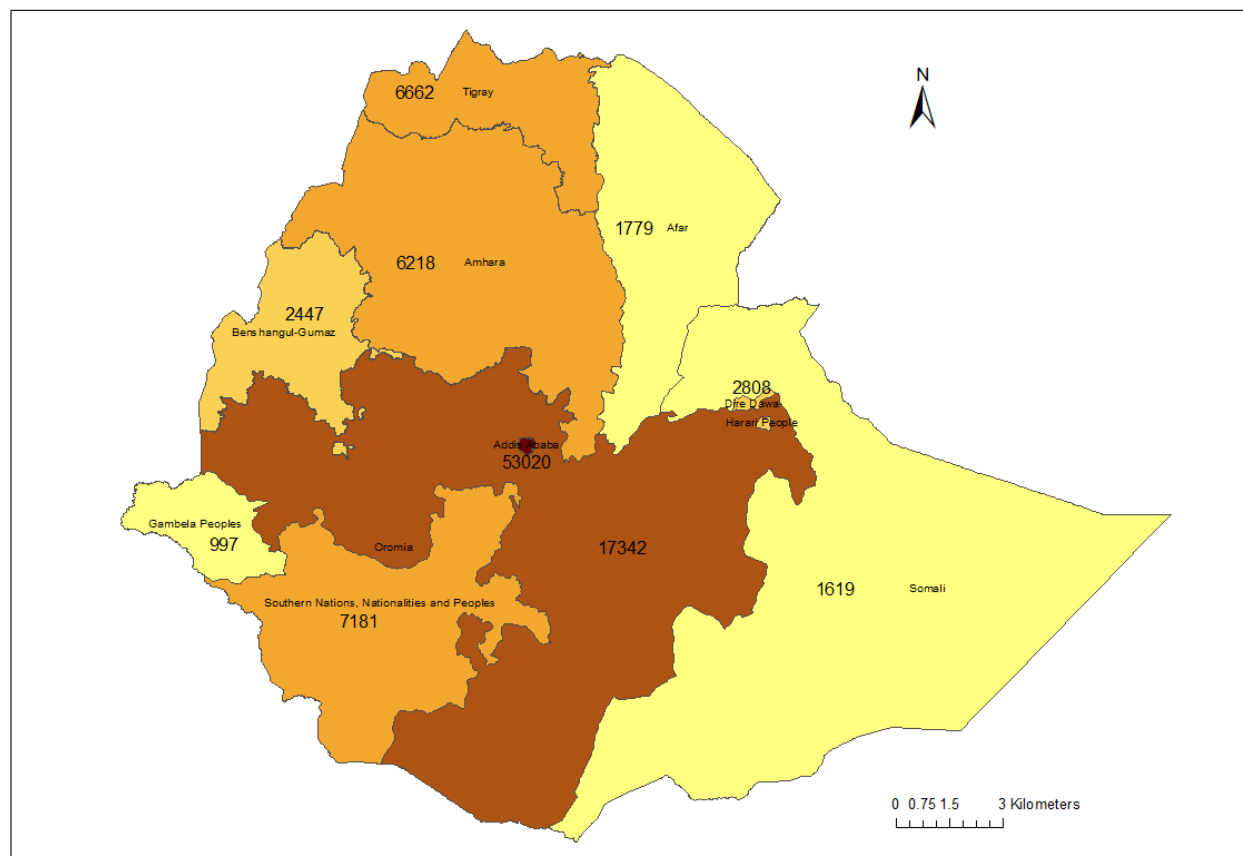
S Figure 4b. Percentage of the population who have not access to mobile phone



S Figure 4d. Percentage of households who have not hand washing facilities

**Supplemental Figure 4: Selected indicators showing the risk of COVID-19 infection in Ethiopia**

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**Supplemental Figure 5:** Number of COVID-19 confirmed cases at regional level in Ethiopia on 15 November 2020.

**Supplemental Table 1: STROBE Statement—Checklist of items included in this study**

Item No	Recommendation	Page number
<b>Title and abstract</b>		
1	(a) Indicate the study's design with a commonly used term in the title or the abstract	1
	(b) Provide in the abstract an informative and balanced summary of what was done and what was found	3
<b>Introduction</b>		
2	Background/rationale	5
3	Objectives	6
<b>Methods</b>		
4	Study design	6
5	Setting	6
6	Participants	6, 7 & 8
7	Variables	6, 7 & 8
8	Data sources/measurement	6, 7, 8 & Table 1
9	Bias	9
10	Study size	NA
11	Quantitative variables	8 & 9
12	Statistical methods	8 & 9
	(a) Describe all statistical methods, including those used to control for confounding	8 & 9
	(b) Describe any methods used to examine subgroups and interactions	8 & 9
	(c) Explain how missing data were addressed	8 & 9
	(d) If applicable, describe analytical methods taking account of sampling strategy	NA
	(e) Describe any sensitivity analyses	9
<b>Results</b>		
13	Participants	9 & 10
	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	9 & 10
	(b) Give reasons for non-participation at each stage	9 & 10
	(c) Consider use of a flow diagram	Figure 1
14	Descriptive data	Table 1
	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	Table 1
	(b) Indicate number of participants with missing data for each variable of interest	NA
15	Outcome data	9 & 10
	Report numbers of outcome events or summary measures	9 & 10
16	Main results	NA
	(a) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	NA
	(b) Report category boundaries when continuous variables were categorized	NA
	(c) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	NA
17	Other analyses	9
	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	9
<b>Discussion</b>		
18	Key results	10
19	Limitations	13
	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	13
20	Interpretation	10-13
	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	10-13
21	Generalisability	13
	Discuss the generalisability (external validity) of the study results	13
<b>Other information</b>		
22	Funding	15
	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	15

# BMJ Open

## COVID-19 in Ethiopia: A geospatial analysis of vulnerability to infection, case severity, and death

Journal:	<i>BMJ Open</i>
Manuscript ID	bmjopen-2020-044606.R2
Article Type:	Original research
Date Submitted by the Author:	27-Jan-2021
Complete List of Authors:	<p>Alene, Kefyalew; Curtin University, Faculty of Health Sciences; Telethon Kids Institute, Wesfarmers Centre of Vaccines and Infectious Diseases  Assefa, Yalemzewod; University of Gondar; University of New South Wales, School of Women's and Children's Health  Fetene, Dagnachew ; Burnet Institute  Koye, Digsu ; The University of Melbourne School of Population and Global Health  Melaku, Yohannes Adama; Flinders University, Public Health; The University of Adelaide Adelaide Medical School  Gesesew, Hailay; Mekelle University, Epidemiology Department, School of Health Sciences; Flinders University  Birhanu, Mulugeta ; St Paul's Hospital Millennium Medical College  Adane, Akilew; Telethon Kids Institute  Muluneh, Muluken; Western Sydney University; Amref Health Africa in Ethiopia, Monitoring Evaluation and Research  Dachew, Berihun; University of Gondar, Institute of Public Health; Curtin University, School of Public Health  Abrha, Solomon; University of Canberra; Mekelle University, School of Pharmacy  Aregay, Atsed; Monash University; Mekelle University, School of Nursing  Ayele, Asnakew ; University of Gondar, School of Pharmacy; University of New England  Bezabhe, Woldesellassie; University of Tasmania Faculty of Health  Tadesse, Kidane ; Queensland University of Technology; Mekelle University, School of Public Health  Gebremedhin, Tesfaye; University of Canberra  Tesfay, Amanuel; Telethon Kids Institute, Wesfarmers Centre of Vaccines and Infectious Diseases; Curtin University, School of Public health  Gebremichael, Lemlem; Mekelle University, Pharmacology Department; University of South Australia, School of Pharmacy and Medical Sciences, Therapeutics Research Centre  Geleto, Ayele; Haramaya University; The University of Newcastle Faculty of Health and Medicine  Kassahun, Habtamu ; Griffith University, Australian Rivers Institute  Kibret, Getiye ; Debre Markos University, Public Health; The University of Sydney  Leshargie, Cheru; Debre Markos University College of Health Science; University of Technology Sydney  Mekonnen, Alemayehu; Deakin University; The University of Sydney, School of Pharmacy</p>



	Mirkuzie, Alemnesh; Ethiopian Public Health Institute; University of Washington, Institute for Health Metrics and Evaluation Mohammed, Hassen; The University of Adelaide; Women's and Children's Health Network Tegegn, Henok; University of New England; University of Gondar Gebresilassie, A; Mekelle University, Epidemiology; University of New South Wales, The George Institute for Global Health Tesfay, Fisaha; Flinders University Faculty of Medicine Nursing and Health Sciences, South gate institute for Health, Society and Equity ; Mekelle University College of Health Sciences, School of Public Health Wubishet, Befikadu ; University of Canberra Kinfu, Yohannes; University of Canberra; Qatar University, College of Medicine
<b>&lt;b&gt;Primary Subject Heading&lt;/b&gt;:</b>	Epidemiology
Secondary Subject Heading:	Public health, Infectious diseases
Keywords:	Epidemiology < TROPICAL MEDICINE, Public health < INFECTIOUS DISEASES, PUBLIC HEALTH

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## 1 COVID-19 in Ethiopia: A geospatial analysis of vulnerability to infection, 2 case severity, and death

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5 Awoke Adane<sup>12</sup>, Muluken Dessalegn Muluneh<sup>13,14</sup>, Berihun Assefa Dachew<sup>3,15</sup>, Solomon Abrha<sup>16,17</sup>,  
6 Atsedo Aregay<sup>18,19</sup>, Asnakew Achaw Ayele<sup>20,21</sup>, Woldesellassie M Bezabhe<sup>22</sup>, Kidane Tadesse  
7 Gebremariam<sup>23,24</sup>, Tesfaye Gebremedhin<sup>25</sup>, Amanuel Tesfay<sup>15,2</sup>, Lemlem Gebremedhin  
8 Gebremichael<sup>26,27</sup>, Ayele Geleto<sup>28,29</sup>, Habtamu Tilahun Kassahun<sup>30</sup>, Getiye Dejenu Kibret<sup>31,32</sup>, Cheru  
9 Tesema Leshargie<sup>33,34</sup>, Alemayehu Mekonnen<sup>35,36</sup>, Alemnesh H. Mirkuzie<sup>37,38,39</sup>, Hassen  
10 Mohammed<sup>40,41</sup>, Henok Getachew Tegegn<sup>21,42</sup>, Azeb Gebresilassie Tesema<sup>22,43</sup>, Fisaha Tesfay<sup>9,10,44</sup>,  
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32 75 +61404705064; E-mail: [kefyalew.alene@curtin.edu.au](mailto:kefyalew.alene@curtin.edu.au)  
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54 85 **Keywords:** Risk map, vulnerability, infection, severity, death, COVID-19, Ethiopia, geospatial  
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3 88 **Abstract**  
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6 89 **Background:** COVID-19 has caused a global public health crisis affecting most countries,  
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8 90 including Ethiopia, in various ways. This study maps the vulnerability to infection, case  
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10 91 severity, and likelihood of death from COVID-19 in Ethiopia.  
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13 92 **Methods:** Thirty-eight potential indicators of vulnerability to COVID-19 infection, case  
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15 93 severity and likelihood of death, identified based on a literature review and the availability of  
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17 94 nationally representative data at a low geographic scale, were assembled from multiple sources  
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19 95 for geospatial analysis. Geospatial analysis techniques were applied to produce maps showing  
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21 96 the vulnerability to infection, case severity, and likelihood of death in Ethiopia at a spatial  
22  
23 97 resolution of 1 km X 1 km.  
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25 98 **Results:** This study showed that vulnerability to COVID-19 infection is likely to be high  
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27 99 across most parts of Ethiopia, particularly in the Somali, Afar, Amhara, Oromia, and Tigray  
28  
29 100 regions. The number of severe cases of COVID-19 infection requiring hospitalisation and  
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31 101 intensive care unit admission is likely to be high across Amhara, most parts of Oromia and  
32  
33 102 some parts of the Southern Nations, Nationalities, and Peoples' Region. The risk of COVID-  
34  
35 103 19-related death is high in the country's border regions, where public health preparedness for  
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37 104 responding to COVID-19 is limited.  
38

39 105 **Conclusion:** This study revealed geographical differences in vulnerability to infection, case  
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41 106 severity, and likelihood of death from COVID-19 in Ethiopia. The study offers maps that can  
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43 107 guide the targeted interventions necessary to contain the spread of COVID-19 in Ethiopia.  
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5**Strengths and limitations of this study**

- This is the first study that maps vulnerability to COVID-19 infection, severe cases, and associated death in Ethiopia at a high level of resolution across the entire territory of Ethiopia.
- This is also the first study that has attempted to present the degree of service preparedness for COVID-19 across the country.
- The study incorporated a wide range of indicators from multiple sources and applied rigorous geospatial techniques to provide the best possible prediction maps.
- However, some important indicators such as psychosocial and clinical factors were not captured in our modelling due to the lack of geocoded data.

