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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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Abstract

Background: COVID-19 has caused a global public health crisis affecting most countries, including Ethiopia, in various ways. This study maps the vulnerability to infection, case severity, and likelihood of death from COVID-19 in Ethiopia.

Methods: Thirty-eight potential indicators of vulnerability to COVID-19 infection, case severity and likelihood of death, identified based on a literature review and the availability of nationally representative data at a low geographic scale, were assembled from multiple sources for geospatial analysis. Geospatial analysis techniques were applied to produce maps showing the vulnerability to infection, case severity, and likelihood of death in Ethiopia at a high level of resolution (1 km X 1 km).

Results: This study showed that vulnerability to COVID-19 infection is likely to be high across most parts of Ethiopia, particularly in the Somali, Afar, Amhara, Oromia, and Tigray regions. The number of severe cases of COVID-19 infection requiring hospitalisation and intensive care unit admission is likely to be high across Amhara, most parts of Oromia and some parts of the Southern Nations, Nationalities, and Peoples' Region. The risk of COVID-19-related death is high in the country's border regions, where public health preparedness for responding to COVID-19 is limited.

Conclusion: This study revealed geographical differences in vulnerability to infection, case severity, and likelihood of death from COVID-19 in Ethiopia. The study offers high-resolution maps that can guide the targeted interventions necessary to contain the spread of COVID-19 in Ethiopia.

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.

Introduction

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

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

Given Ethiopia's large population size, variation in resources and vast geographic size, the risk of COVID-19 infection, case severity and likelihood of death are likely to differ across regions, zones, and districts, suggesting that local and context-specific interventions be implemented. Therefore, this study aimed to map the vulnerability to infection, case severity, and likelihood of death from COVID-19 in Ethiopia at a higher geographic resolution (1 km X 1 km) over the whole territory of Ethiopia using rigorous state-of-the-art geospatial techniques.

Methods

Study area

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

Data sources and variable selection

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

The following area-level demographic and socio-economic indicators were used as indicators of COVID-19 infection and case severity: the average number of persons per household, the proportion of the population aged ≥ 65 years, the proportion of males, and the number of households in the lowest wealth quintile. All of these socio-economic and demographic indicators were obtained from the latest Ethiopia Demographic and Health Survey (EDHS) [13]. Population density, estimated as the number of people per grid, was obtained from WorldPop [14].

Connectivity indicators, which measure the population-level vulnerability to infection, were also captured using distance and time-bounded markers. Specifically, average travel time (measured in minutes) to the nearest city with at least 50,000 people and proximity to international borders (measured in kilometres) were included to measure each area's level of susceptibility to infection. Data on travel time to the nearest city, obtained from the University of Oxford's Malaria Atlas Project (MAP), were used to quantify the accessibility of an area to high-density urban centres at a resolution of 1 km×1 km. [15]. Data on proximity to international borders were obtained from the EDHS spatial data repository and were used to measure [16] the geodesic distance to the nearest international border in kilometres, indicating the risk of cross-border transmission and the spread of COVID-19. Infection rates and the spread of COVID-19 were also positively correlated with the per capita public transportation use rate [17]. Thus, to determine the nearest cross-country road to each location on the map, we obtained and applied data for major roads from the World Bank [18].

It is evident that inadequate knowledge about COVID-19 and a lack of awareness of prevention measures exacerbate the community transmission of the disease [19]. Therefore, we extracted data on the adult literacy rate, access to media (such as radio, television, and mobile phone messages) and knowledge about other infectious diseases (e.g., HIV) from the EDHS as proxies for knowledge of COVID-19 prevention measures in each area of the country [13]. According to the WHO, maintaining good hand hygiene through regular washing with soap and water is one of the most effective preventative measures for reducing the transmission of COVID-19 [20,21]. Using the same data as above, we also assessed hand hygiene practices, access to water, and the availability of handwashing stations in a household.

Previous studies have shown that underlying chronic comorbidities and behavioural factors such as cigarette, alcohol and khat consumption were associated with more severe COVID-19 infections [22,23]. Data on khat chewing and the alcohol consumption rate were obtained from the EDHS 2016 [13], and data on cigarette smoking were obtained from the Ethiopia Public Health Institute STEP wise approach to Surveillance (STEPS) study [24]. The STEP survey was also used to measure the prevalence of select non-communicable diseases (NCDs) such as hypertension, heart disease, and diabetes mellitus (DM).

The level of preparedness and readiness of health facilities to detect, manage, and control the COVID-19 pandemic at a given location was measured using data from the Service Availability and Readiness Assessment (SARA) survey [25]. For each geo-location, the obtained measures include the availability and readiness of facilities in terms of basic amenities and equipment, standard precautions, diagnostic capacities, and essential medicines. In addition, data on service readiness for specific diseases such as DM, chronic respiratory disease (CRD), and tuberculosis (TB), as well as the availability of intensive care units (ICUs) and laboratory facilities, were obtained from this same survey. To augment the health facility data, we extracted population-level indicators on health care access and barriers to care from EDHS 2016 [13].

Finally, climatic data (temperature, precipitation, humidity, and sunlight exposure) were obtained from the WorldClim v2.0 Global Climate Database [26]. These data were extracted at a spatial resolution of 30 seconds or ~1 km^2 and were considered indicators of COVID-19 infection in this study.

Geospatial data processing

All data were georeferenced using a geographical information system, ArcGIS 10.6.1 software (ESRI Inc., Redlands CA, USA). A very small rectangular polygon (fishnet) with its centroid (fishnet centroid) covering the whole territory of Ethiopia was created using tools in ArcGIS (Figure 2). The fishnet centroid contained a unique identification number and was used as a common georeferenced system to process, join, and extract the raster and vector data collected from various sources. All vector data (point, polygon, and line) were converted to raster data using geostatistical methods [27]. Raster grids were then resampled to the common georeferenced system at a spatial resolution of 1 km x 1 km. Finally, a raster mask covering the entire country was created by clipping smaller spatial units from a large global raster data source.

Statistical analyses

Geostatistical techniques such as spatial autocorrelation, kriging and semivariograms were applied to create a prediction grid surface from a scattered set of points [28]. Kriging assumes that the distance or direction between sample points reflects a spatial correlation that can be used to explain variation in the surface [29]. Since the variables had different units of measurement, the datasets were normalised using a min-max approach to a standard scale ranging from 0 (the lowest risk) to 100 (the highest risk) [30]. After normalisation, the indicators were averaged to create a vulnerability index, measuring the risk of COVID-19 for each geo-location [31]. The vulnerability indices were calculated separately for each domain, namely, the vulnerability to infection, case severity, and likelihood death from COVID-19. The three domains were then averaged to produce the overall COVID-19 vulnerability index. Given that COVID-19 is a new virus, there is a lack of evidence for assigning weights for each indicator. Hence, equal weight was given to all indicators when calculating the arithmetic mean for the aggregate vulnerability indices. We also used principal component analysis (PCA) and geometric means as alternative aggregation methods, producing broadly similar results

(Supplemental Figure 1 and Supplemental Figure 2). The risk maps were then created separately for infection, case severity, service preparedness, and death from the composite index using geostatistical tools in ArcGIS. All data transformations and aggregations were performed in R [32].

Ethics aspects: Ethical approval was not required for this study as it was based on publicly available data.

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

Funding: There was no funding source for this study.

Results

Vulnerability to COVID-19 infection

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

Vulnerability to severe cases of COVID-19 infection

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

Vulnerability to death from COVID-19

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

Discussion

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

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

Despite the proportionally high infection rate in Addis Ababa at present, we found that the risk of COVID-19 infection is likely to become rather high in other regions. The high infection rate in Addis Ababa at this initial stage is expected, given that Addis Ababa is a major travel hub and Bole International Airport, located in the city, is one of the largest international airports in Africa. This exposes the city to a higher risk of imported cases and, subsequently, to an early surge of infections, leaving the areas outside the city at a higher risk of later infection. Second, we considered multifaceted risk factors (indicators) for COVID-19 infection in our geospatial model. This means that although the city has a high degree of connectivity, it is also characterised by higher scores for information penetration, knowledge of disease prevention and hand hygiene practices that could help slow the rate of infection in the city [13]. Third, Addis Ababa has relatively better and more consistent test-and-contact tracing practices than in other parts of the country, which means that the chance of new infections being detected in the city are much greater than in other parts of the country [5]. Future efforts to expand testing and tracing practices in other areas of the county are likely to increase the extent of confirmed infections in those other areas. Recent studies have demonstrated that effective social distancing and contact tracing can significantly reduce the rate of infection [33,34]. These interventions should be strengthened and expanded to areas identified as high risk in this study.

Our study also showed that the risk for severe cases of COVID-19 infection is high in most parts of the Amhara and Oromia regions. This may be due to the high prevalence of NCDs, which are associated with severe cases of COVID-19. Previous studies have revealed that the burden of NCDs, such as DM and hypertension, is high in these two regions [24,35,36]. With the COVID-19 epidemic evolving rapidly in Ethiopia, fast-tracked public health education and interventions to control and limit the spread of infection should be strengthened. In addition, to address severe cases and potential mortality risks, strengthening and expanding tailored health care services, including ICUs in high-risk areas, are crucial to prevent the exacerbation of the COVID-19-induced public health crisis.

Our study also revealed that peripheral areas sharing international borders are likely to see a greater number of COVID-19-related deaths. The high risk of death along the border areas might be attributed to low preparedness in case management and weak health care systems. In contrast, although the Amhara and Oromia regions may have more severe cases, the preparedness indicators show that the regions are better equipped to cope with these anticipated severe cases. However, our study suggests that additional preparation and capacity strengthening are needed mainly in the following areas: emergency response systems, case detection and capacity to care for patients. It is also equally important that hospitals have adequate supplies, health care personnel and life-saving medical intervention resources. Despite encouraging efforts by the Ethiopian government and stakeholders to prepare the health care system for the pandemic, the existing health care services in the country may face unprecedented challenges and crises due to the surge of patients that will require hospitalisation and ICU services at the same time. This can, however, be eased by implementing public health and social measures at the individual, community, and public authority levels to prevent infections and subsequent health, economic, and social consequences [37]. Studies have shown that implementing non-pharmaceutical interventions, especially during the early stages of infection, can reduce transmission and subsequent potential public health and economic crises [38].

Further, we found notable regional disparities in health system preparedness and readiness levels in the country. This is important because if the health care system is well equipped to prevent and mitigate the spread of the pandemic, then the mortality rate from the disease can be markedly reduced [39]. However, we observed that Ethiopia's border regions (i.e., Benishangul-Gumuz, Gambella, Afar, and Somali) have low preparedness levels. Nevertheless, comparisons need to be treated with care because Ethiopia in general has very low doctor-to-resident (1 doctor per 10,000 people) and hospital bed-to-population (3 hospital beds per 10,000 people) ratios [40]. Several long-, medium- and short-term strategies, can be implemented to mitigate these problems: (i) providing short-term training for potential actors such as community leaders, students, and traditional and modern medical practitioners, (ii) recruiting additional staff to work in COVID-19-related heath care, (iii) establishing COVID-19 clinics and changing outpatient rooms to emergency clinics, (iv) collaborating with private hospitals ahead of surges so that they can be used in the case such surges occur, and (v) establishing mobile clinics and temporary admission rooms in highly vulnerable areas.

Policy implications

The findings of this study provide vital evidence that can inform policymakers in allocating resources and guide health professionals in responding to and preventing COVID 19 infections. With the limited resources that Ethiopia has, the measures implemented to limit the spread of COVID-19 infection should be sustainable, should be tailored and should consider the national and local contexts, such as varying socio-economic conditions. Strengthening the health care system and improving the capacity of health extension workers (HEWs) needs to be top priority. The national measures implemented in Ethiopia seem to be skewed towards procurement-heavy interventions, such as establishing isolation facilities and obtaining personal protective equipment and ventilators. While these interventions are critical, community response should never be a secondary intervention. In this regard, the delayed engagement of communities and HEWs hinders an effective outbreak response. Overall, it is crucial that the Ethiopian government and all stakeholders strengthen their ongoing efforts to prevent and slow the infection rate.

Strength and Limitations

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

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

Conclusions

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

Declaration

Authors' contributions

KAA, YAG, YK, DMF, DNK, YAM, HAG, MB, MDM, AAA, and BAD conceptualised the study. KAA designed and run the geospatial analysis. YAG involved in the data analysis. KAA, YAG, DMF, DNK, and YAM drafted the manuscript. HAG, MB, AAA_1, MDM, BAD, SA, AA, AAA_2, WMB, KTG, TG, ATG, LGG, AG, HTK, GDK, CTL, LBM, AAM, HM, HGT, AGT, FT, BLW, and YK Critically reviewed and revised the drafted manuscript. KAA, YK, and AHM were responsible for quality control of accuracy and integrity of data. All the authors interpreted the data. All authors contributed to the final draft and finally approved it to be published. All authors agreed to be accountable for all aspects of the work for any issue related to the accuracy or integrity of any part of the work. The corresponding author attests that all listed authors meet authorship criteria and that no others meeting the criteria have been omitted.

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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
Demographic indicators		
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 >=65 years divided by the total number of people participated in the survey
Socio-economic indicators		
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
Connectivity indicators		
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
Climatic indicators		
Mean temperature	WorldClime	Annual mean environmental air temperature (°C)
Mean precipitation	WorldClime	Annual mean rainfall (mm)
Wind speed	WorldClime	Annual mean wind speed (m s^{-1})
Solar radiation	WorldClime	Annual mean solar radiation (kJ m^{-2} day^{-1})
Water vapour pressure	WorldClime	Annual mean water vapour pressure (kPa), equivalent to absolute humidity.
Behavioural indicators		
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
Disease prevention knowledge indicators		
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

Mobile phone ownership	EDHS 2016	Total number of people have no access to mobile phone divide by the total number of survey participants
Knowledge toward HIV	EDHS 2016	Number of people with poor knowledge towards HIV divided by the total number of people participating in the survey
Hand hygiene indicators		
Travel time to water sources	EDHS 2016	Mean travel time in minutes to obtain water source (i.e. access to a water source)
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
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
Comorbidities indicators		
HTN	EPHI STEPS	Total number of people with HTN divided by the total number of survey participants
DM	EPHI STEPS	Total number of people with DM divided by the total number of survey participants
BMI	EPHI STEPS	Mean body mass index
CVD	EPHI STEPS	Total number of people with heart disease divided by total number of people in the survey
Cholesterol	EPHI STEPS	Mean cholesterol level
HIV prevalence	EDHS 2016	Total number of people with HIV divided by survey participants
TB SMR	EMOH	Standardized morbidity ratio (SMR) as measured by observed number of TB cases divided by the expected number of TB cases
Service availability and readiness indicators		
Health care access problem	EDHS 2016	Difficulty of getting advice or treatment due to lack of money, or distance to a health facility
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
ICU availability	EPHI SARA	Availability of Critical Care Services (ICU) in hospitals
CRD readiness index	EPHI SARA	Availability of specific services for Chronic respiratory disease (CRD) diagnosis, management, and follow up
TB readiness index	EPHI SARA	Availability of specific services for tuberculosis diagnosis, management, and follow up
Diabetes readiness index	EPHI SARA	Availability of specific service for diabetes diagnosis and management and follow up

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

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

Indicators	Risk factors	Evidence	References
Demographic indicators			
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 [41]
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 [23]
Socio-economic indicators			
Population density	Infection	High population density is a risk factor for COVID-19 infection	Ahmadi M [42]
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 [43]
Low wealth index	Infection	Socio-economic deprivation (RR 1.26 per SD increase in Townsend Index) associated with COVID -19 infection	Ho FK [44]
Connectivity indicators			
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 [45]
Proximity to national borders	Infection	Cross country moment is a risk factor for COVID-19 transmission and importation	Chinazz M [46]
Distance to major roads	Infection	Spread of COVID-19 was correlated positively with public transportation per capita	Tian H [47]
Climatic indicators			
Mean temperature	Infection	Low ambient temperatures are associated with more rapid spread of COVID-19	Holtmann M [48]
Mean precipitation	Infection	Countries with higher rainfall measurements showed an increase in COVID-19 transmission	Sobral MFF[49]
Wind speed	Infection	Areas with low values of wind speed associated with a high rate of COVID-19 infection	Ahmadi M [42]
Solar radiation	Infection	Areas with low values of solar radiation exposure associated with a high rate of COVID-19 infection	Ahmadi M [42]
Water vapour pressure	Infection	High humidity reduces the transmission of COVID-19. Water vapour pressure negatively correctly with COVID-19 infection.	Wang J [50], Li J[51]
Behavioural indicators			
Khat chewing	Severity	There is an association between khat chewing and chronic illness such as HIV infection, elevated diastolic blood pressure	Basker GV[52]
Alcohol drinking	Severity	Patients with alcohol use disorders at increased risk for COVID-19	Testino G [22]
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 [23]
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 [43]
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 [43]
Disease prevention knowledge indicators			
Adult illiteracy rate	Infection	Adult learning education is a tool to contain the COVID-19 pandemics	Lopes H [53]
Access to listen to radio	Infection	Access to media is a crucial factor in public health responses to an outbreak	Ayedee N[54]
Access to watch TV	Infection	Media (Television) has a significant role in creating a positive atmosphere in COVID-19	Ayedee N[54]
Mobile phone ownership	Infection	Mobile phone calls and text messages help for the diagnosis, management, and control of infectious diseases	Wood S [55]
Knowledge towards HIV	Infection	Knowledge towards an infectious disease such as HIV can help to control the transmission of the diseases	Bertozzi S[56]
Hand hygiene indicators			

Travel time to water sources	Infection	Adequate water supply is essential for the control of COVID-19 infection	WHO [57]
Place for handwashing	Infection	Hand washing is recommended by WHO for the control of COVID-19 infection	WHO [58]
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 [58]
Comorbidities indicators			
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 [23]
DM	Severity	Death from COVID-19 was associated with DM (HR 1.50, 95%CI: 1.40-1.60) 1.50	Williamson E [41]
BMI	Severity	Death from COVID-19 was associated with higher BMI (HR 1.27, 95%CI: 1.18-1.36)	Williamson E [41]
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 [23]
HIV prevalence	Severity	Mortality from COVID-19 was associated with immunosuppression (HR 1.69, 95%CI: 1.21-1.34)	Williamson E [41]
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 [23]
Service availability and readiness indicators			
Health care access problem	Death	Healthcare resource availability is associated with COVID-19 mortality	Ji Y [7]
General service readiness	Death	General health service preparedness is essential for combating the COVID-19 pandemic	WHO [59]
ICU availability	Death	Lack of critical care unite increase the risk of death from COVID-19	Murthy S [60]
CRD readiness	Death	Cardiorespiratory disease (CRD) is a risk factor for COVID-19 related death	Zheng Z [23]
TB readiness	Death	TB determinants outcomes of patients with COVID-19	Tadolini M [61]
Diabetes readiness	Death	Diabetes affects the prognosis of patients with COVID-19	Zheng Z [23]

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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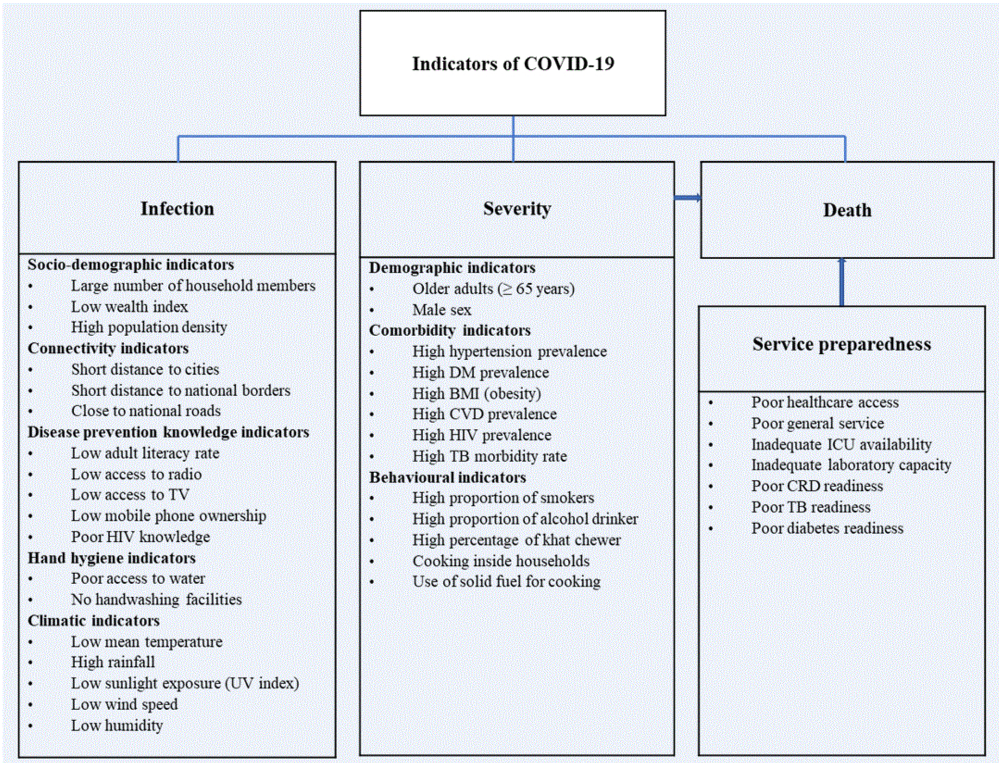

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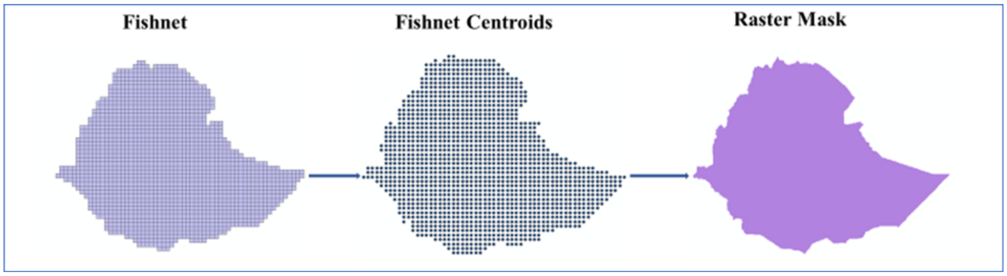

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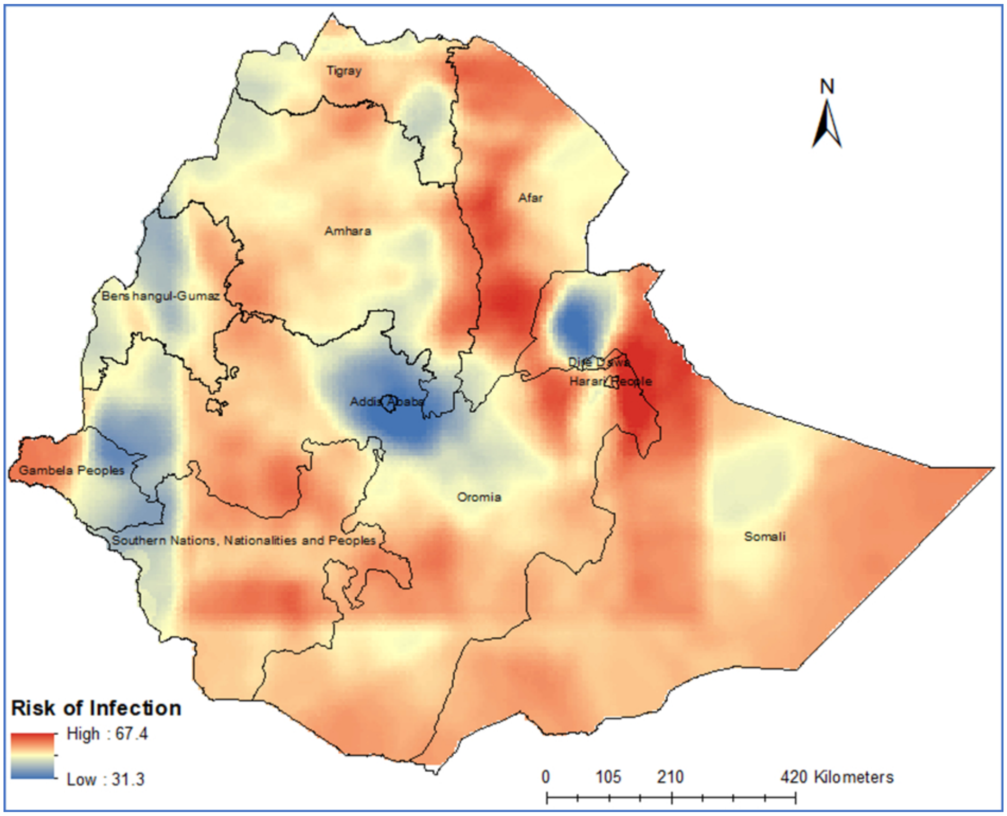

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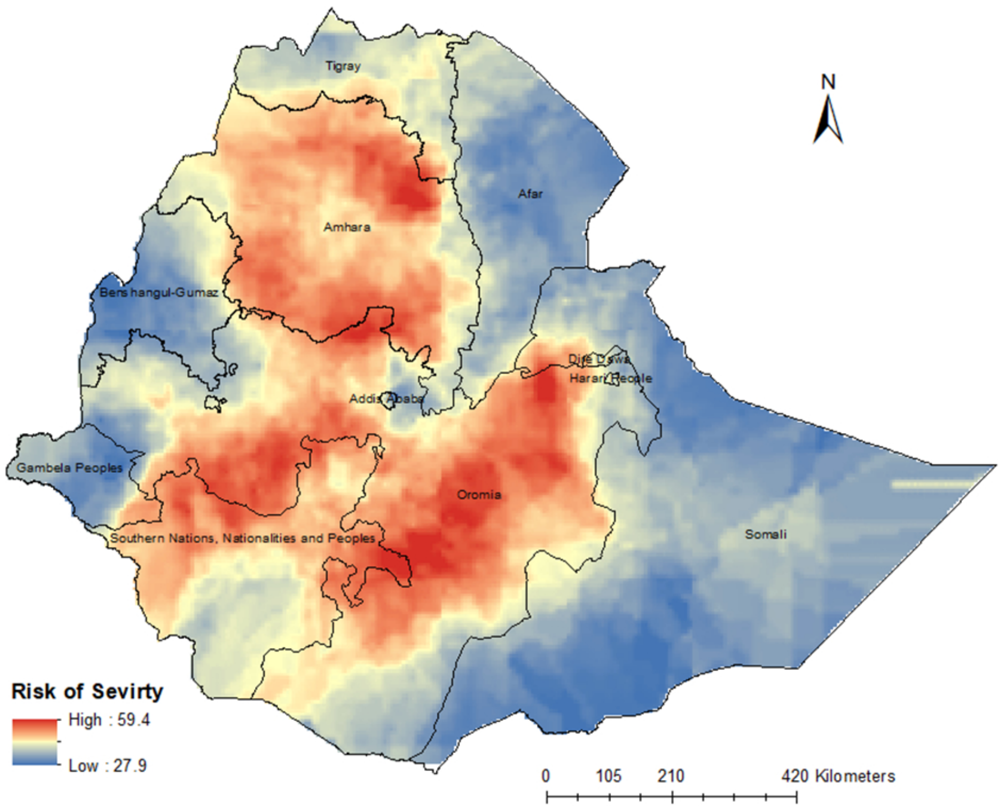