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## 128 **Introduction**

129 Coronavirus disease (COVID-19) has become one of the most serious global public health  
130 crises in modern times <sup>1</sup>. The disease was declared a pandemic on 11 March 2020 and has  
131 currently affected more than 216 countries and territories <sup>2</sup>. As of 3 August 2020, there were  
132 more than 17.6 million confirmed COVID-19 cases and over 680,000 associated deaths around  
133 the globe <sup>3</sup>. The highest numbers of cases and deaths have been reported from the USA, Brazil,  
134 India, and some European countries, such as Russia, the United Kingdom, Italy, and Spain <sup>3</sup>.  
135 African countries, including Ethiopia, have reported a low number of COVID-19, although the  
136 number of cases and deaths are currently on the rise <sup>4</sup>. In Ethiopia, the first case of COVID-19  
137 was reported on 13 March 2020 in Addis Ababa, but at the time of this study almost all regions  
138 of the country were affected by COVID-19 at different magnitudes <sup>5</sup>. However, the number of  
139 cases in Ethiopia is still very low due to limited testing capacity and delays in reporting  
140 confirmed cases.

141 Multiple factors, such as socio-demographic, connectivity, behavioural, climatic, and  
142 comorbidity factors, are strong predictors of the differences in transmission, hospitalisation,  
143 and mortality rates among and within countries <sup>6,7</sup>. Studies conducted in Africa have provided  
144 limited information on the vulnerability of different areas to COVID-19 infection <sup>4,8</sup>. These  
145 studies have been conducted at the country level using a limited number of indicators <sup>4,8</sup>.  
146 Mapping the risks of COVID-19 (infection, case severity, service preparedness and death) at  
147 the lowest administrative unit, such as the district is important in many ways. First, the  
148 generated evidence can help the government and community better prepare and respond to the  
149 health- and non-health-related impacts of COVID-19 according to their contextual  
150 circumstances. Second, it can help the relevant bodies determine effective and efficient  
151 resource-mobilisation efforts, such as providing training for health care workers, supplying  
152 hospitals with necessary equipment, prioritising testing practices, and distributing hand  
153 sanitizer and protective facemasks. Third, the information can be utilised as a guide for  
154 designing targeted travel restrictions or applying full or partial lockdowns as needed. Fourth,  
155 the evidence can stimulate further study on COVID-19 in the country.

156 Given Ethiopia's large population size, variation in resources and vast geographic size, the risk  
157 of COVID-19 infection, case severity and likelihood of death are likely to differ across regions,  
158 zones, and districts, suggesting that local and context-specific interventions be implemented.

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3 159 Therefore, this study aimed to map the vulnerability to infection, case severity, and likelihood  
4 160 of death from COVID-19 in Ethiopia using rigorous state-of-the-art geospatial techniques.

## 161 **Methods**

### 162 **Study area**

163 This study focused on Ethiopia, the second-most populous country in Africa, with an estimated  
164 population size of more than 115 million <sup>9</sup>. Ethiopia has a total area of approximately 1.1  
165 million square kilometres, making it the 10<sup>th</sup> largest country in Africa and the 27<sup>th</sup> largest in  
166 the world. The country has a tiered administrative system consisting of regional states (first  
167 level), zones (second level), woredas or districts (third level), and kebeles or neighbourhoods  
168 (fourth level) <sup>10</sup>. There are nine administrative regional states in Ethiopia, including Tigray,  
169 Afar, Amhara, Oromia, Somali, Benishangul-Gumuz, Harari, Gambella, and the Southern  
170 Nations, Nationalities, and Peoples' Region (SNNPR), and two administrative cities (Addis  
171 Ababa and Diredawa). Four of these regional states (namely, Afar, Somali, Benishangul-  
172 Gumuz, and Gambella) are relatively less developed, and categorised as developing regional  
173 states. They lag behind the rest of the country in all indicators related to human development  
174 and disease prevention and control programs. The administrative units of Ethiopia (shapefiles)  
175 were obtained from the Database for Global Administrative Areas <sup>11</sup>.

### 176 **Data sources and variable selection**

177 The data for this study were assembled from multiple sources (Table 1). Potential indicators  
178 were selected based on evidence of association with COVID-19 infection, case severity, and  
179 death based on a literature review and the availability of country-wide representative data at a  
180 district geographic scale or lower (Figure 1). Table 2 presents the evidence for the association  
181 between indicators and COVID-19, as well as the rationale for selecting these indicators for  
182 the study.

183 The following area-level demographic and socio-economic indicators were used as indicators  
184 of COVID-19 infection and case severity: the average number of persons per household, the  
185 proportion of the population aged  $\geq 65$  years, the proportion of males, and the number of  
186 households in the lowest wealth quintile. All of these socio-economic and demographic  
187 indicators were obtained from the latest Ethiopia Demographic and Health Survey (EDHS) <sup>12</sup>.  
188 A map showing the distribution of EDHS datapoints are available as supplementary  
189 information (Supplemental Figure 1). Population density, estimated as the number of people  
190 per grid, was obtained from WorldPop <sup>13</sup>.



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3 191 Connectivity indicators, which measure the population-level vulnerability to infection, were  
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5 192 also captured using distance and time-bounded markers. Specifically, average travel time  
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7 193 (measured in minutes) to the nearest city and proximity to international borders (measured in  
8  
9 194 kilometres) were included to measure each area's level of susceptibility to infection. Data on  
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11 195 travel time to the nearest city, obtained from the University of Oxford's Malaria Atlas Project  
12  
13 196 (MAP), were used to quantify the accessibility of an area to high-density urban centres at a  
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15 197 resolution of 1 km×1 km<sup>14</sup>. Data on proximity to international borders were obtained from the  
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17 198 EDHS spatial data repository and were used to measure<sup>15</sup> the geodesic distance to the nearest  
18  
19 199 international border in kilometres, indicating the risk of cross-border transmission and the  
20  
21 200 spread of COVID-19. Infection rates and the spread of COVID-19 were also positively  
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23 201 correlated with the per capita public transportation use rate<sup>16</sup>. Thus, to determine the nearest  
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25 202 cross-country road to each location on the map, we obtained and applied data for major roads  
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27 203 from the World Bank<sup>17</sup>.

28  
29 204 It is evident that inadequate knowledge about COVID-19 and a lack of awareness of prevention  
30  
31 205 measures exacerbate community transmission of the disease<sup>18</sup>. Therefore, we extracted data  
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33 206 on adult literacy rate, access to media (such as radio, television, and mobile phone messages)  
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35 207 and knowledge about other infectious diseases (e.g., HIV) from the EDHS as proxies for  
36  
37 208 knowledge of COVID-19 prevention measures in each area of the country<sup>12</sup>. According to the  
38  
39 209 WHO, maintaining good hand hygiene through regular washing with soap and water is one of  
40  
41 210 the most effective preventative measures for reducing the transmission of COVID-19<sup>19,20</sup>.  
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43 211 Using the same data as above, we also assessed hand hygiene practices, access to water, and  
44  
45 212 the availability of handwashing stations in a household.

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47 213 Previous studies have shown that underlying chronic comorbidities and behavioural factors  
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49 214 such as cigarette, alcohol and khat consumption were associated with more severe COVID-19  
50  
51 215 infections<sup>21,22</sup>. Data on khat chewing and the alcohol consumption rate were obtained from the  
52  
53 216 EDHS 2016<sup>12</sup>, and data on cigarette smoking were obtained from the Ethiopia Public Health  
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55 217 Institute STEP wise approach to Surveillance (STEPS) study<sup>23</sup>. The STEPS survey was also  
56  
57 218 used to measure the prevalence of selected non-communicable diseases (NCDs) such as  
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59 219 hypertension, heart disease, and diabetes mellitus (DM).

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220 The level of preparedness and readiness of health facilities to detect, manage, and control the  
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222 COVID-19 pandemic at a given location was measured using data from the Service Availability  
and Readiness Assessment (SARA) survey<sup>24</sup>. For each geo-location, the obtained measures

223 include the availability and readiness of facilities in terms of basic amenities and equipment,  
224 standard precautions, diagnostic capacities, and essential medicines. In addition, data on  
225 service readiness for specific diseases such as DM, chronic respiratory disease (CRD), and  
226 tuberculosis (TB), as well as the availability of intensive care units (ICUs) and laboratory  
227 facilities, were obtained from this same survey. To augment the health facility data, we  
228 extracted population-level indicators on health care access and barriers to care from EDHS  
229 2016<sup>12</sup>.

230 Finally, climatic data (temperature, precipitation, humidity, and sunlight exposure) were  
231 obtained from the WorldClim v2.0 Global Climate Database<sup>25</sup>. These data were extracted at a  
232 spatial resolution of 30 seconds or ~1 km<sup>2</sup> and were considered indicators of COVID-19  
233 infection in this study.

### 234 **Geospatial data processing**

235 All data were georeferenced using a geographical information system, ArcGIS 10.6.1 software  
236 (ESRI Inc., Redlands CA, USA). The ideal resolution for spatial analysis was a latitude and  
237 longitude point that represented the location of the data cluster (point-level data), but when  
238 these were not available, we geolocated the available data to the smallest geographical areal  
239 unit, typically representing an administrative unit such as village or districts. In instances when  
240 the latitude and longitude coordinates of the village or district were not available in the dataset,  
241 centroids of the village or districts were also identified using Google Maps. A very small  
242 rectangular polygon (fishnet) with its centroid (fishnet centroid) covering the whole territory  
243 of Ethiopia was created using a sampling tool under the data management tools in the  
244 ArcToolbox (Figure 2). The fishnet centroid contained a unique identification number and was  
245 used as a common georeferenced system to process, join, and extract the raster and vector data  
246 collected from various sources. All vector data (point, polygon, and line) were converted to  
247 raster data using geostatistical methods<sup>26</sup>. Raster grids were then resampled to the common  
248 georeferenced system at a spatial resolution of 1 km x 1 km. Finally, a raster mask covering  
249 the entire country was created by clipping smaller spatial units from a large global raster data  
250 source.