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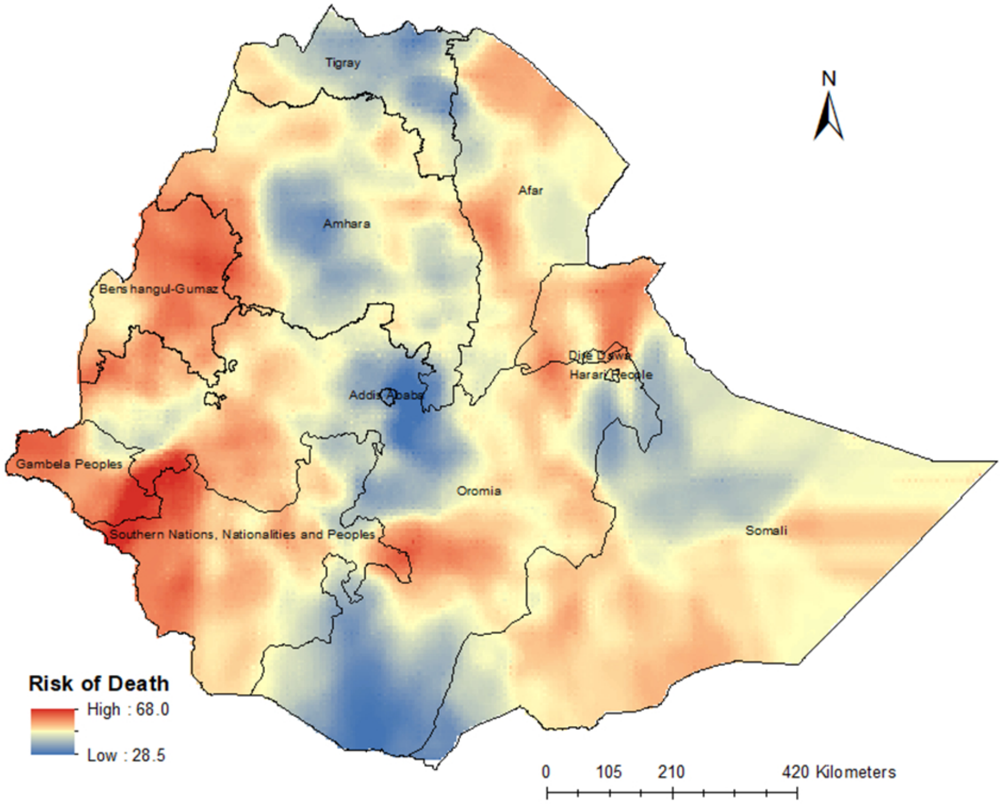

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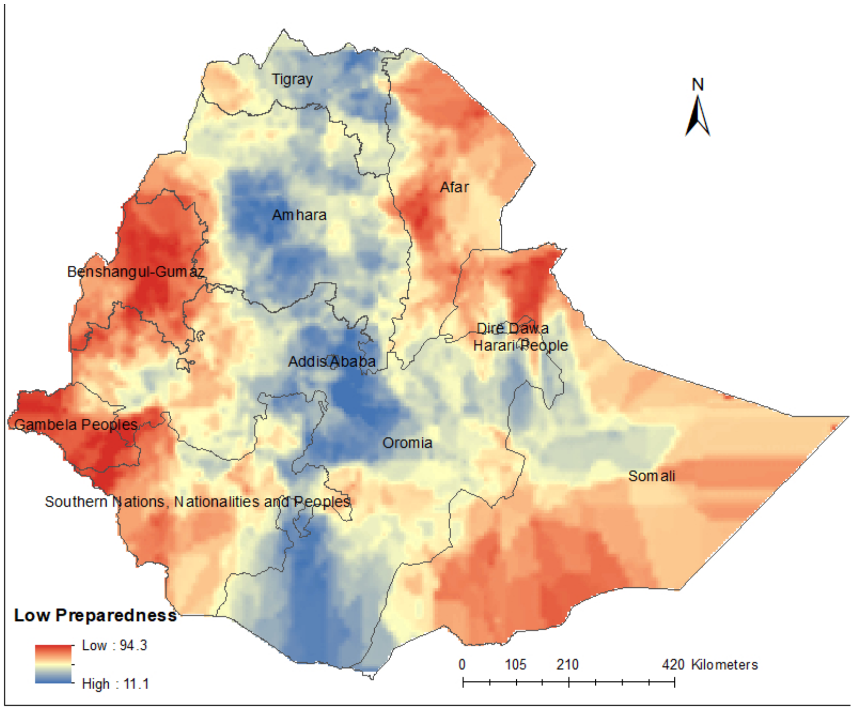

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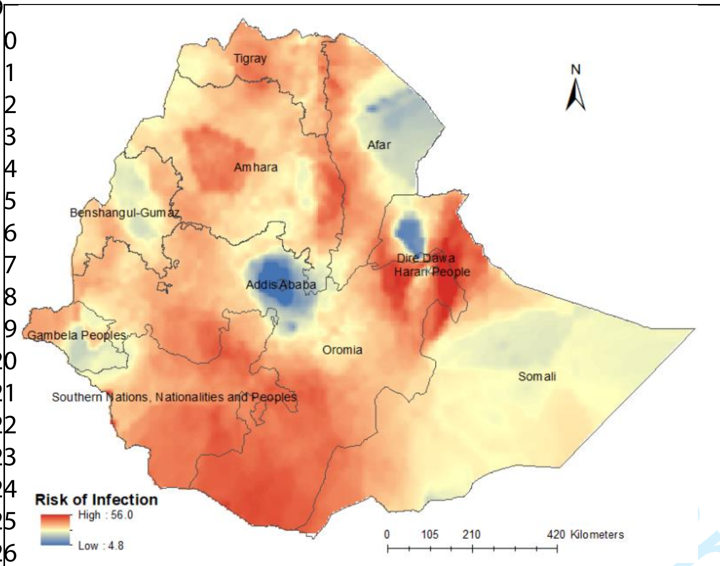
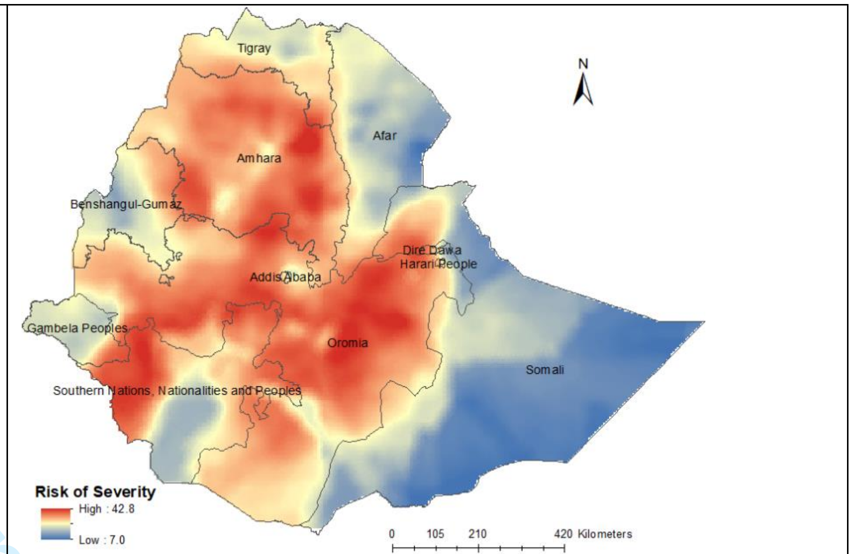
Supplemental Information

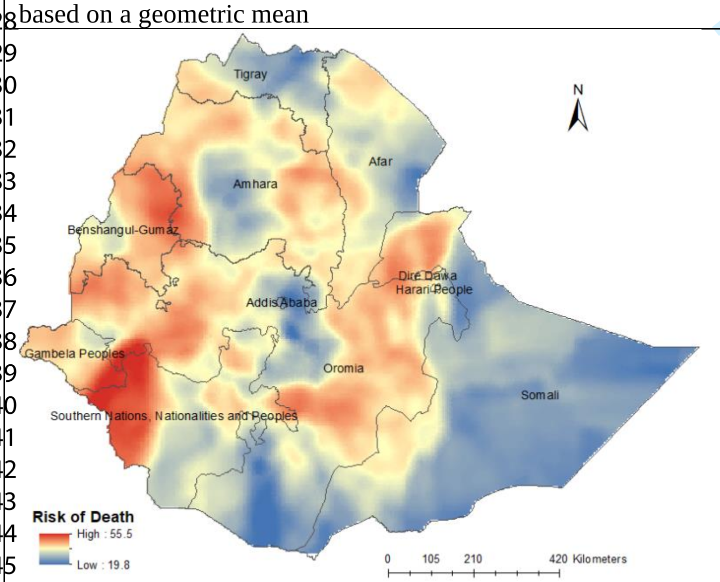
Supplemental Figure 1: Vulnerability maps of COVID-19 infection, severity, preparedness, and death in Ethiopia, created based on a geometric mean as alternative aggregation method.



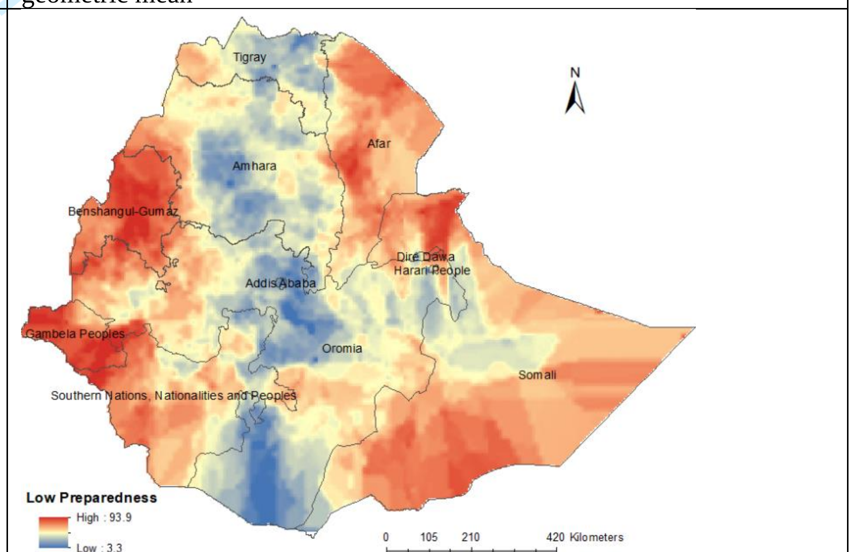
S Figure 1a. COVID-19 infection risk map in Ethiopia, created based on a geometric mean



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

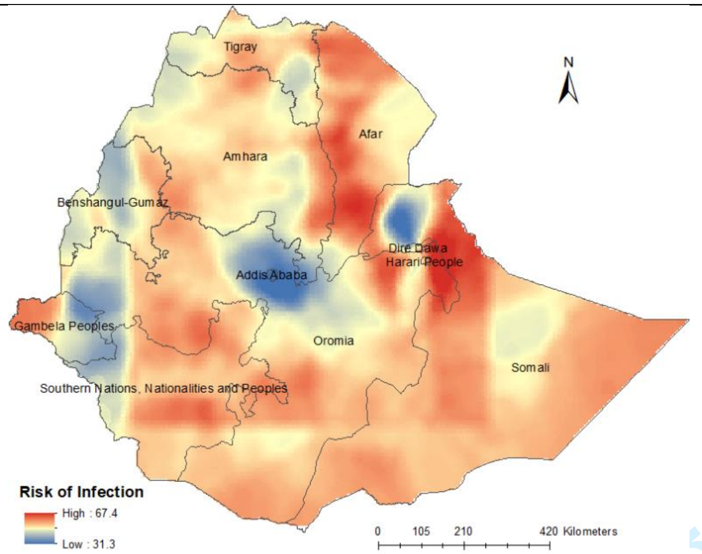


S Figure 2c. Death risk map of COVID-19 in Ethiopia, created based on a geometric mean

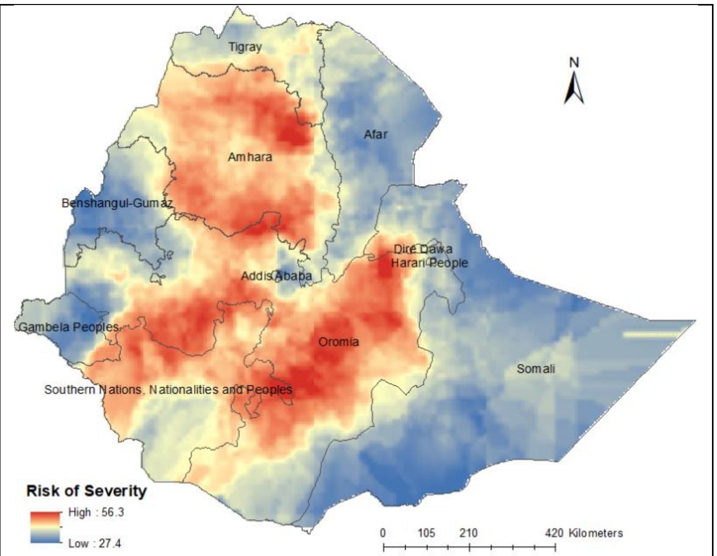


S Figure 3d. Service preparedness map of COVID-19 in Ethiopia, created based on a geometric mean

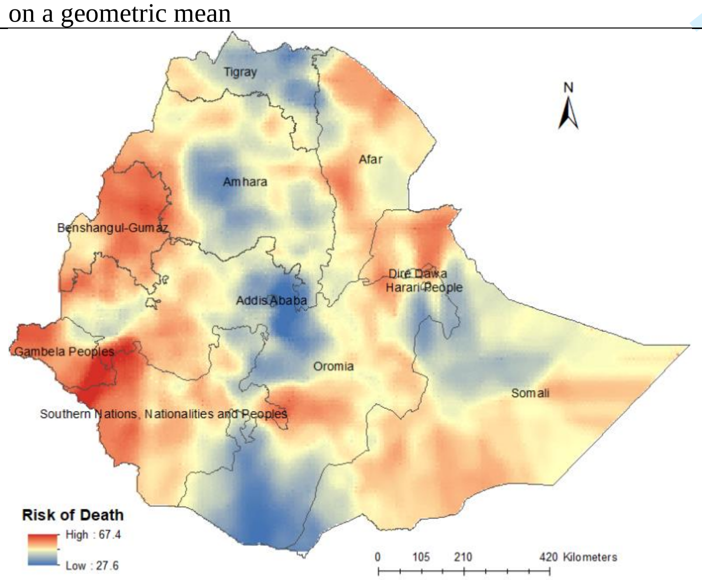
Supplemental Figure 2: Vulnerability maps of COVID-19 infection, severity, preparedness, and death in Ethiopia, created based on a principal component analysis (PCA) as alternative aggregation method.