### 251 **Statistical analyses**

252 Geostatistical techniques such as spatial autocorrelation, kriging and semivariograms were  
253 applied to create a prediction grid surface from a scattered set of points<sup>27</sup>. Kriging assumes  
254 that the distance or direction between sample points reflects a spatial correlation that can be  
255 used to explain variation in the surface<sup>28</sup>. Since the variables had different units of

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3 256 measurement, the datasets were normalised using a min-max approach to a standard scale  
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5 257 ranging from 0 (the lowest risk) to 100 (the highest risk)<sup>29</sup>. After normalisation, the indicators  
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7 258 were averaged to create a vulnerability index, measuring the risk of COVID-19 for each geo-  
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9 259 location<sup>30</sup>. The vulnerability indices were calculated separately for each domain, namely, the  
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11 260 vulnerability to infection, case severity, and likelihood of death from COVID-19. The three  
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13 261 domains were then averaged to produce the overall COVID-19 vulnerability index. Given that  
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15 262 COVID-19 is a new virus, there is a lack of evidence for assigning weights for each indicator.  
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17 263 Hence, equal weight was given to all indicators when calculating the arithmetic mean for the  
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19 264 vulnerability indices. However, we also used principal component analysis (PCA) and  
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21 265 geometric mean methods, which produced broadly similar results (Supplemental Figure 2 and  
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23 266 Supplemental Figure 3). The risk maps were then created separately for infection, case severity,  
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25 267 service preparedness, and death from the composite index using geostatistical tools in ArcGIS.  
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27 268 All data transformations were performed in R<sup>31</sup>. All items included in this study are available  
28  
29 269 in the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology)  
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31 270 Statement checklist (Supplemental Table 1).

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33 271 **Ethics aspects:** Ethical approval was not required for this study as it was based on publicly  
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35 272 available data.

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37 273 **Patient and public involvement:** This research was done without patient and public  
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39 274 involvement.

40  
41 275 **Funding:** There was no funding source for this study.

## 42 276 **Results**

### 43 277 **Vulnerability to COVID-19 infection**

44  
45 278 Figure 3 shows the vulnerability map of COVID-19 infection in Ethiopia. The map highlights  
46  
47 279 that most parts of the country are likely to have a relatively high vulnerability and be at  
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49 280 substantial risk for COVID-19 infection. Most parts of the country are identified as vulnerable  
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51 281 to COVID-19 infection, with the exception of Addis Ababa and the north-western Somali  
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53 282 region. The peripheral areas of the country bordering Djibouti, Somalia, Eritrea, and South  
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55 283 Sudan appeared to be vulnerable to COVID-19 infection. These outlying areas are  
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57 284 characterised by a low level of geographical connectivity and low scores for disease  
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59 285 knowledge, hand hygiene and socio-economic indices (Supplemental Figure 4). They also have  
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286 certain climatic factors that were found to be important indicators of COVID-19 transmission.

## 287 **Vulnerability to severe cases of COVID-19 infection**

288 Areas across the Amhara region and most parts of the Oromia region are likely to experience  
289 severe forms of COVID-19 that require hospitalisation and ICU admission. Some parts of the  
290 SNNPR are also expected to be at high risk of severe COVID-19 infections. The combination  
291 of demographic (high proportion of older adults), comorbidity (high prevalence of  
292 hypertension, DM, obesity, HIV, and TB), and behavioural and economic indicators (high  
293 proportion of smokers and high level of alcohol and khat consumption, interior cooking, and  
294 solid fuel use) renders these parts of the country at a higher risk of severe forms of COVID-19.  
295 Figure 4 shows the levels of vulnerability to severe forms of COVID-19.

## 296 **Vulnerability to death from COVID-19**

297 People living around border areas in Ethiopia are at a high risk for COVID-19-related death,  
298 as illustrated in Figure 5. Districts and zones in the Benishangul-Gumuz, Gambela, Afar,  
299 SNNPR, Dire Dawa, Southwest Somali, Northwest Amhara, Western Tigray, and Western and  
300 Eastern Oromia regions are at high risk for COVID-19-related death. The level of service  
301 preparedness and readiness to mitigate the health effects of COVID-19 appear to be very low  
302 in these regions (Figure 6). Ethiopia's border regions have inadequate ICU availability and  
303 laboratory capacity as well as limited health care access. They also have low general and  
304 service-specific readiness, as shown in Figure 6.

## 305 **Discussion**

306 This is the first study that maps vulnerability to COVID-19 infection, severe cases, and  
307 associated death in Ethiopia at a high resolution. This is also the first study that has attempted  
308 to present the degree of service preparedness for COVID-19 across the country.

309 We found that most parts of the country are vulnerable to COVID-19 infections, and the  
310 greatest burden might be outside of Addis Ababa. It is likely that compared to other regions, a  
311 higher proportion of people from the Amhara and Oromia regions, the two most populous  
312 regions of the country, will develop severe forms of COVID-19 leading to hospitalisation and  
313 ICU admission. Border areas of the country are also expected to face a higher risk of death than  
314 areas located in the central regions. The findings of this study are of paramount importance in  
315 preventing and controlling COVID-19 transmission and in designing targeted interventions,  
316 such as enacting travel restrictions, distributing preventative masks and determining which  
317 areas to prioritise if a COVID-19 vaccine becomes available. As some of these areas also have  
318 lower preparedness scores and low general and service-specific readiness scores, the findings

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3 319 have wider implications for allocating resources and strengthening the health care system after  
4 320 the COVID-19 pandemic.

7 321 Despite the disproportionately high infection rate in Addis Ababa at present (Supplemental  
8 322 Figure 5), we found that the risk of COVID-19 infection is likely to become rather high in other  
9 323 regions. The high infection rate in Addis Ababa at this initial stage is expected, given that Addis  
10 324 Ababa is a major travel hub and Bole International Airport, located in the city, is one of the  
11 325 largest international airports in Africa. This exposes the city to a higher risk of imported cases  
12 326 and, subsequently, to an early surge of infections, leaving the areas outside the city at a higher  
13 327 risk of later infection. Second, we considered multifaceted risk factors (indicators) for COVID-  
14 328 19 infection in our geospatial model. This means that although the city has a high degree of  
15 329 connectivity, it is also characterised by higher scores for information penetration, knowledge  
16 330 of disease prevention and hand hygiene practices that could help slow the rate of infection in  
17 331 the city<sup>12</sup>. Third, Addis Ababa has relatively better and more consistent test-and-contact tracing  
18 332 practices than in other parts of the country, which means that the chance of new infections  
19 333 being detected in the city are much greater than in other parts of the country<sup>5</sup>. Future efforts to  
20 334 expand testing and tracing practices in other areas of the county are likely to increase the extent  
21 335 of confirmed infections in those other areas. Recent studies have demonstrated that effective  
22 336 social distancing and contact tracing can significantly reduce the rate of infection<sup>32,33</sup>. These  
23 337 interventions should be strengthened and expanded to areas identified as high risk in this study.

24 338 Our study also showed that the risk for severe cases of COVID-19 infection is high in most  
25 339 parts of the Amhara and Oromia regions. This may be due to the high prevalence of NCDs,  
26 340 which are associated with severe cases of COVID-19. Previous studies have revealed that the  
27 341 burden of NCDs, such as DM and hypertension, is high in these two regions<sup>23,34,35</sup>.

28 342 Our study also revealed that peripheral areas sharing international borders are likely to see a  
29 343 greater number of COVID-19-related deaths. The high risk of death along the border areas  
30 344 might be attributed to low preparedness in case management and weak health care systems. In  
31 345 contrast, although the Amhara and Oromia regions may have more severe cases, the  
32 346 preparedness indicators show that the regions are better equipped to cope with these anticipated  
33 347 severe cases. However, our study suggests that additional preparation and capacity  
34 348 strengthening are needed mainly in the following areas: emergency response systems, case  
35 349 detection and capacity to care for patients. It is also equally important that hospitals have  
36 350 adequate supplies, health care personnel and life-saving medical intervention resources.

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3 351 Despite encouraging efforts by the Ethiopian government and stakeholders to prepare the  
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5 352 health care system for the pandemic, the existing health care services in the country may face  
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7 353 unprecedented challenges and crises due to the surge of patients that will require hospitalisation  
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9 354 and ICU services at the same time. This can, however, be eased by implementing public health  
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11 355 and social measures at the individual, community, and public authority levels to prevent  
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13 356 infections and subsequent health, economic, and social consequences <sup>36</sup>. Studies have shown  
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15 357 that implementing non-pharmaceutical interventions such as physical distancing, mask use, and  
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17 358 closure of schools, especially during the early stages of infection, can reduce transmission and  
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19 359 subsequent potential public health and economic crises <sup>37</sup>.

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21 360 Further, we found notable regional disparities in health system preparedness and readiness  
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23 361 levels in the country. This is important because if the health care system is well equipped to  
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25 362 prevent and mitigate the spread of the pandemic, then the mortality rate from the disease can  
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27 363 be markedly reduced <sup>38</sup>. However, we observed that Ethiopia's border regions (i.e.,  
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29 364 Benishangul-Gumuz, Gambella, Afar, and Somali) have low preparedness levels.  
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31 365 Nevertheless, comparisons between the border regions and other regions of the country need  
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33 366 to be treated with care because Ethiopia in general has very low doctor-to-resident (1 doctor  
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35 367 per 10,000 people) and hospital bed-to-population (3 hospital beds per 10,000 people) ratios  
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37 368 <sup>39</sup>. Several long-, medium- and short-term strategies, can be implemented to mitigate these  
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39 369 problems: (i) providing short-term training for potential actors such as community leaders,  
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41 370 students, and traditional and modern medical practitioners, (ii) recruiting additional staff to  
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43 371 work in COVID-19-related health care, (iii) establishing COVID-19 clinics and changing  
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45 372 outpatient rooms to emergency clinics, (iv) collaborating with private hospitals ahead of surges  
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47 373 so that they can be used in the case such surges occur, and (v) establishing mobile clinics and  
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49 374 temporary admission rooms in highly vulnerable areas.

### 46 375 **Strength and Limitations**

48 376 This study has several strengths. First, the current study was conducted at a spatial resolution  
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50 377 of 1 km x 1 km across the entire territory of Ethiopia. Second, it incorporated a wide range of  
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52 378 indicators from multiple sources. Third, it applied rigorous geospatial techniques, including  
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54 379 spatial autocorrelation, kriging and semivariograms, to provide the best possible prediction  
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56 380 maps. Finally, we produced vulnerability mapping for infection or transmission, case severity,  
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58 381 and associated death separately to assist with policy interventions related to each risk.  
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3 382 However, it is important to note some potential limitations of the study when interpreting the  
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5 383 findings. First, the results need constant updating, as some of the variables used in the study  
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7 384 may change overtime. Second, the data used in this study were not collected in the same year  
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9 385 and the results might be changed if recently available data were used in the analysis. However,  
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11 386 many of the variables used in this study were static and may not change over time. Moreover,  
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13 387 we used the most recently available data for non-static variables such as EDHS data. Third,  
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15 388 ongoing political turmoil in the country means that the dynamics of transmission may change  
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17 389 depending on the location and severity of these incidents. For example, in areas of low security  
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19 390 resulting from active conflict, the local health systems might be ill-prepared to prevent and  
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21 391 control COVID-19. Insecurity also may generate unpredictable population movements, and  
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23 392 this in turn could exacerbate infection dynamics in the country. Fourth, the calculation of the  
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25 393 composite risk factor index was based on an unweighted average under the assumption that all  
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27 394 indicators have equal importance, which may or may not be the case. Some of the variables  
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29 395 included in our score may have greater effects on vulnerability to infection, case severity, and  
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31 396 likelihood of death than others. Giving equal weight for all these variables may influence the  
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33 397 findings of our study, but the exact effect is hard to tell. However, we have calculated a  
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35 398 weighted index using PCA as an alternative method, which produced broadly similar results  
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37 399 (Supplemental Figure 2 and Supplemental Figure 3). Last, some important indicators, such as  
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39 400 psychosocial and clinical factors (e.g., mental illness, quality of life, and social support), were  
40  
41 401 not captured in our modelling due to the lack of geocoded data.

## 402 **Conclusions**

403 Although nearly three-quarters of the current COVID-19 cases reported in Ethiopia are  
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405 concentrated in and around Addis Ababa, this study predicts that over time, the risk of COVID-  
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407 19 infection will be higher across most other parts of the country. A higher proportion of people  
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409 from the Amhara region, most of the Oromia region, and some parts of the SNNPR will develop  
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411 severe cases of infection. Additionally, the risk of death will be higher in the regions of the  
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413 country with low preparedness scores for COVID response. Hence, the preventative and  
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415 control measures that are currently in place in the capital city should be strengthened and  
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417 extended to regional areas, especially to high-risk areas, to prevent and mitigate the risk of  
418  
419 COVID-19 infection, lower the number of severe cases, and limit the number of associated  
420  
421 deaths in Ethiopia.

## 414 Declaration

### 415 Authors' contributions

416 KAA, YAG, YK, DMF, DNK, YAM, HAG, MB, MDM, AAA, and BAD conceptualised the  
417 study. KAA designed and run the geospatial analysis. YAG involved in the data analysis. KAA,  
418 YAG, DMF, DNK, and YAM drafted the manuscript. HAG, MB, AAA<sub>1</sub>, MDM, BAD, SA,  
419 AA, AAA<sub>2</sub>, WMB, KTG, TG, ATG, LGG, AG, HTK, GDK, CTL, LBM, AAM, HM, HGT,  
420 AGT, FT, BLW, and YK Critically reviewed and revised the drafted manuscript. KAA, YK,  
421 and AHM were responsible for quality control of accuracy and integrity of data. All the authors  
422 interpreted the data. All authors contributed to the final draft and finally approved it to be  
423 published. All authors agreed to be accountable for all aspects of the work for any issue related  
424 to the accuracy or integrity of any part of the work. The corresponding author attests that all  
425 listed authors meet authorship criteria and that no others meeting the criteria have been omitted.

426 **Funding:** There is no funding source for this study.

427 **Competing interests:** None declared.

428 **Patient and public involvement:** This research was done without patient and public  
429 involvement.

430 **Data availability statement:** Extra data is available by emailing the corresponding author  
431 (KAA): kefyalew.alene@curtin.edu.au

## 432 Figures

433 **Figure 1:** Indicators for the vulnerability of COVID-19 infection, severity, service,  
434 preparedness, and related death. DM: diabetes mellitus, BMI: body mass index, CVD:  
435 cardiovascular disease prevalence; TB: tuberculosis; HIV: Human immunodeficiency virus;  
436 ICU: intensive care unit; CRD: cardiorespiratory diseases

437 **Figure 2:** Rectangular polygon (fishnet), fishnet centroids, and raster mask covering the whole  
438 territory of Ethiopia.

439 **Figure 3.** Vulnerability map to COVID-19 infection in Ethiopia.

440 **Figure 4.** Vulnerability map to COVID-19 severity in Ethiopia.

441 **Figure 5.** Vulnerability map to death from COVID-19 in Ethiopia.

442 **Figure 6.** Vulnerability map to service preparedness for COVID-19 in Ethiopia.



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## Tables

**Table 1:** Data sources and definitions of indicators for the vulnerability of COVID-19 in Ethiopia.

Indicators	Data sources	Spatial resolution	Definitions
<b>Demographic indicators</b>			
Male sex	EDHS 2016	Latitude and longitude point	Total number of male populations divided by the total number of people participated in the survey
Older age	EDHS 2016	Latitude and longitude point	Total number of people with age $\geq 65$ years divided by the total number of people participated in the survey
<b>Socio-economic indicators</b>			
Population density	WorldPop	1 km X 1 km	Number of people per square kilometre (grid)
Number of household members	EDHS 2016	Latitude and longitude point	Average number of people living in a house
Low wealth index	EDHS 2016	Latitude and longitude point	Number of people with low wealth index (poorer and poorest) divided by the total number of people participated in the survey
<b>Connectivity indicators</b>			
Travel times to cities	MAP	1 km $\times$ 1 km	Travel time in minutes to the nearest city with a population of more than 50,000
Proximity to national borders	DHS Spatial Repository	Latitude and longitude point	The geodesic distance to the nearest international borders
Distance to major roads	World Bank	District	Distance in km to cross-country round
<b>Climatic indicators</b>			
Mean temperature	WorldClim	1 km $\times$ 1 km	Annual mean environmental air temperature ( $^{\circ}$ C)
Mean precipitation	WorldClim	1 km $\times$ 1 km	Annual mean rainfall (mm)

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3 Wind speed	WorldClim	1 km×1 km	Annual mean wind speed (m s <sup>-1</sup> )
4 Solar radiation	WorldClim	1 km×1 km	Annual mean solar radiation (kJ m <sup>-2</sup> day <sup>-1</sup> )
5 Water vapour pressure	WorldClim	1 km×1 km	Annual mean water vapour pressure (kPa), equivalent to absolute humidity.

#### 8 Behavioural indicators

9 Khat chewing	EDHS 2016	Latitude and longitude point	Total number of people chewing khat in the last one month prior to the survey divided by the total number of people participating in the survey
12 Alcohol drinking	EDHS 2016	Latitude and longitude point	Total number of people drinking alcohol in the month prior to the survey divided by the total number of people participating in the survey
15 Cigarette smoking	EPHI STEPS	Latitude and longitude point	Total number of people currently smoke cigarettes divided by the total number of people participating in the survey
18 Cooking inside the household	EDHS 2016	Latitude and longitude point	Total number of households where cooking takes place inside the house without a separate building or outdoors (i.e. exposure to smoke inside the home) divided by the total number of households in the survey
23 Use solid fuel for cooking	EDHS 2016	Latitude and longitude point	Number of households used some type of solid fuel (wood, dung, grass, crop) for cooking food divided by all households in the survey

#### 20 Disease prevention knowledge indicators

27 Adult illiteracy rate	EDHS 2016	Latitude and longitude point	Total number of adults (aged 15 years and above) who had not attended school or who cannot read and write divided by the total number of adults participated in the survey
31 Access to listen to the radio	EDHS 2016	Latitude and longitude point	Total number of people who had not access to listen to the radio divided by total survey participants
34 Access to watch TV	EDHS 2016	Latitude and longitude point	Total number of people have no access to watch television divided by total survey participants
38 Mobile phone ownership	EDHS 2016	Latitude and longitude point	Total number of people have no access to mobile phone divide by the total number of survey participants
41 Knowledge toward HIV	EDHS 2016	Latitude and longitude point	Number of people with poor knowledge towards HIV divided by the total number of people participating in the survey

#### 44 Hand hygiene indicators

45 Travel time to water sources	EDHS 2016	Latitude and longitude point	Mean travel time in minutes to obtain water source (i.e. access to a water source)
48 Place for handwashing	EDHS 2016	Latitude and longitude point	Number of households have no fixed or mobile place for handwashing divided by total number of households in the survey
52 Soap or detergent availability for handwashing	EDHS 2016	Latitude and longitude point	Number of households have no essential handwashing agents (i.e. soap, and detergent) divided by total household in the survey

#### 55 Comorbidities indicators

56 HTN	EPHI STEPS	Latitude and longitude point	Total number of people with HTN divided by the total number of survey participants
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DM	EPHI STEPS	Latitude and longitude point	Total number of people with DM divided by the total number of survey participants
BMI	EPHI STEPS	Latitude and longitude point	Mean body mass index
CVD	EPHI STEPS	Latitude and longitude point	Total number of people with heart disease divided by total number of people in the survey
Cholesterol	EPHI STEPS	Latitude and longitude point	Mean cholesterol level
HIV prevalence	EDHS 2016	Latitude and longitude point	Total number of people with HIV divided by survey participants
TB SMR	EMOH	District	Standardized morbidity ratio (SMR) as measured by observed number of TB cases divided by the expected number of TB cases
<b>Service availability and readiness indicators</b>			
Health care access problem	EDHS 2016	Latitude and longitude point	Difficulty of getting advice or treatment due to lack of money, or distance to a health facility
General service readiness and availability	EPHI SARA	Latitude and longitude point	Availability of equipment and supplies (i.e. basic amenities, equipment, standard precautions, diagnostic capacity, essential medicines) necessary to provide general health services
ICU availability	EPHI SARA	Latitude and longitude point	Availability of Critical Care Services (ICU) in hospitals
CRD readiness index	EPHI SARA	Latitude and longitude point	Availability of specific services for Chronic respiratory disease (CRD) diagnosis, management, and follow up
TB readiness index	EPHI SARA	Latitude and longitude point	Availability of specific services for tuberculosis diagnosis, management, and follow up
Diabetes readiness index	EPHI SARA	Latitude and longitude point	Availability of specific service for diabetes diagnosis and management and follow up
<i>G-Econ: Geographically based Economic data; EDHS: Ethiopia demographic and health survey; UN OCHA: United Nation Office for Coordination of Humanitarian Affairs; MAP: SRTM: Malaria Atlas Project; Shuttle Radar Topography Mission; EPHI: Ethiopia Public Health Institute; EMOH: Ethiopia Ministry of Health; SARA: Service Availability and Readiness Assessment</i>			

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**Table 2: Evidence for risk of COVID-19 infection, severity, and death**

Indicators	Risk factors	Evidence	References
<b>Demographic indicators</b>			
Male sex	Severity	Death from and severity of COVID-19 was strongly associated with being male (HR 1.99, 95%CI: 1.88-2.10)	Williamson E <sup>40</sup>
Older age	Severity	Older than 65 years were risk factors for disease progression in patients with COVID-19 (OR =6.06, 95% CI: 3.98, 9.22)	Zheng Z <sup>22</sup>
<b>Socio-economic indicators</b>			
Population density	Infection	High population density is a risk factor for COVID-19 infection	Ahmadi M <sup>41</sup>
Number of household members	Infection	Areas with a higher percentage of households with more than one person per room had a higher incidence of COVID-19	Ahmad K <sup>42</sup>
Low wealth index	Infection	Socio-economic deprivation (RR 1.26 per SD increase in Townsend Index) associated with COVID -19 infection	Ho FK <sup>43</sup>
<b>Connectivity indicators</b>			
Travel times to cities	Infection	The distance between Wuhan and other cities was inversely associated with the numbers of COVID-19 cases in that city	Zheng R <sup>44</sup>
Proximity to national borders	Infection	Cross country moment is a risk factor for COVID-19 transmission and importation	Chinazz M <sup>45</sup>
Distance to major roads	Infection	Spread of COVID-19 was correlated positively with public transportation per capita	Ayene B <sup>16</sup> .
<b>Climatic indicators</b>			
Mean temperature	Infection	Low ambient temperatures are associated with more rapid spread of COVID-19	Holtmann M <sup>46</sup>
Mean precipitation	Infection	Countries with higher rainfall measurements showed an increase in COVID-19 transmission	Sobral MFF <sup>47</sup>
Wind speed	Infection	Areas with low values of wind speed associated with a high rate of COVID-19 infection	Ahmadi M <sup>41</sup>
Solar radiation	Infection	Areas with low values of solar radiation exposure associated with a high rate of COVID-19 infection	Ahmadi M <sup>41</sup>