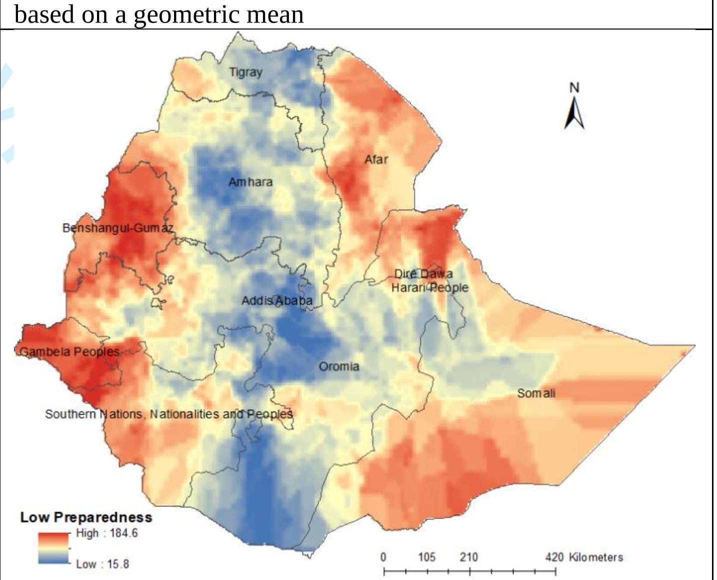
S Figure 2a. COVID-19 infection risk map in Ethiopia, created based on a geometric mean



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

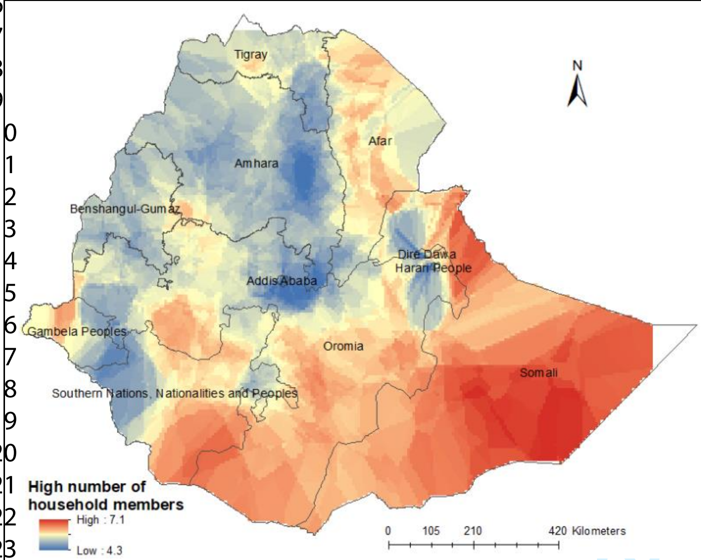


S Figure 2c. Death risk map of COVID-19 in Ethiopia, created based on a geometric mean

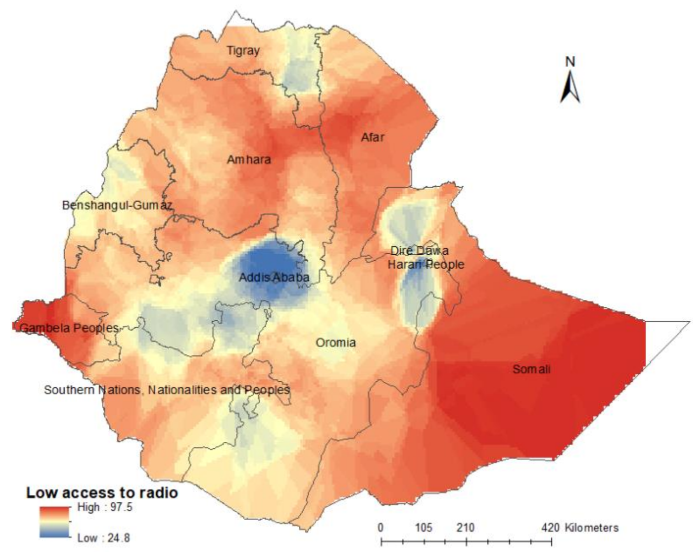


S Figure 2d. Service preparedness map of COVID-19 in Ethiopia, created based on a geometric mean

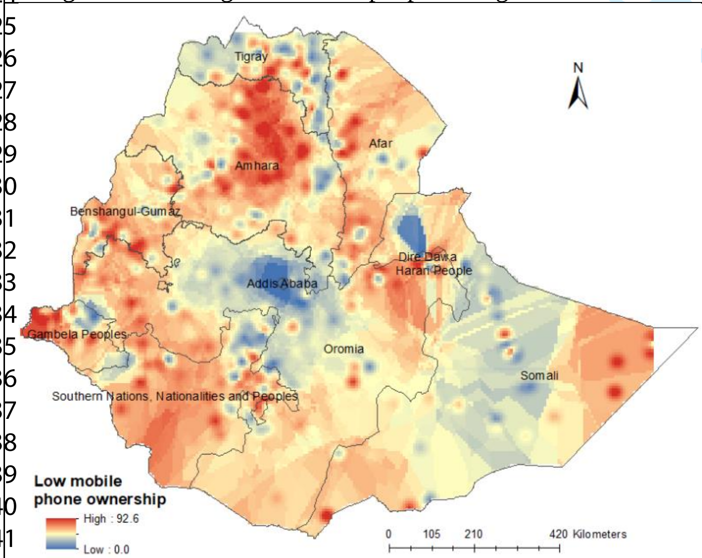
Supplemental Figure 3: Selected indicators showing the risk of COVID-19 infection in Ethiopia



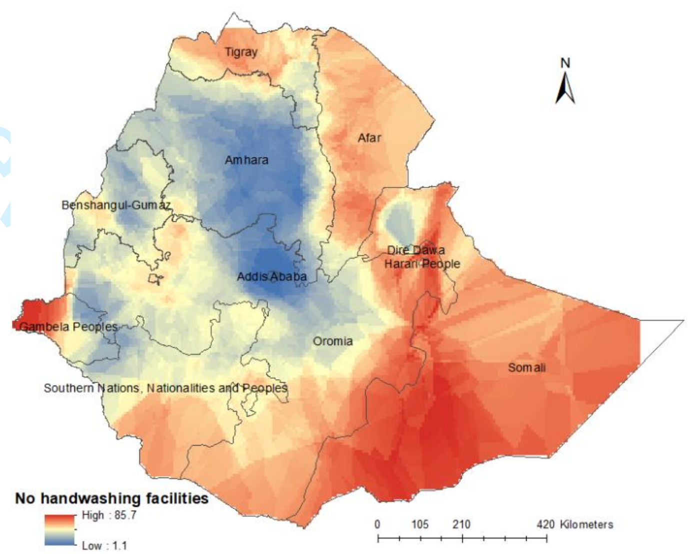
S Figure 3a. Average number of people living in a house



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

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

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Abstract

Background: COVID-19 has caused a global public health crisis affecting most countries, including Ethiopia, in various ways. This study maps the vulnerability to infection, case severity, and likelihood of death from COVID-19 in Ethiopia.

Methods: Thirty-eight potential indicators of vulnerability to COVID-19 infection, case severity and likelihood of death, identified based on a literature review and the availability of nationally representative data at a low geographic scale, were assembled from multiple sources for geospatial analysis. Geospatial analysis techniques were applied to produce maps showing the vulnerability to infection, case severity, and likelihood of death in Ethiopia at a spatial resolution of 1 km X 1 km.

Results: This study showed that vulnerability to COVID-19 infection is likely to be high across most parts of Ethiopia, particularly in the Somali, Afar, Amhara, Oromia, and Tigray regions. The number of severe cases of COVID-19 infection requiring hospitalisation and intensive care unit admission is likely to be high across Amhara, most parts of Oromia and some parts of the Southern Nations, Nationalities, and Peoples' Region. The risk of COVID-19-related death is high in the country's border regions, where public health preparedness for responding to COVID-19 is limited.

Conclusion: This study revealed geographical differences in vulnerability to infection, case severity, and likelihood of death from COVID-19 in Ethiopia. The study offers maps that can guide the targeted interventions necessary to contain the spread of COVID-19 in Ethiopia.

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.

Introduction

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

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

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

Methods

Study area

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

Data sources and variable selection

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

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

Connectivity indicators, which measure the population-level vulnerability to infection, were also captured using distance and time-bounded markers. Specifically, average travel time (measured in minutes) to the nearest city and proximity to international borders (measured in kilometres) were included to measure each area's level of susceptibility to infection. Data on travel time to the nearest city, obtained from the University of Oxford's Malaria Atlas Project (MAP), were used to quantify the accessibility of an area to high-density urban centres at a resolution of 1 km×1 km [14]. Data on proximity to international borders were obtained from the EDHS spatial data repository and were used to measure [15] the geodesic distance to the nearest international border in kilometres, indicating the risk of cross-border transmission and the spread of COVID-19. Infection rates and the spread of COVID-19 were also positively correlated with the per capita public transportation use rate[16]. Thus, to determine the nearest cross-country road to each location on the map, we obtained and applied data for major roads from the World Bank [17].

It is evident that inadequate knowledge about COVID-19 and a lack of awareness of prevention measures exacerbate community transmission of the disease [18]. Therefore, we extracted data on adult literacy rate, access to media (such as radio, television, and mobile phone messages) and knowledge about other infectious diseases (e.g., HIV) from the EDHS as proxies for knowledge of COVID-19 prevention measures in each area of the country [12]. According to the WHO, maintaining good hand hygiene through regular washing with soap and water is one of the most effective preventative measures for reducing the transmission of COVID-19 [19,20]. Using the same data as above, we also assessed hand hygiene practices, access to water, and the availability of handwashing stations in a household.

Previous studies have shown that underlying chronic comorbidities and behavioural factors such as cigarette, alcohol and khat consumption were associated with more severe COVID-19 infections [21,22]. Data on khat chewing and the alcohol consumption rate were obtained from the EDHS 2016 [12], and data on cigarette smoking were obtained from the Ethiopia Public Health Institute STEP wise approach to Surveillance (STEPS) study [23]. The STEP survey was also used to measure the prevalence of selected non-communicable diseases (NCDs) such as hypertension, heart disease, and diabetes mellitus (DM).

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

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

Geospatial data processing

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

Statistical analyses

Geostatistical techniques such as spatial autocorrelation, kriging and semivariograms were applied to create a prediction grid surface from a scattered set of points [27]. Kriging assumes that the distance or direction between sample points reflects a spatial correlation that can be used to explain variation in the surface [28]. Since the variables had different units of measurement, the datasets were normalised using a min-max approach to a standard scale ranging from 0 (the lowest risk) to 100 (the highest risk) [29]. After normalisation, the indicators were averaged to create a vulnerability index, measuring the risk of COVID-19 for each geo-location [30]. The vulnerability indices were calculated separately for each domain, namely, the vulnerability to infection, case severity, and likelihood of death from COVID-19. The three domains were then averaged to produce the overall COVID-19 vulnerability index. Given that COVID-19 is a new virus, there is a lack of evidence for assigning weights for each indicator. Hence, equal weight was given to all indicators when calculating the arithmetic mean for the vulnerability indices. However, we also used principal component analysis (PCA) and geometric mean methods, which produced broadly similar results (Supplemental Figure 2 and Supplemental Figure 3). The risk maps were then created separately for infection, case severity, service preparedness, and death from the composite index using geostatistical tools in ArcGIS. All data transformations were performed in R [31]. All items included in this study are available in the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) Statement checklist (Supplemental Table 1).

Ethics aspects: Ethical approval was not required for this study as it was based on publicly available data.

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

Funding: There was no funding source for this study.

Results

Vulnerability to COVID-19 infection

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

Vulnerability to severe cases of COVID-19 infection

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

Vulnerability to death from COVID-19

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

Discussion

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

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

Despite the disproportionately high infection rate in Addis Ababa at present (Supplemental Figure 5), we found that the risk of COVID-19 infection is likely to become rather high in other regions. The high infection rate in Addis Ababa at this initial stage is expected, given that Addis Ababa is a major travel hub and Bole International Airport, located in the city, is one of the largest international airports in Africa. This exposes the city to a higher risk of imported cases and, subsequently, to an early surge of infections, leaving the areas outside the city at a higher risk of later infection. Second, we considered multifaceted risk factors (indicators) for COVID-19 infection in our geospatial model. This means that although the city has a high degree of connectivity, it is also characterised by higher scores for information penetration, knowledge of disease prevention and hand hygiene practices that could help slow the rate of infection in the city [12]. Third, Addis Ababa has relatively better and more consistent test-and-contact tracing practices than in other parts of the country, which means that the chance of new infections being detected in the city are much greater than in other parts of the country [5]. Future efforts to expand testing and tracing practices in other areas of the county are likely to increase the extent of confirmed infections in those other areas. Recent studies have demonstrated that effective social distancing and contact tracing can significantly reduce the rate of infection [32,33]. These interventions should be strengthened and expanded to areas identified as high risk in this study.

Our study also showed that the risk for severe cases of COVID-19 infection is high in most parts of the Amhara and Oromia regions. This may be due to the high prevalence of NCDs, which are associated with severe cases of COVID-19. Previous studies have revealed that the burden of NCDs, such as DM and hypertension, is high in these two regions [23,34,35].