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3 4 5	Water vapour pressure	Infection	High humidity reduces the transmission of COVID-19. Water vapour pressure negatively correctly with COVID-19 infection.	Wang J <sup>48</sup> , Li J <sup>49</sup>
<b>Behavioural indicators</b>				
6 7	Khat chewing	Severity	There is an association between khat chewing and chronic illness such as HIV infection, elevated diastolic blood pressure	Basker GV <sup>50</sup>
8	Alcohol drinking	Severity	Patients with alcohol use disorders at increased risk for COVID-19	Testino G <sup>21</sup>
9 10 11	Cigarette smoking	Severity	Current smoking was a risk factor for disease progression in patients with COVID-19 (OR =2.51, 95% CI: 1.39, 3.32)	Zheng Z <sup>22</sup>
12 13	Cooking inside the household	Severity	Areas with a higher percentage of incomplete kitchen facilities had a higher incidence of, and mortality associated with, COVID-19	Ahmad K <sup>42</sup>
14 15	Use solid fuel for cooking	Severity	Areas with a higher percentage of incomplete kitchen facilities had a higher incidence of, and mortality associated with, COVID-19	Ahmad K <sup>42</sup>
<b>Disease prevention knowledge indicators</b>				
16 17	Adult illiteracy rate	Infection	Adult learning education is a tool to contain the COVID-19 pandemics	Lopes H <sup>51</sup>
18 19	Access to listen to radio	Infection	Access to media is a crucial factor in public health responses to an outbreak	Ayedee N <sup>52</sup>
20 21	Access to watch TV	Infection	Media (Television) has a significant role in creating a positive atmosphere in COVID-19	Ayedee N <sup>52</sup>
22 23	Mobile phone ownership	Infection	Mobile phone calls and text messages help for the diagnosis, management, and control of infectious diseases	Wood S <sup>53</sup>
24 25	Knowledge towards HIV	Infection	Knowledge towards an infectious disease such as HIV can help to control the transmission of the diseases	Bertozzi S <sup>54</sup>
<b>Hand hygiene indicators</b>				
26 27	Travel time to water sources	Infection	Adequate water supply is essential for the control of COVID-19 infection	WHO <sup>55</sup>
28 29	Place for handwashing	Infection	Hand washing is recommended by WHO for the control of COVID-19 infection	WHO <sup>56</sup>
30 31	Soap or detergent availability for handwashing	Infection	Availability of soap or detergent is essential to keep hand hygiene for the prevention of COVID-19 infection	WHO <sup>56</sup>
<b>Comorbidities indicators</b>				
32 33	HTN	Severity	Hypertension was statistically significant with a higher rate of severity and death (OR = 2.72, 95% CI: 1.60,4.64)	Zheng Z <sup>22</sup>
34 35	DM	Severity	Death from COVID-19 was associated with DM (HR 1.50, 95%CI: 1.40-1.60) 1.50	Williamson E <sup>40</sup>
36 37	BMI	Severity	Death from COVID-19 was associated with higher BMI (HR 1.27, 95%CI: 1.18-1.36)	Williamson E <sup>40</sup>
38 39	CVD	Severity	Cardiovascular disease was significantly associated with higher COVID-19 severity and death (OR = 5.19, 95% CI: 3.25, 8.29)	Zheng Z <sup>22</sup>
40 41	HIV prevalence	Severity	Mortality from COVID-19 was associated with immunosuppression (HR 1.69, 95%CI: 1.21-1.34)	Williamson E <sup>40</sup>
42 43	TB SMR	Severity	respiratory diseases were significantly associated with COVID-19 death and severity (OR = 5.15, 95% CI: 2.51, 10.57)	Zheng Z <sup>22</sup>
<b>Service availability and readiness indicators</b>				
44 45	Health care access problem	Death	Healthcare resource availability is associated with COVID-19 mortality	Ji Y <sup>6</sup>
46 47	General service readiness	Death	General health service preparedness is essential for combating the COVID-19 pandemic	WHO <sup>57</sup>
48 49	ICU availability	Death	Lack of critical care unite increase the risk of death from COVID-19	Murthy S <sup>58</sup>
50 51	CRD readiness	Death	Cardiorespiratory disease (CRD) is a risk factor for COVID-19 related death	Zheng Z <sup>22</sup>
52 53	TB readiness	Death	TB determinants outcomes of patients with COVID-19	Tadolini M <sup>59</sup>
54 55	Diabetes readiness	Death	Diabetes affects the prognosis of patients with COVID-19	Zheng Z <sup>22</sup>



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*G-Econ: Geographically based Economic data; EDHS: Ethiopia demographic and health survey; UN OCHA: United Nation Office for Coordination of Humanitarian Affairs; MAP: SRTM: Malaria Atlas Project; Shuttle Radar Topography Mission; EPHI: Ethiopia Public Health Institute; EMOH: Ethiopia Ministry of Health; SARA: Service Availability and Readiness Assessment*

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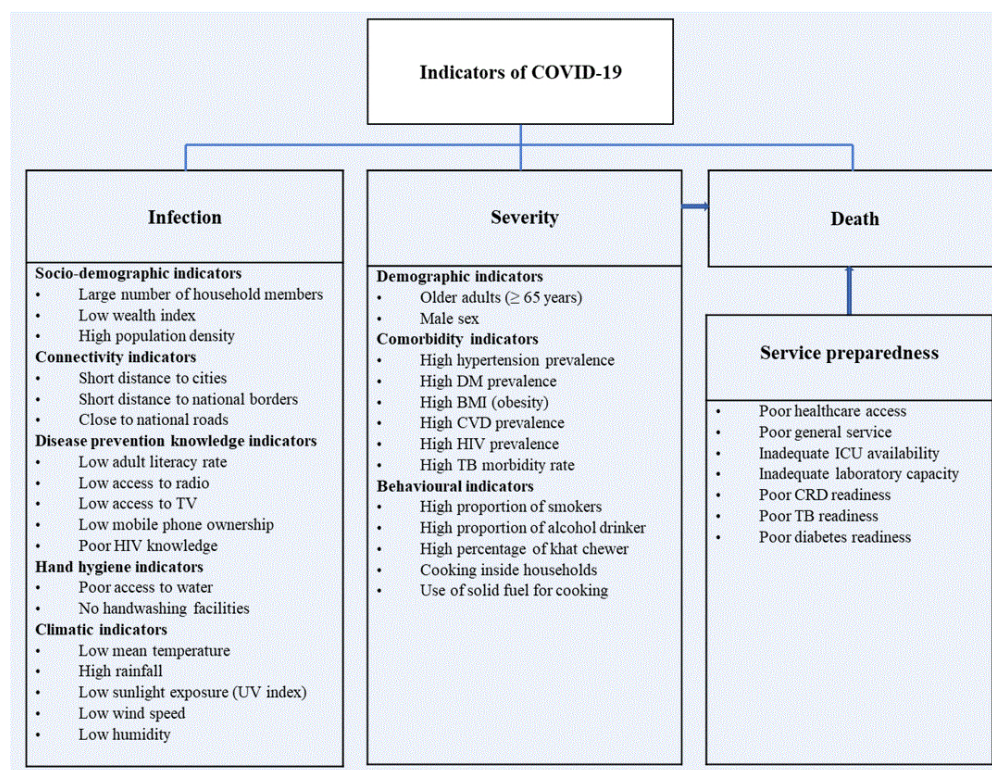


Figure 1: Indicators for the vulnerability of COVID-19 infection, severity, service, preparedness, and related death. DM: diabetes mellitus, BMI: body mass index, CVD: cardiovascular disease prevalence; TB: tuberculosis; HIV: Human immunodeficiency virus; ICU: intensive care unit; CRD: cardiorespiratory diseases

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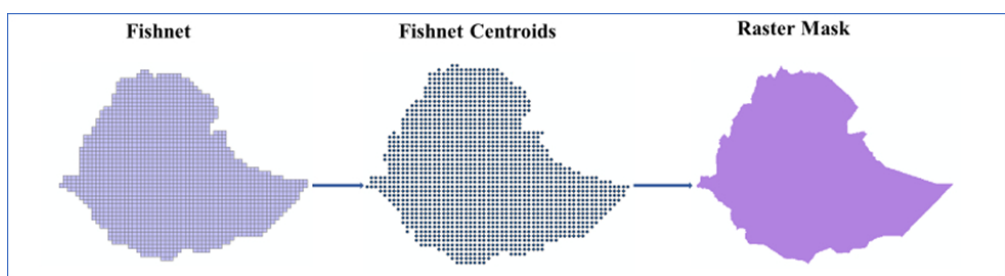


Figure 2: Rectangular polygon (fishnet), fishnet centroids, and raster mask covering the whole territory of Ethiopia.

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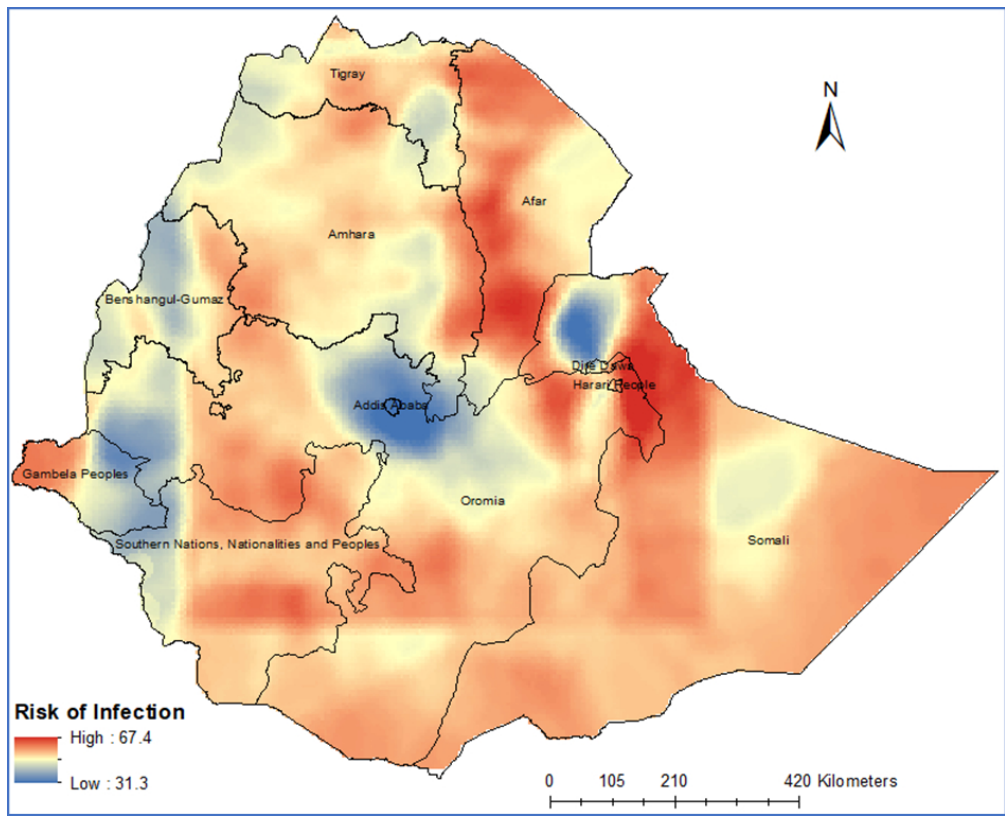


Figure 3. Vulnerability map to COVID-19 infection in Ethiopia.