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

Despite encouraging efforts by the Ethiopian government and stakeholders to prepare the health care system for the pandemic, the existing health care services in the country may face unprecedented challenges and crises due to the surge of patients that will require hospitalisation and ICU services at the same time. This can, however, be eased by implementing public health and social measures at the individual, community, and public authority levels to prevent infections and subsequent health, economic, and social consequences [36]. Studies have shown that implementing non-pharmaceutical interventions such as physical distancing, mask use, and closure of schools, especially during the early stages of infection, can reduce transmission and subsequent potential public health and economic crises [37].

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

Strength and Limitations

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

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

Conclusions

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

Declaration

Authors' contributions

KAA, YAG, YK, DMF, DNK, YAM, HAG, MB, MDM, AAA, and BAD conceptualised the study. KAA designed and run the geospatial analysis. YAG involved in the data analysis. KAA, YAG, DMF, DNK, and YAM drafted the manuscript. HAG, MB, AAA_1, MDM, BAD, SA, AA, AAA_2, WMB, KTG, TG, ATG, LGG, AG, HTK, GDK, CTL, LBM, AAM, HM, HGT, AGT, FT, BLW, and YK Critically reviewed and revised the drafted manuscript. KAA, YK, and AHM were responsible for quality control of accuracy and integrity of data. All the authors interpreted the data. All authors contributed to the final draft and finally approved it to be published. All authors agreed to be accountable for all aspects of the work for any issue related to the accuracy or integrity of any part of the work. The corresponding author attests that all listed authors meet authorship criteria and that no others meeting the criteria have been omitted.

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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
Demographic indicators			
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 >=65 years divided by the total number of people participated in the survey
Socio-economic indicators			
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
Connectivity indicators			
Travel times to cities	MAP	1 km×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
Climatic indicators			
Mean temperature	WorldClime	1 km×1 km	Annual mean environmental air temperature (°C)
Mean precipitation	WorldClime	1 km×1 km	Annual mean rainfall (mm)
Wind speed	WorldClime	1 km×1 km	Annual mean wind speed ($m\ s^{-1}$)
Solar radiation	WorldClime	1 km×1 km	Annual mean solar radiation ($kJ\ m^{-2}\ day^{-1}$)
Water vapour pressure	WorldClime	1 km×1 km	Annual mean water vapour pressure (kPa), equivalent to absolute humidity.
Behavioural indicators			
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

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
Disease prevention knowledge indicators			
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
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
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
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
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
Hand hygiene indicators			
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)
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
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
Comorbidities indicators			
HTN	EPHI STEPS	Latitude and longitude point	Total number of people with HTN divided by the total number of survey participants
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
Service availability and readiness indicators			

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

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

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

Indicators	Risk factors	Evidence	References
Demographic indicators			
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 [40]
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 [22]
Socio-economic indicators			
Population density	Infection	High population density is a risk factor for COVID-19 infection	Ahmadi M [41]
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 [42]
Low wealth index	Infection	Socio-economic deprivation (RR 1.26 per SD increase in Townsend Index) associated with COVID -19 infection	Ho FK [43]
Connectivity indicators			
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 [44]
Proximity to national borders	Infection	Cross country moment is a risk factor for COVID-19 transmission and importation	Chinazz M [45]
Distance to major roads	Infection	Spread of COVID-19 was correlated positively with public transportation per capita	Ayenew B[16].
Climatic indicators			
Mean temperature	Infection	Low ambient temperatures are associated with more rapid spread of COVID-19	Holtmann M [46]
Mean precipitation	Infection	Countries with higher rainfall measurements showed an increase in COVID-19 transmission	Sobral MFF[47]
Wind speed	Infection	Areas with low values of wind speed associated with a high rate of COVID-19 infection	Ahmadi M [41]
Solar radiation	Infection	Areas with low values of solar radiation exposure associated with a high rate of COVID-19 infection	Ahmadi M [41]
Water vapour pressure	Infection	High humidity reduces the transmission of COVID-19. Water vapour pressure negatively correctly with COVID-19 infection.	Wang J [48], Li J[49]
Behavioural indicators			
Khat chewing	Severity	There is an association between khat chewing and chronic illness such as HIV infection, elevated diastolic blood pressure	Basker GV[50]
Alcohol drinking	Severity	Patients with alcohol use disorders at increased risk for COVID-19	Testino G [21]
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 [22]
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 [42]
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 [42]
Disease prevention knowledge indicators			
Adult illiteracy rate	Infection	Adult learning education is a tool to contain the COVID-19 pandemics	Lopes H [51]
Access to listen to radio	Infection	Access to media is a crucial factor in public health responses to an outbreak	Ayedee N[52]
Access to watch TV	Infection	Media (Television) has a significant role in creating a positive atmosphere in COVID-19	Ayedee N[52]
Mobile phone ownership	Infection	Mobile phone calls and text messages help for the diagnosis, management, and control of infectious diseases	Wood S [53]

Knowledge towards HIV	Infection	Knowledge towards an infectious disease such as HIV can help to control the transmission of the diseases	Bertozzi S[54]
Hand hygiene indicators			
Travel time to water sources	Infection	Adequate water supply is essential for the control of COVID-19 infection	WHO [55]
Place for handwashing	Infection	Hand washing is recommended by WHO for the control of COVID-19 infection	WHO [56]
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 [56]
Comorbidities indicators			
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 [22]
DM	Severity	Death from COVID-19 was associated with DM (HR 1.50, 95%CI: 1.40-1.60) 1.50	Williamson E [40]
BMI	Severity	Death from COVID-19 was associated with higher BMI (HR 1.27, 95%CI: 1.18-1.36)	Williamson E [40]
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 [22]
HIV prevalence	Severity	Mortality from COVID-19 was associated with immunosuppression (HR 1.69, 95%CI: 1.21-1.34)	Williamson E [40]
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 [22]
Service availability and readiness indicators			
Health care access problem	Death	Healthcare resource availability is associated with COVID-19 mortality	Ji Y [6]
General service readiness	Death	General health service preparedness is essential for combating the COVID-19 pandemic	WHO [57]
ICU availability	Death	Lack of critical care unite increase the risk of death from COVID-19	Murthy S [58]
CRD readiness	Death	Cardiorespiratory disease (CRD) is a risk factor for COVID-19 related death	Zheng Z [22]
TB readiness	Death	TB determinants outcomes of patients with COVID-19	Tadolini M [59]
Diabetes readiness	Death	Diabetes affects the prognosis of patients with COVID-19	Zheng Z [22]

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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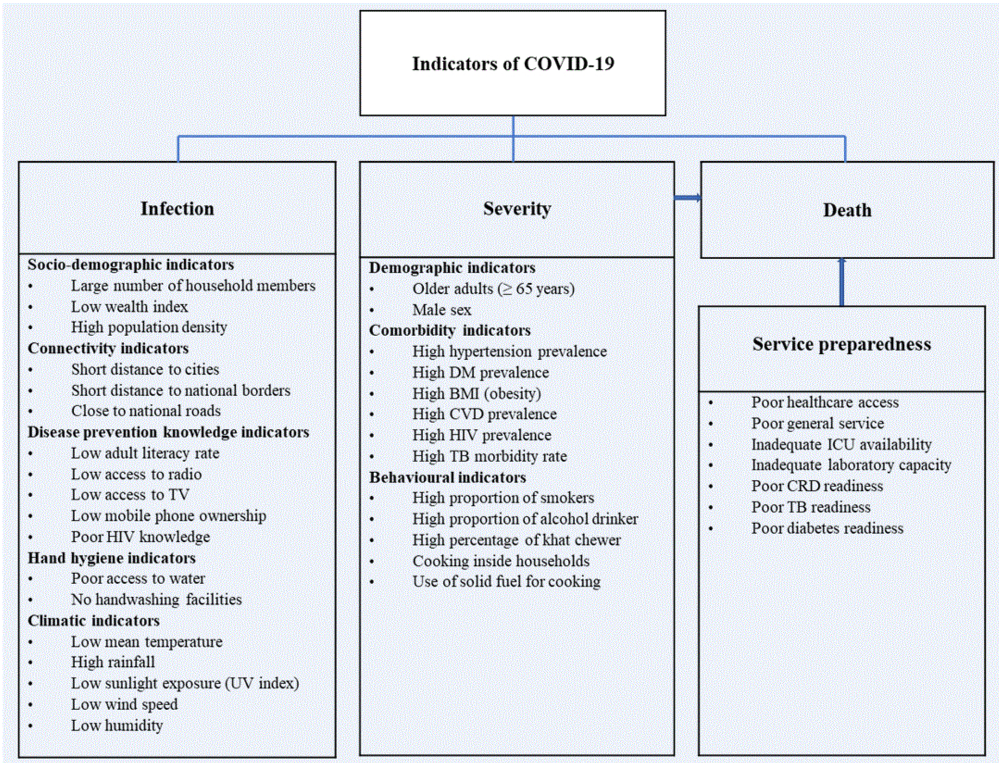

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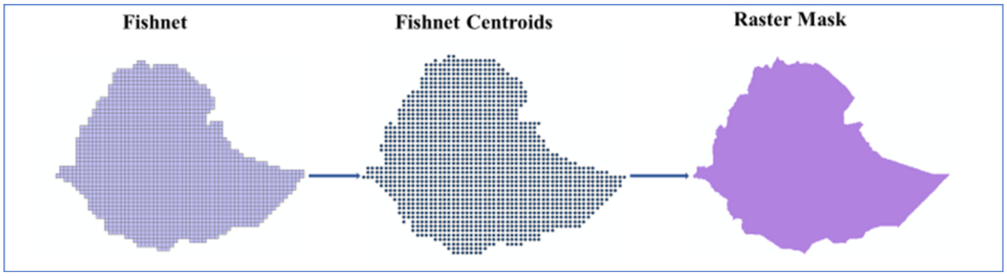

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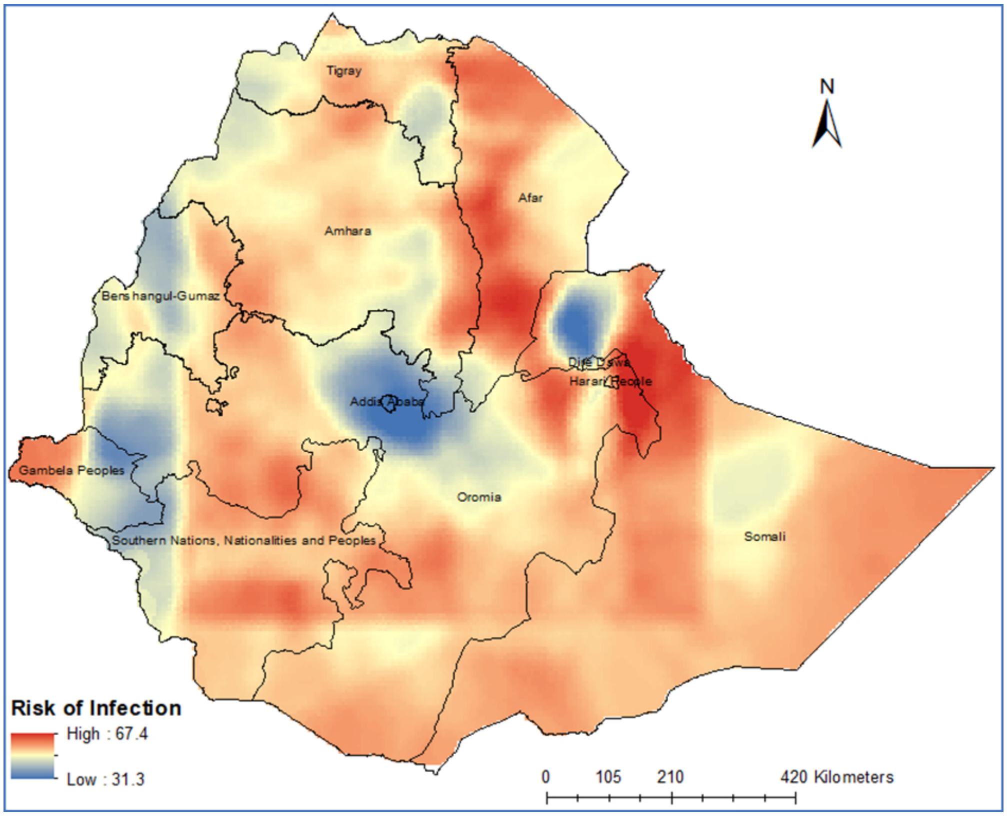

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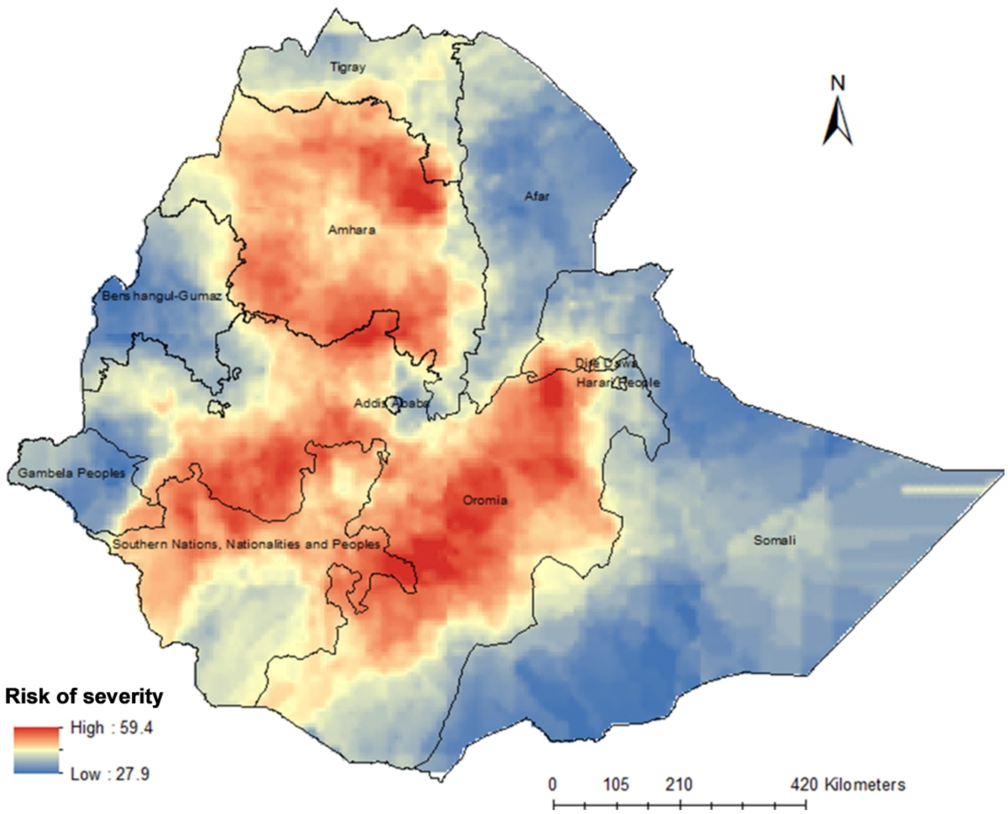
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Harari People
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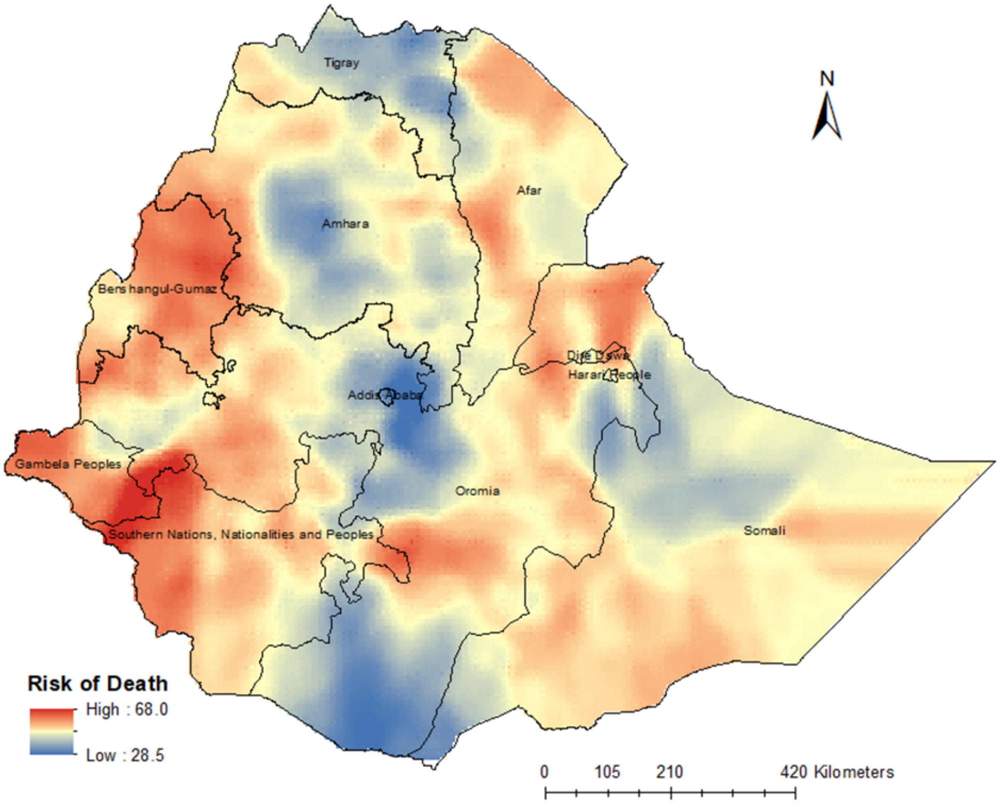
Figure 4



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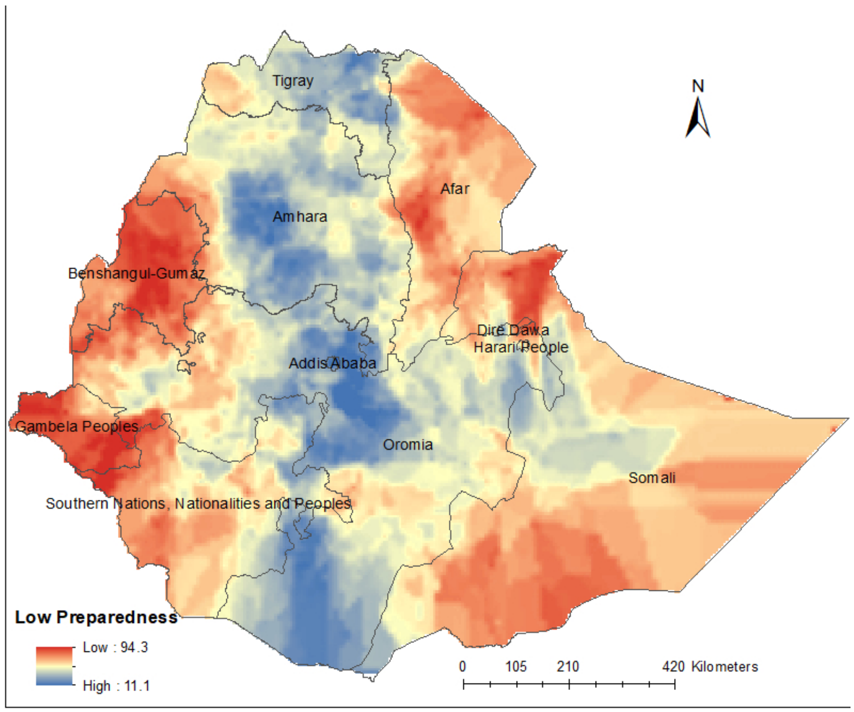

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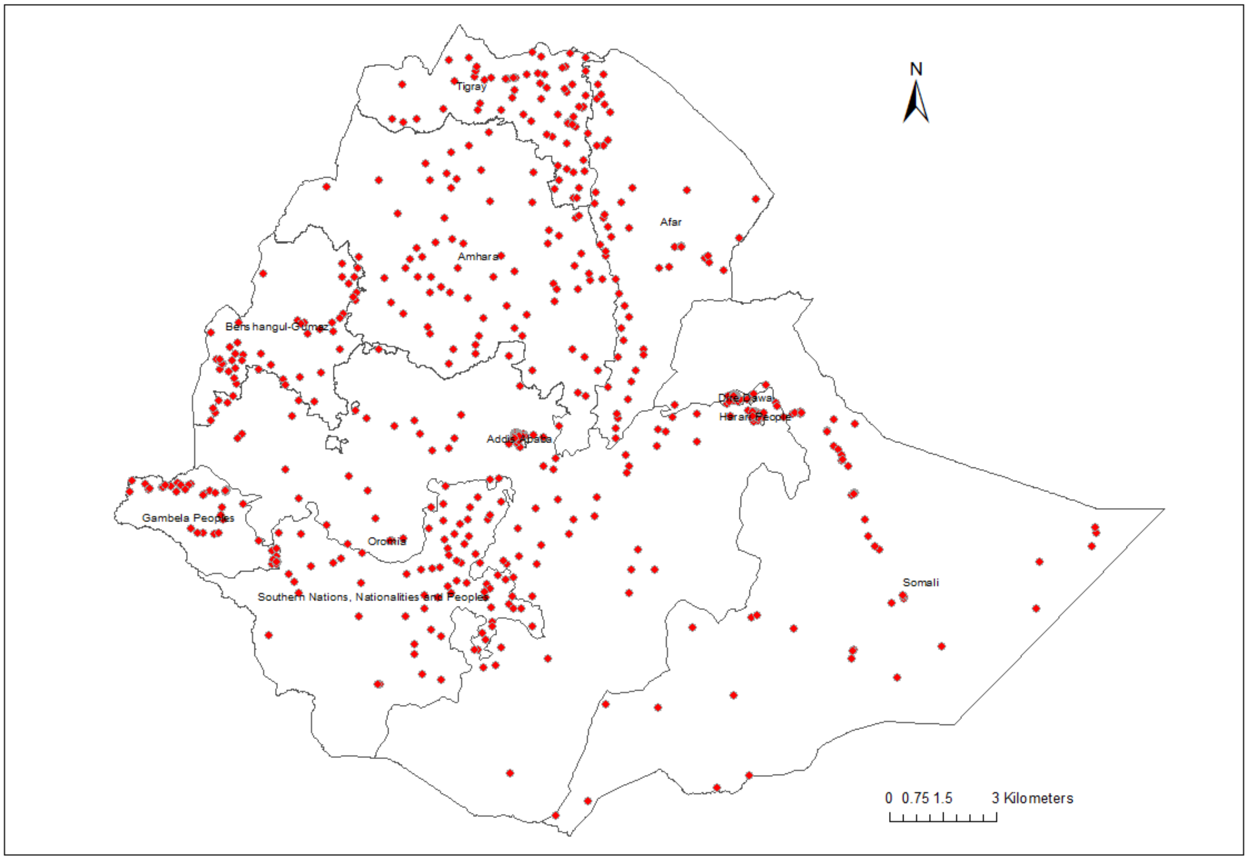
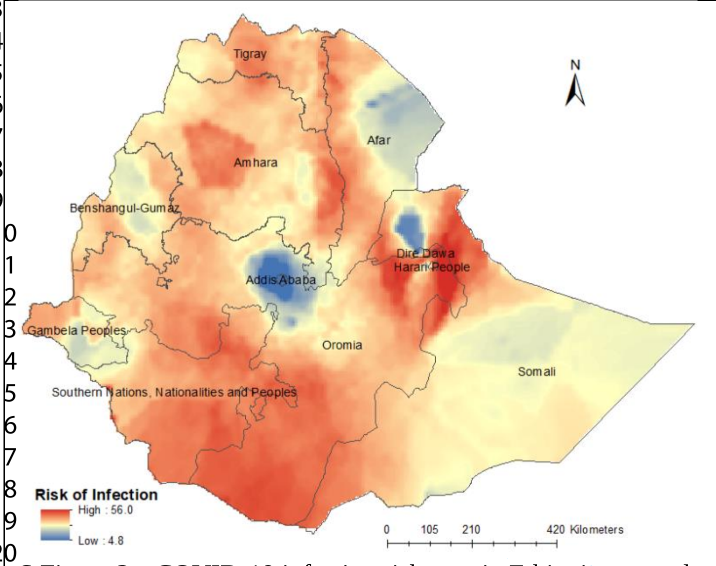
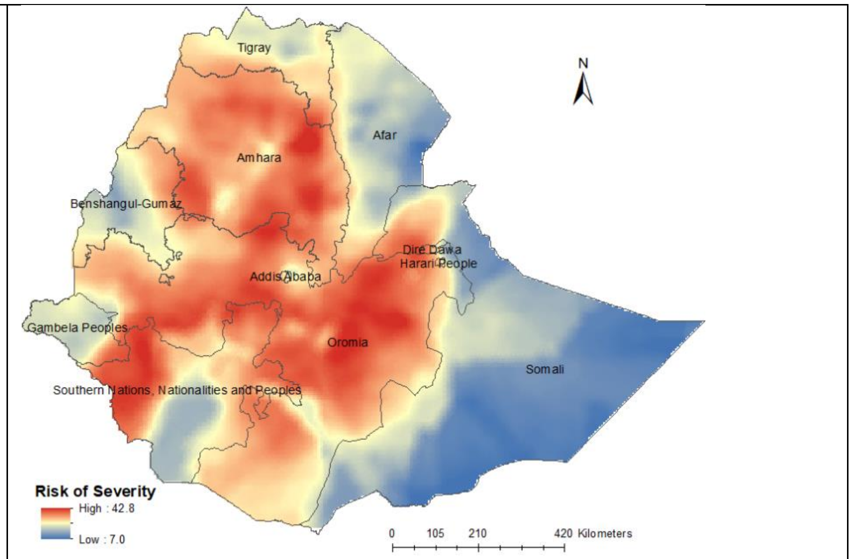
Supplemental Information



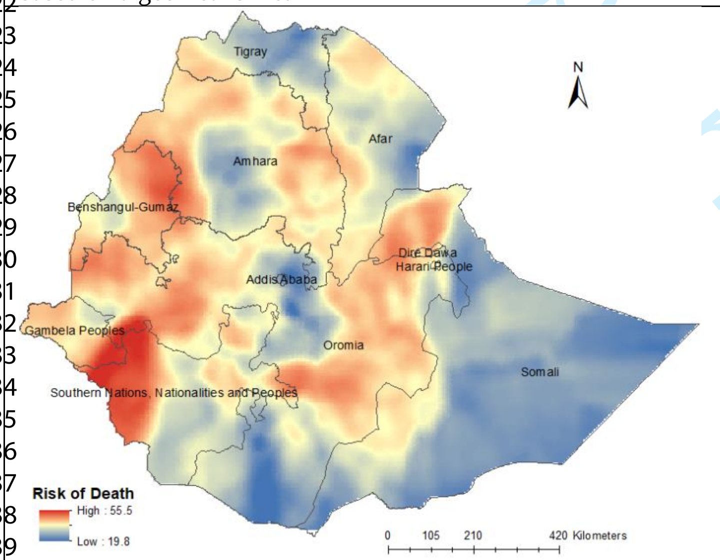
Supplemental Figure 1: A map showing the distribution of the Ethiopia Demographic and Health Survey (EDHS 2016) datapoints.