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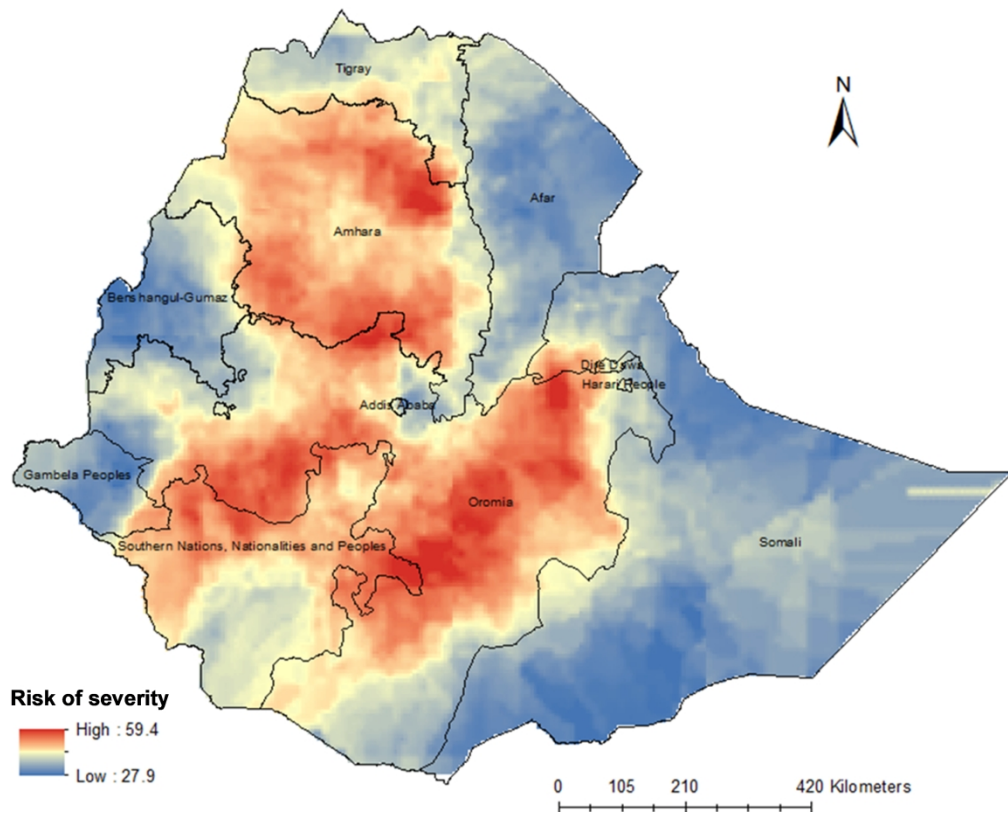


Figure 4. Vulnerability map to COVID-19 severity in Ethiopia.

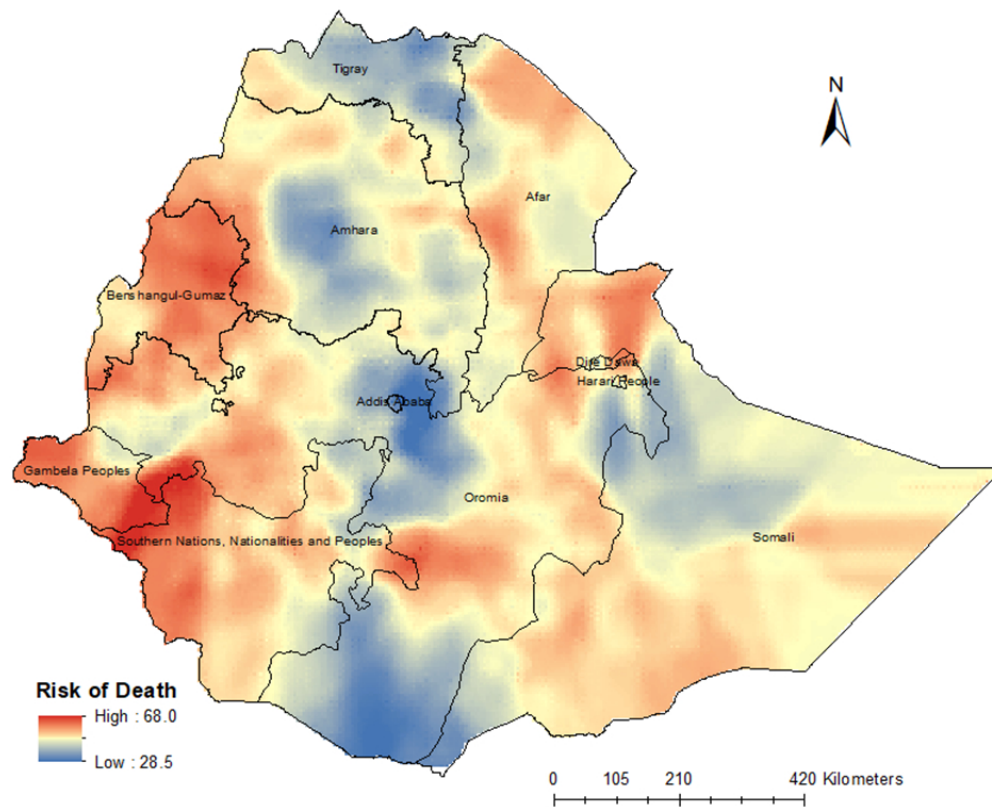


Figure 5. Vulnerability map to death from COVID-19 in Ethiopia.

248x200mm (96 x 96 DPI)

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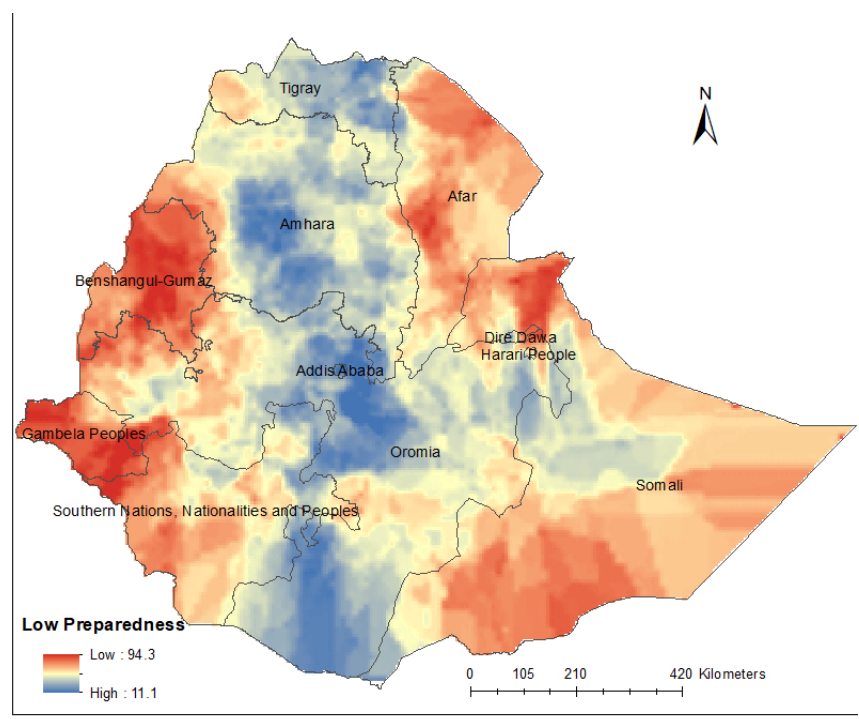
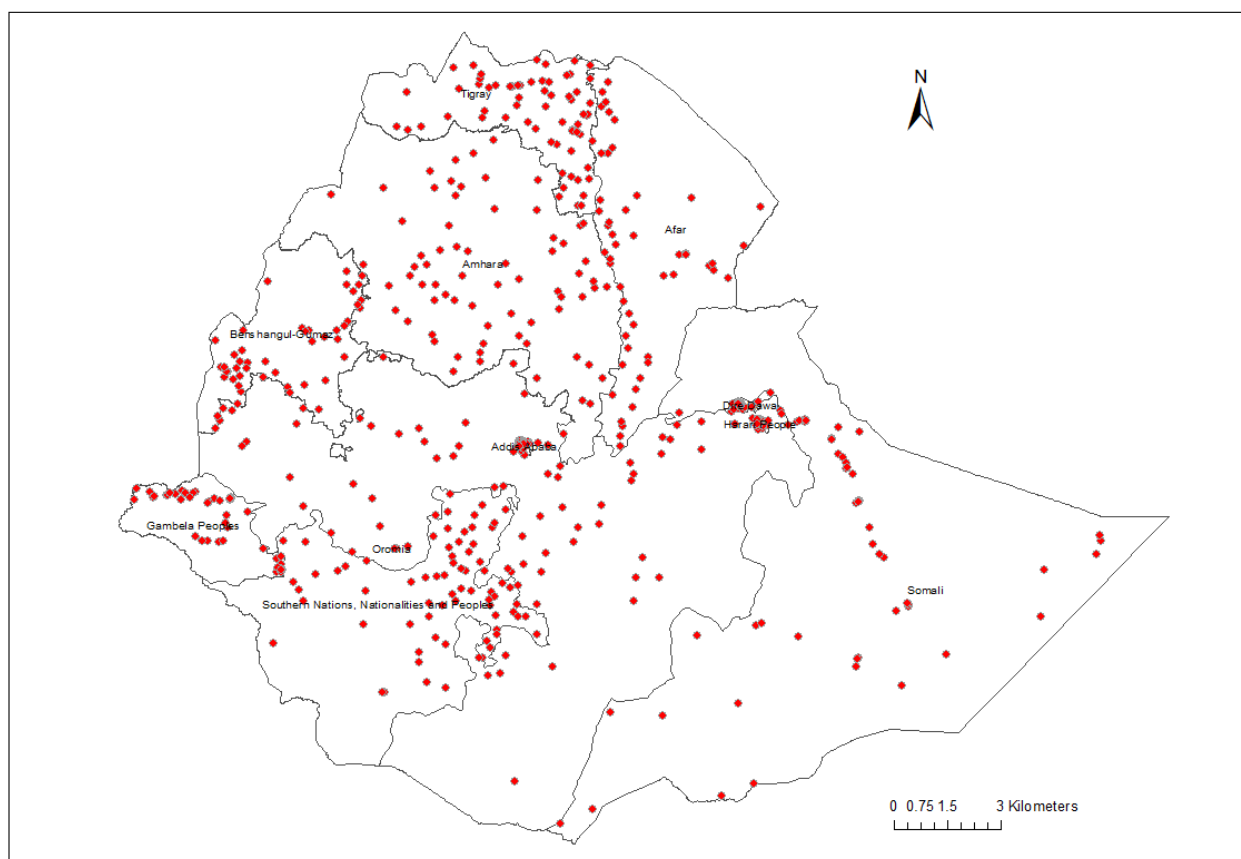


Figure 6. Vulnerability map to service preparedness for COVID-19 in Ethiopia.