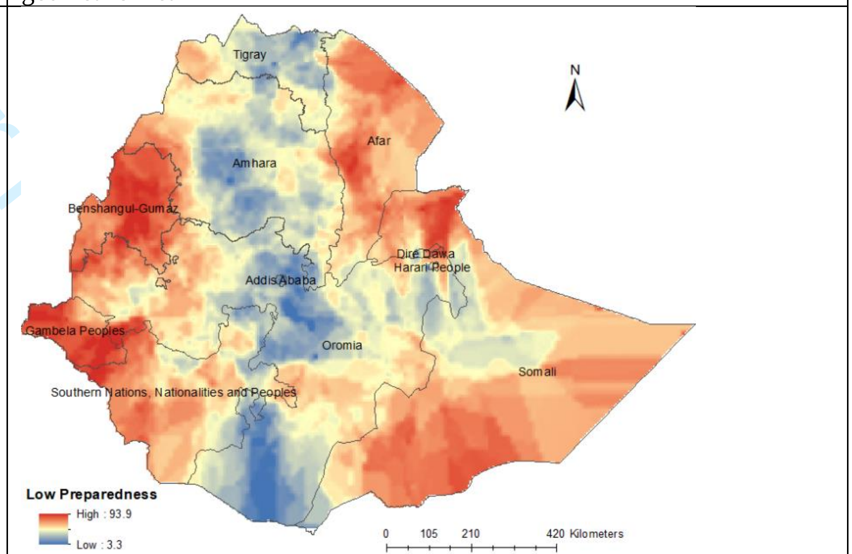
S Figure 2a. COVID-19 infection risk map in Ethiopia, created based on a geometric mean



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

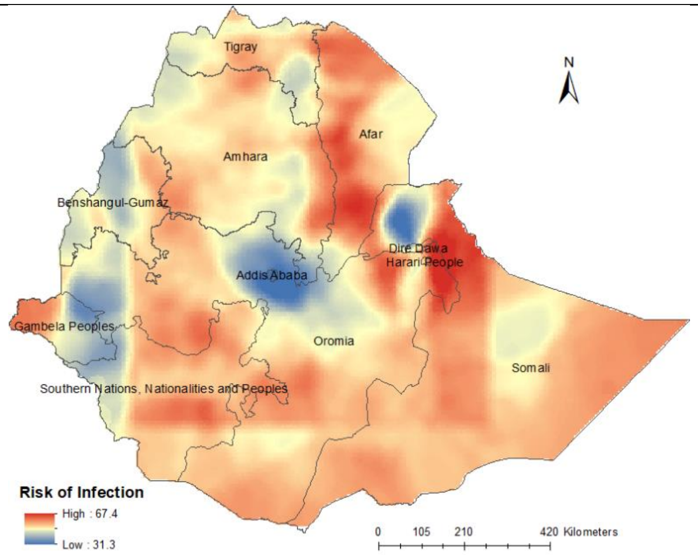


S Figure 2c. Death risk map of COVID-19 in Ethiopia, created based on a geometric mean

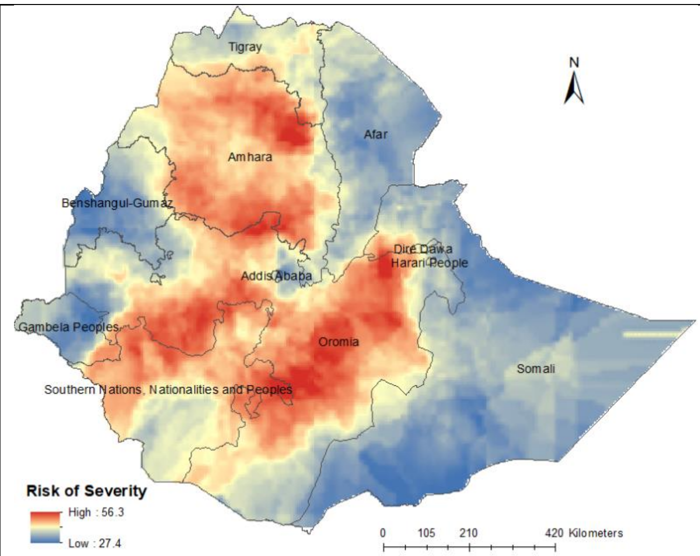


S Figure 2d. Service preparedness map of COVID-19 in Ethiopia, created based on a geometric mean

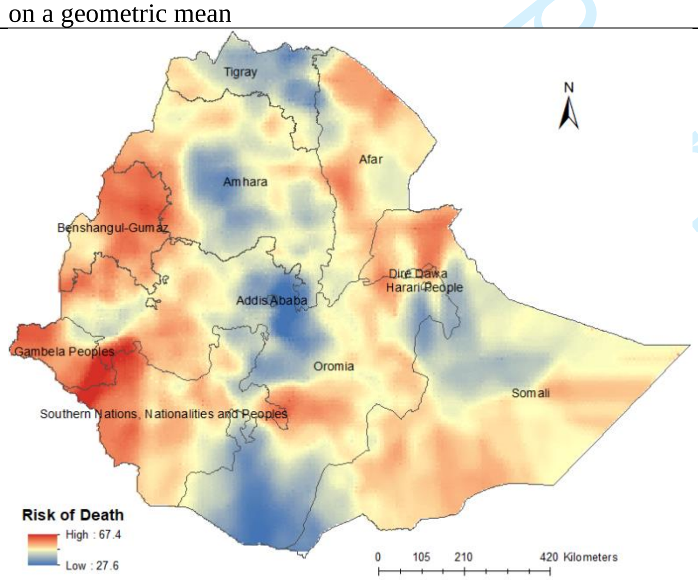
Supplemental Figure 2: Vulnerability maps of COVID-19 infection, severity, preparedness, and death in Ethiopia, created based on a geometric mean as alternative aggregation method.



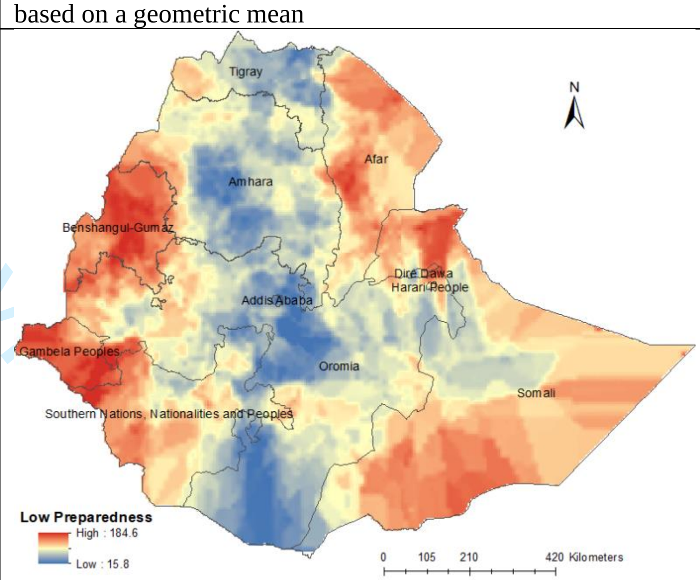
S Figure 3a. COVID-19 infection risk map in Ethiopia, created based on a geometric mean



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

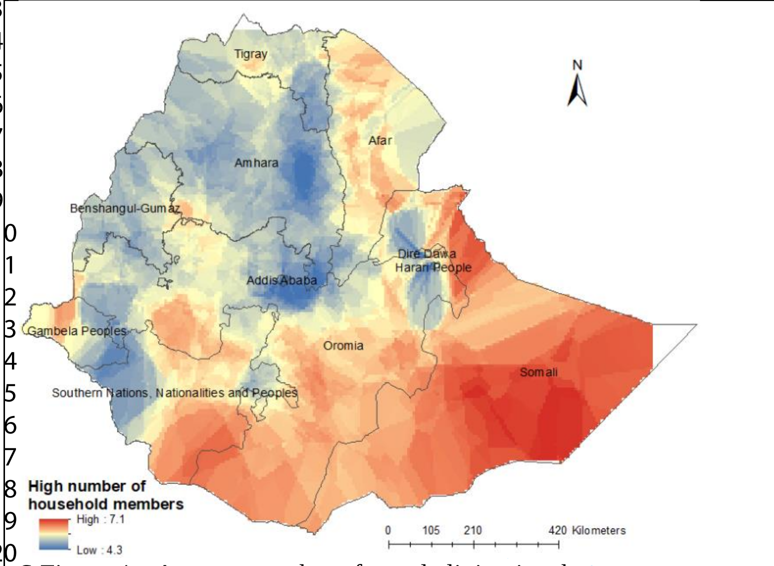


S Figure 3c. Death risk map of COVID-19 in Ethiopia, created based on a geometric mean

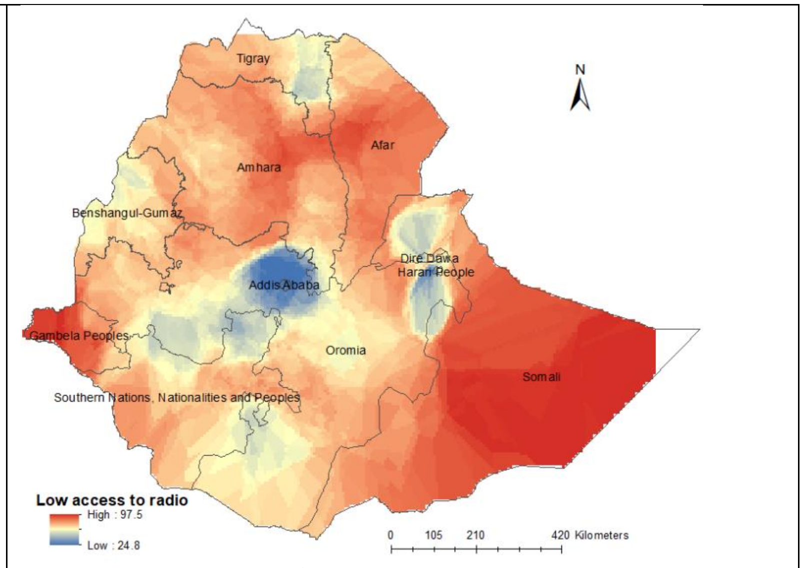


S Figure 3d. Service preparedness map of COVID-19 in Ethiopia, created based on a geometric mean

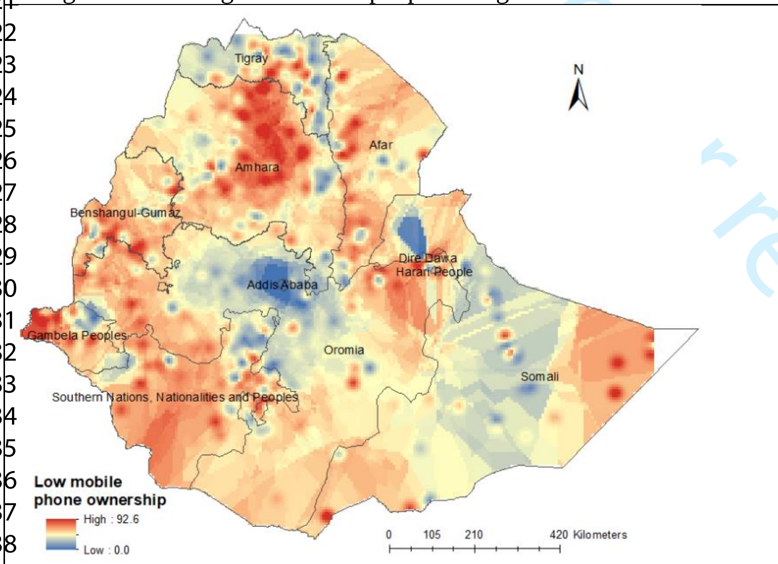
Supplemental Figure 3: Vulnerability maps of COVID-19 infection, severity, preparedness, and death in Ethiopia, created based on a principal component analysis (PCA) as alternative aggregation method.



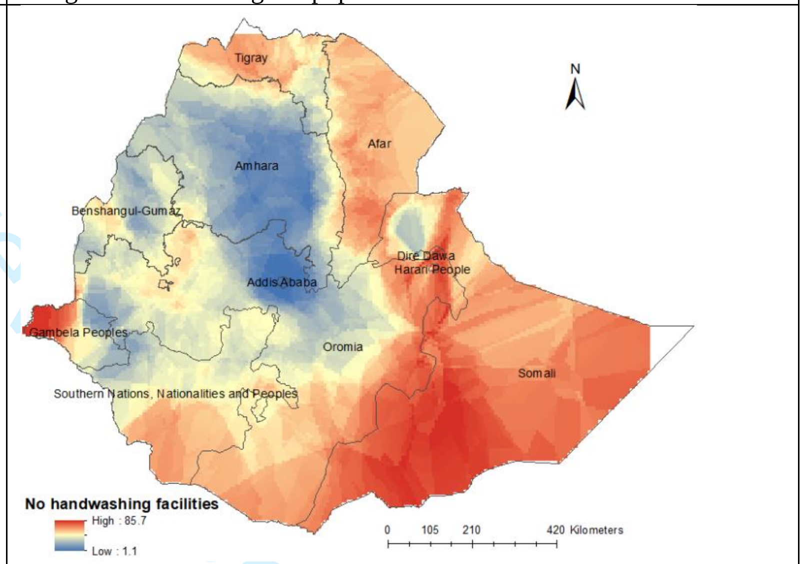
S Figure 4a. Average number of people living in a house