210x296mm (96 x 96 DPI)

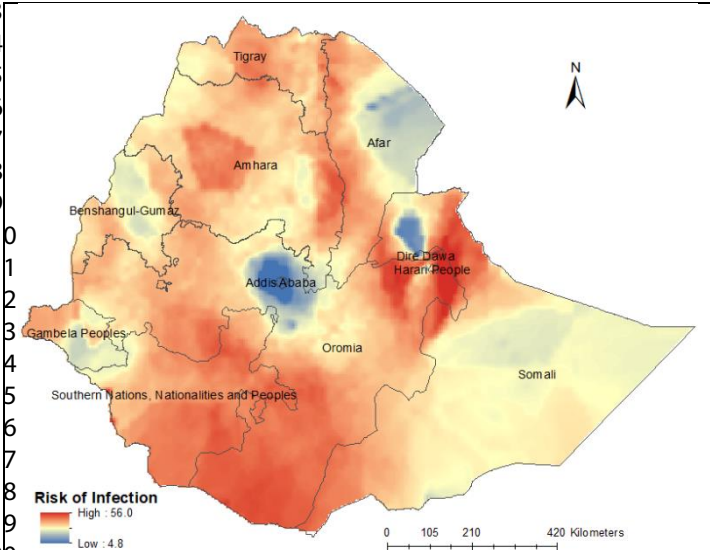
## Supplemental Information



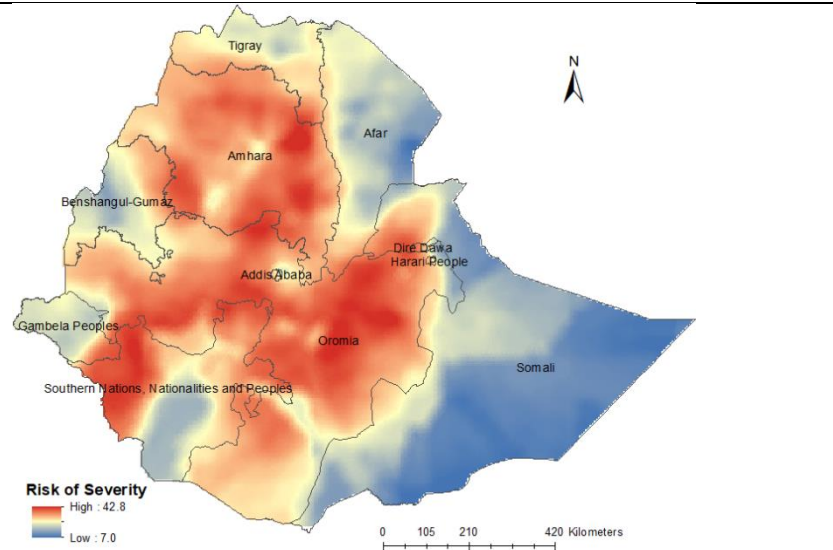
**Supplemental Figure 1:** A map showing the distribution of the Ethiopia Demographic and Health Survey (EDHS 2016) datapoints.



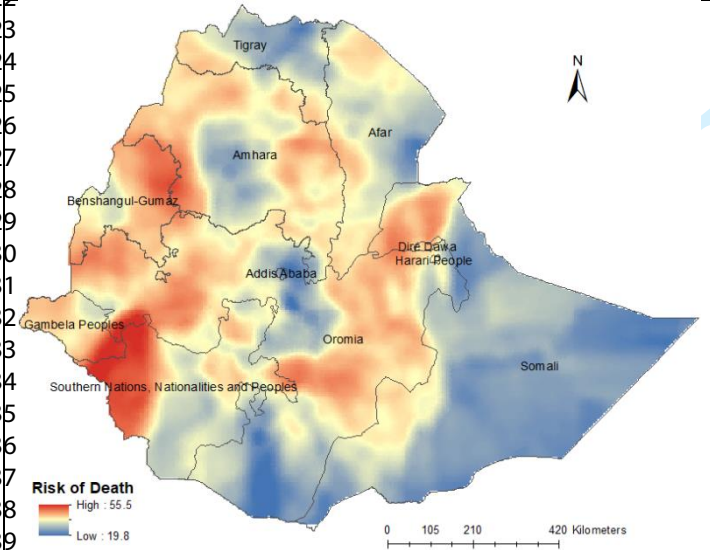
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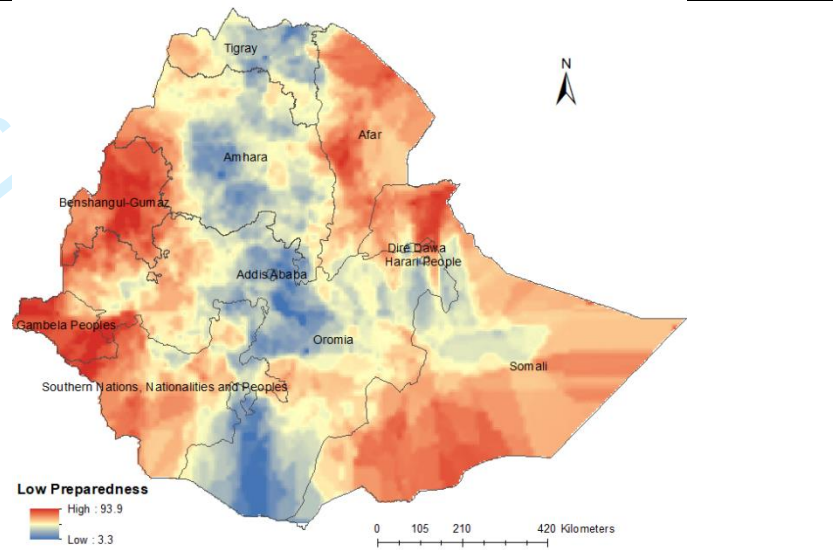
S Figure 2a. COVID-19 infection risk map in Ethiopia, created based on a geometric mean



S Figure 2b. COVID-19 severity risk map in Ethiopia, created based on a geometric mean



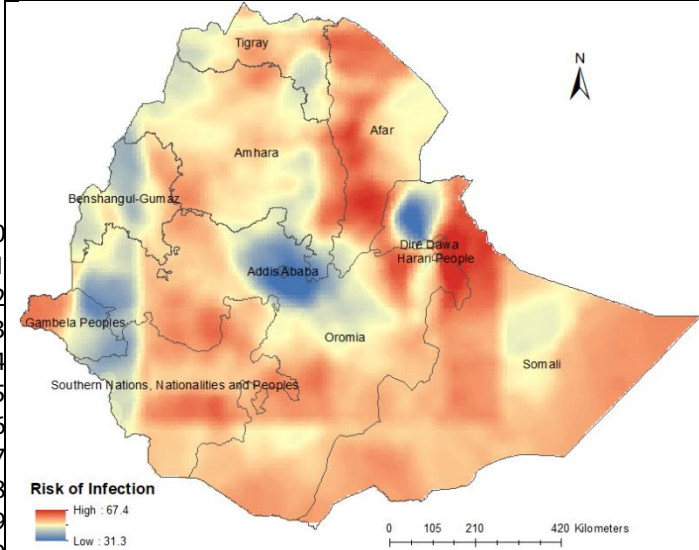
S Figure 2c. Death risk map of COVID-19 in Ethiopia, created based on a geometric mean



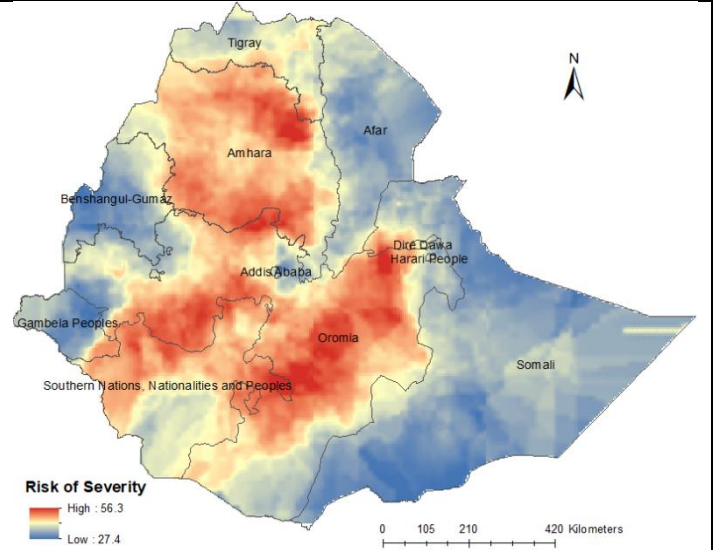
S Figure 2d. Service preparedness map of COVID-19 in Ethiopia, created based on a geometric mean

**Supplemental Figure 2:** Vulnerability maps of COVID-19 infection, severity, preparedness, and death in Ethiopia, created based on a geometric mean as alternative aggregation method.

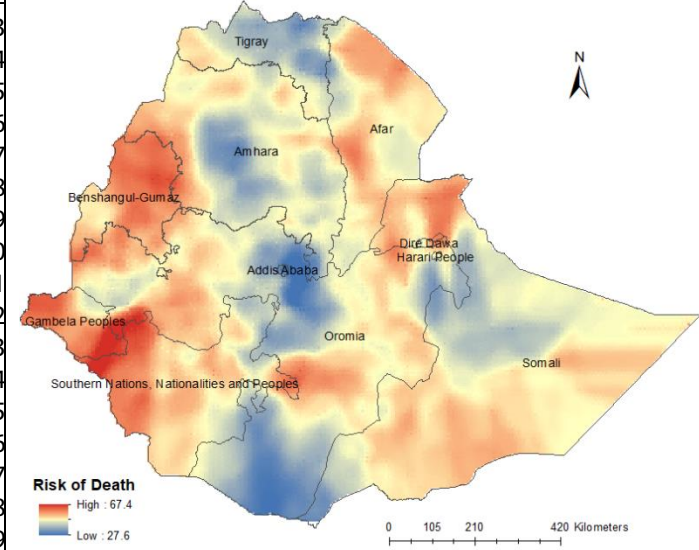
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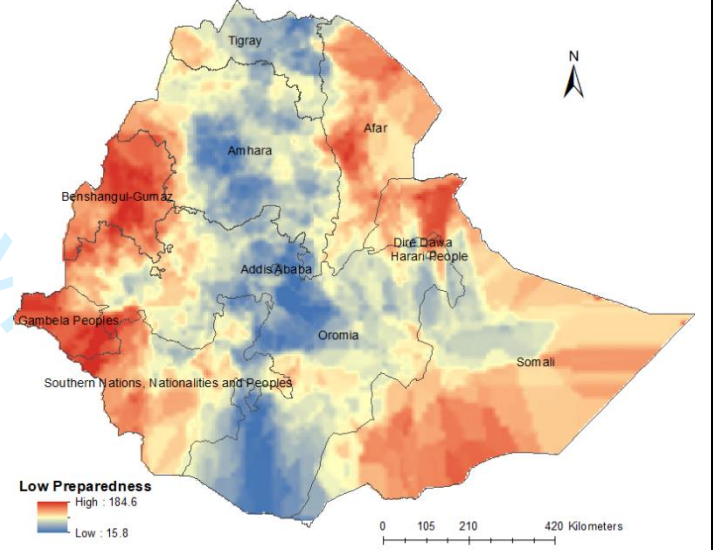
S Figure 3a. COVID-19 infection risk map in Ethiopia, created based on a geometric mean



S Figure 3b. COVID-19 severity risk map in Ethiopia, created based on a geometric mean



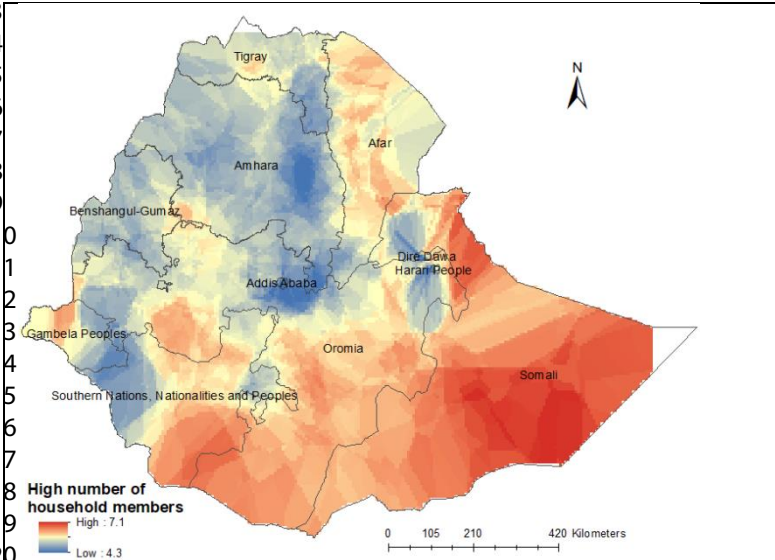
S Figure 3c. Death risk map of COVID-19 in Ethiopia, created based on a geometric mean



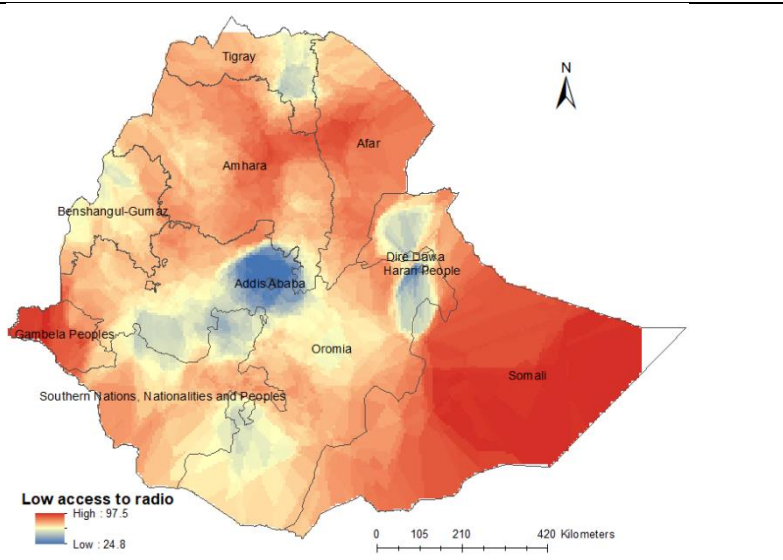
S Figure 3d. Service preparedness map of COVID-19 in Ethiopia, created based on a geometric mean

**Supplemental Figure 3:** Vulnerability maps of COVID-19 infection, severity, preparedness, and death in Ethiopia, created based on a principal component analysis (PCA) as alternative aggregation method.

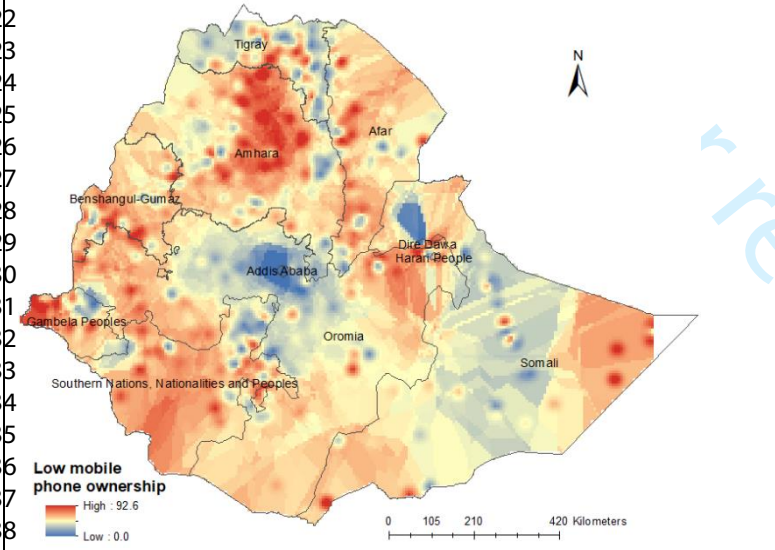
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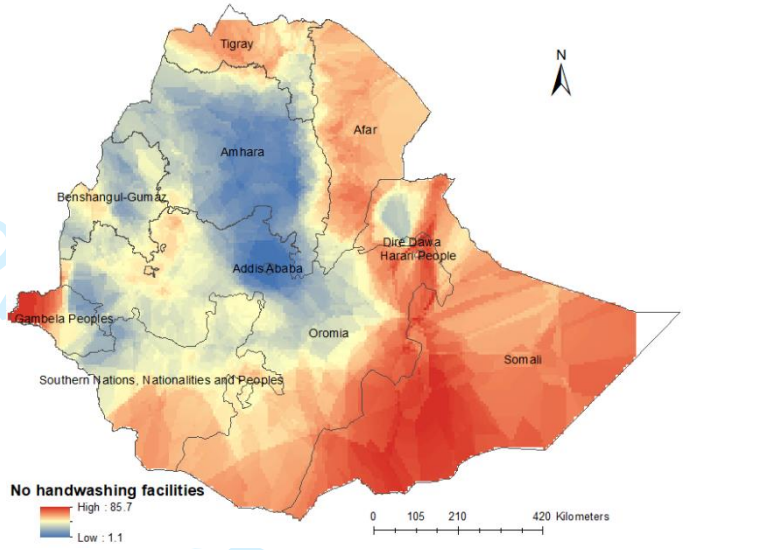
S Figure 4a. Average number of people living in a house



S Figure 4b. Percentage of population have no access to radio

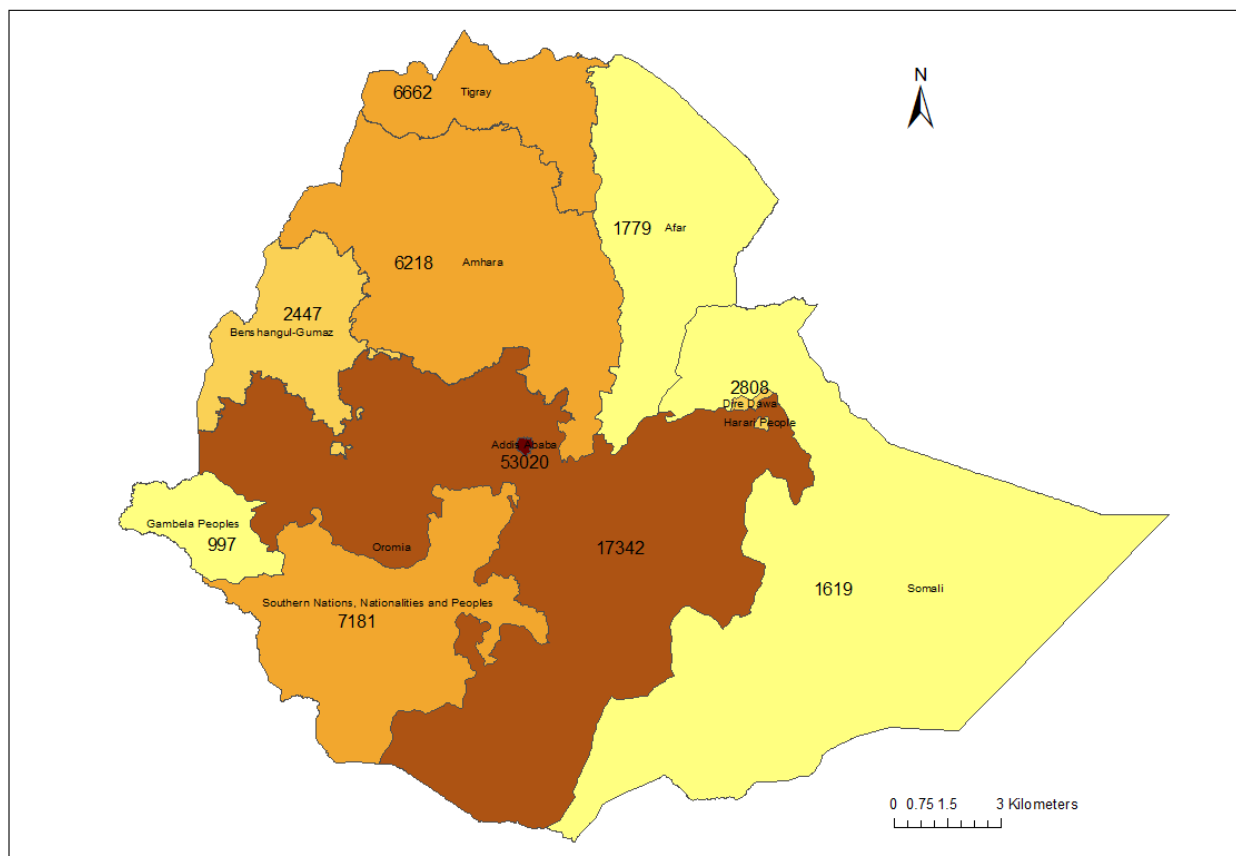


S Figure 4b. Percentage of the population who have not access to mobile phone



S Figure 4d. Percentage of households who have not hand washing facilities

**Supplemental Figure 4: Selected indicators showing the risk of COVID-19 infection in Ethiopia**



**Supplemental Figure 5:** Number of COVID-19 confirmed cases at regional level in Ethiopia on 15 November 2020.

**Supplemental Table 1: STROBE Statement—Checklist of items included in this study**

	Item No	Recommendation	Page number
<b>Title and abstract</b>	1	(a) Indicate the study's design with a commonly used term in the title or the abstract	1
		(b) Provide in the abstract an informative and balanced summary of what was done and what was found	3
<b>Introduction</b>			
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	5
Objectives	3	State specific objectives, including any prespecified hypotheses	6
<b>Methods</b>			
Study design	4	Present key elements of study design early in the paper	6
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	6
Participants	6	(a) Give the eligibility criteria, and the sources and methods of selection of participants	6, 7 & 8
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	6, 7 & 8
Data sources/measurement	8	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	6, 7, 8 & Table 1
Bias	9	Describe any efforts to address potential sources of bias	9
Study size	10	Explain how the study size was arrived at	NA
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	8 & 9
Statistical methods	12	(a) Describe all statistical methods, including those used to control for confounding	8 & 9
		(b) Describe any methods used to examine subgroups and interactions	8 & 9
		(c) Explain how missing data were addressed	8 & 9
		(d) If applicable, describe analytical methods taking account of sampling strategy	NA
		(e) Describe any sensitivity analyses	9
<b>Results</b>			
Participants	13	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	9 & 10
		(b) Give reasons for non-participation at each stage	9 & 10
		(c) Consider use of a flow diagram	Figure 1
Descriptive data	14	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	Table 1
		(b) Indicate number of participants with missing data for each variable of interest	NA
Outcome data	15	Report numbers of outcome events or summary measures	9 & 10
Main results	16	(a) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	NA
		(b) Report category boundaries when continuous variables were categorized	NA
		(c) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	NA
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	9
<b>Discussion</b>			
Key results	18	Summarise key results with reference to study objectives	10
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	13
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	10-13
Generalisability	21	Discuss the generalisability (external validity) of the study results	13
<b>Other information</b>			
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	15