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

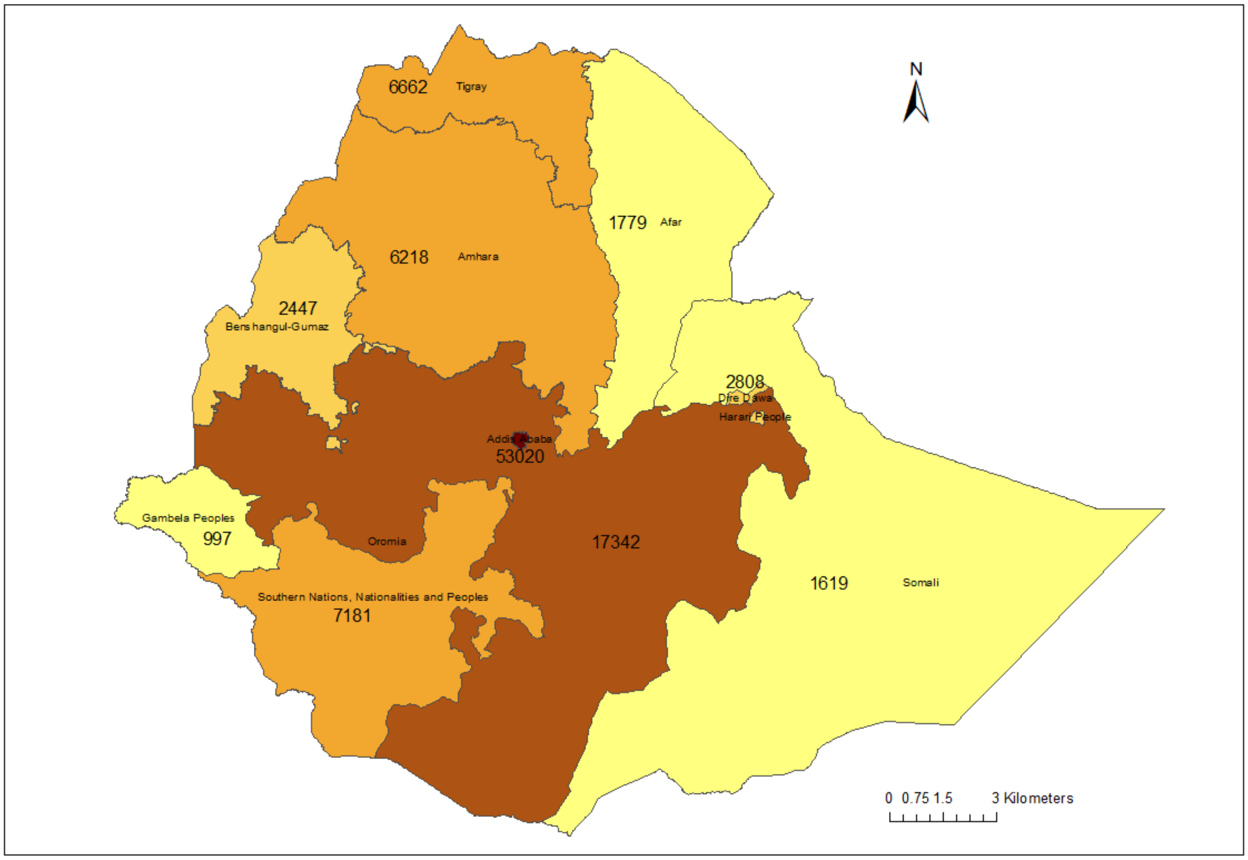


S Figure 4b. Percentage of the population who have not access to mobile phone



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
Title and abstract	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
Introduction			
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
Methods			
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
Results			
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
Discussion			
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
Other information			
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

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

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

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Keywords: Risk map, vulnerability, infection, severity, death, COVID-19, Ethiopia, geospatial

Abstract

Background: COVID-19 has caused a global public health crisis affecting most countries, including Ethiopia, in various ways. This study maps the vulnerability to infection, case severity, and likelihood of death from COVID-19 in Ethiopia.

Methods: Thirty-eight potential indicators of vulnerability to COVID-19 infection, case severity and likelihood of death, identified based on a literature review and the availability of nationally representative data at a low geographic scale, were assembled from multiple sources for geospatial analysis. Geospatial analysis techniques were applied to produce maps showing the vulnerability to infection, case severity, and likelihood of death in Ethiopia at a spatial resolution of 1 km X 1 km.

Results: This study showed that vulnerability to COVID-19 infection is likely to be high across most parts of Ethiopia, particularly in the Somali, Afar, Amhara, Oromia, and Tigray regions. The number of severe cases of COVID-19 infection requiring hospitalisation and intensive care unit admission is likely to be high across Amhara, most parts of Oromia and some parts of the Southern Nations, Nationalities, and Peoples' Region. The risk of COVID-19-related death is high in the country's border regions, where public health preparedness for responding to COVID-19 is limited.

Conclusion: This study revealed geographical differences in vulnerability to infection, case severity, and likelihood of death from COVID-19 in Ethiopia. The study offers maps that can guide the targeted interventions necessary to contain the spread of COVID-19 in Ethiopia.

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.

Introduction

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

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

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

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

Methods

Study area

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

Data sources and variable selection

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

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

Connectivity indicators, which measure the population-level vulnerability to infection, were also captured using distance and time-bounded markers. Specifically, average travel time (measured in minutes) to the nearest city and proximity to international borders (measured in kilometres) were included to measure each area's level of susceptibility to infection. Data on travel time to the nearest city, obtained from the University of Oxford's Malaria Atlas Project (MAP), were used to quantify the accessibility of an area to high-density urban centres at a resolution of 1 km×1 km [14]. Data on proximity to international borders were obtained from the EDHS spatial data repository and were used to measure [15] the geodesic distance to the nearest international border in kilometres, indicating the risk of cross-border transmission and the spread of COVID-19. Infection rates and the spread of COVID-19 were also positively correlated with the per capita public transportation use rate[16]. Thus, to determine the nearest cross-country road to each location on the map, we obtained and applied data for major roads from the World Bank [17].

It is evident that inadequate knowledge about COVID-19 and a lack of awareness of prevention measures exacerbate community transmission of the disease [18]. Therefore, we extracted data on adult literacy rate, access to media (such as radio, television, and mobile phone messages) and knowledge about other infectious diseases (e.g., HIV) from the EDHS as proxies for knowledge of COVID-19 prevention measures in each area of the country [12]. According to the WHO, maintaining good hand hygiene through regular washing with soap and water is one of the most effective preventative measures for reducing the transmission of COVID-19 [19,20]. Using the same data as above, we also assessed hand hygiene practices, access to water, and the availability of handwashing stations in a household.

Previous studies have shown that underlying chronic comorbidities and behavioural factors such as cigarette, alcohol and khat consumption were associated with more severe COVID-19 infections [21,22]. Data on khat chewing and the alcohol consumption rate were obtained from the EDHS 2016 [12], and data on cigarette smoking were obtained from the Ethiopia Public Health Institute STEP wise approach to Surveillance (STEPS) study [23]. The STEP survey was also used to measure the prevalence of selected non-communicable diseases (NCDs) such as hypertension, heart disease, and diabetes mellitus (DM).

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

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

Geospatial data processing

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

Statistical analyses

Geostatistical techniques such as spatial autocorrelation, kriging and semivariograms were applied to create a prediction grid surface from a scattered set of points [27]. Kriging assumes that the distance or direction between sample points reflects a spatial correlation that can be used to explain variation in the surface [28]. Since the variables had different units of measurement, the datasets were normalised using a min-max approach to a standard scale ranging from 0 (the lowest risk) to 100 (the highest risk) [29]. After normalisation, the indicators were averaged to create a vulnerability index, measuring the risk of COVID-19 for each geo-location [30]. The vulnerability indices were calculated separately for each domain, namely, the vulnerability to infection, case severity, and likelihood of death from COVID-19. The three domains were then averaged to produce the overall COVID-19 vulnerability index. Given that COVID-19 is a new virus, there is a lack of evidence for assigning weights for each indicator. Hence, equal weight was given to all indicators when calculating the arithmetic mean for the vulnerability indices. However, we also used principal component analysis (PCA) and geometric mean methods, which produced broadly similar results (Supplemental Figure 2 and Supplemental Figure 3). The risk maps were then created separately for infection, case severity, service preparedness, and death from the composite index using geostatistical tools in ArcGIS. All data transformations were performed in R [31]. All items included in this study are available in the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) Statement checklist (Supplemental Table 1).

Ethics aspects: Ethical approval was not required for this study as it was based on publicly available data.

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

Funding: There was no funding source for this study.

Results

Vulnerability to COVID-19 infection

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

Vulnerability to severe cases of COVID-19 infection

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

Vulnerability to death from COVID-19

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

Discussion

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

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

Despite the disproportionately high infection rate in Addis Ababa at present (Supplemental Figure 5), we found that the risk of COVID-19 infection is likely to become rather high in other regions. The high infection rate in Addis Ababa at this initial stage is expected, given that Addis Ababa is a major travel hub and Bole International Airport, located in the city, is one of the largest international airports in Africa. This exposes the city to a higher risk of imported cases and, subsequently, to an early surge of infections, leaving the areas outside the city at a higher risk of later infection. Second, we considered multifaceted risk factors (indicators) for COVID-19 infection in our geospatial model. This means that although the city has a high degree of connectivity, it is also characterised by higher scores for information penetration, knowledge of disease prevention and hand hygiene practices that could help slow the rate of infection in the city [12]. Third, Addis Ababa has relatively better and more consistent test-and-contact tracing practices than in other parts of the country, which means that the chance of new infections being detected in the city are much greater than in other parts of the country [5]. Future efforts to expand testing and tracing practices in other areas of the county are likely to increase the extent of confirmed infections in those other areas. Recent studies have demonstrated that effective social distancing and contact tracing can significantly reduce the rate of infection [32,33]. These interventions should be strengthened and expanded to areas identified as high risk in this study.

Our study also showed that the risk for severe cases of COVID-19 infection is high in most parts of the Amhara and Oromia regions. This may be due to the high prevalence of NCDs, which are associated with severe cases of COVID-19. Previous studies have revealed that the burden of NCDs, such as DM and hypertension, is high in these two regions [23,34,35].

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

Despite encouraging efforts by the Ethiopian government and stakeholders to prepare the health care system for the pandemic, the existing health care services in the country may face unprecedented challenges and crises due to the surge of patients that will require hospitalisation and ICU services at the same time. This can, however, be eased by implementing public health and social measures at the individual, community, and public authority levels to prevent infections and subsequent health, economic, and social consequences [36]. Studies have shown that implementing non-pharmaceutical interventions such as physical distancing, mask use, and closure of schools, especially during the early stages of infection, can reduce transmission and subsequent potential public health and economic crises [37].

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

Strength and Limitations

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

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

Conclusions

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

Declaration

Authors' contributions

KAA, YAG, YK, DMF, DNK, YAM, HAG, MB, MDM, AAA, and BAD conceptualised the study. KAA designed and run the geospatial analysis. YAG involved in the data analysis. KAA, YAG, DMF, DNK, and YAM drafted the manuscript. HAG, MB, AAA_1, MDM, BAD, SA, AA, AAA_2, WMB, KTG, TG, ATG, LGG, AG, HTK, GDK, CTL, LBM, AAM, HM, HGT, AGT, FT, BLW, and YK Critically reviewed and revised the drafted manuscript. KAA, YK, and AHM were responsible for quality control of accuracy and integrity of data. All the authors interpreted the data. All authors contributed to the final draft and finally approved it to be published. All authors agreed to be accountable for all aspects of the work for any issue related to the accuracy or integrity of any part of the work. The corresponding author attests that all listed authors meet authorship criteria and that no others meeting the criteria have been omitted.

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

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

Figures

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

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

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

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

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

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
Demographic indicators			
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 >=65 years divided by the total number of people participated in the survey
Socio-economic indicators			
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
Connectivity indicators			
Travel times to cities	MAP	1 km×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
Climatic indicators			
Mean temperature	WorldClime	1 km×1 km	Annual mean environmental air temperature (°C)
Mean precipitation	WorldClime	1 km×1 km	Annual mean rainfall (mm)

Wind speed	WorldClime	1 km×1 km	Annual mean wind speed (m s^{-1})
Solar radiation	WorldClime	1 km×1 km	Annual mean solar radiation (kJ m^{-2} day^{-1})
Water vapour pressure	WorldClime	1 km×1 km	Annual mean water vapour pressure (kPa), equivalent to absolute humidity.
Behavioural indicators			
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
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
Disease prevention knowledge indicators			
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
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
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
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
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
Hand hygiene indicators			
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)
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
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
Comorbidities indicators			
HTN	EPHI STEPS	Latitude and longitude point	Total number of people with HTN divided by the total number of survey participants

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
Service availability and readiness indicators			
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

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

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

Indicators	Risk factors	Evidence	References
Demographic indicators			
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 [40]
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 [22]
Socio-economic indicators			
Population density	Infection	High population density is a risk factor for COVID-19 infection	Ahmadi M [41]
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 [42]
Low wealth index	Infection	Socio-economic deprivation (RR 1.26 per SD increase in Townsend Index) associated with COVID -19 infection	Ho FK [43]
Connectivity indicators			
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 [44]
Proximity to national borders	Infection	Cross country moment is a risk factor for COVID-19 transmission and importation	Chinazz M [45]
Distance to major roads	Infection	Spread of COVID-19 was correlated positively with public transportation per capita	Ayenew B[16].
Climatic indicators			
Mean temperature	Infection	Low ambient temperatures are associated with more rapid spread of COVID-19	Holtmann M [46]
Mean precipitation	Infection	Countries with higher rainfall measurements showed an increase in COVID-19 transmission	Sobral MFF[47]
Wind speed	Infection	Areas with low values of wind speed associated with a high rate of COVID-19 infection	Ahmadi M [41]
Solar radiation	Infection	Areas with low values of solar radiation exposure associated with a high rate of COVID-19 infection	Ahmadi M [41]

Water vapour pressure	Infection	High humidity reduces the transmission of COVID-19. Water vapour pressure negatively correctly with COVID-19 infection.	Wang J [48], Li J[49]
Behavioural indicators			
Khat chewing	Severity	There is an association between khat chewing and chronic illness such as HIV infection, elevated diastolic blood pressure	Basker GV[50]
Alcohol drinking	Severity	Patients with alcohol use disorders at increased risk for COVID-19	Testino G [21]
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 [22]
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 [42]
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 [42]
Disease prevention knowledge indicators			
Adult illiteracy rate	Infection	Adult learning education is a tool to contain the COVID-19 pandemics	Lopes H [51]
Access to listen to radio	Infection	Access to media is a crucial factor in public health responses to an outbreak	Ayedee N[52]
Access to watch TV	Infection	Media (Television) has a significant role in creating a positive atmosphere in COVID-19	Ayedee N[52]
Mobile phone ownership	Infection	Mobile phone calls and text messages help for the diagnosis, management, and control of infectious diseases	Wood S [53]
Knowledge towards HIV	Infection	Knowledge towards an infectious disease such as HIV can help to control the transmission of the diseases	Bertozzi S[54]
Hand hygiene indicators			
Travel time to water sources	Infection	Adequate water supply is essential for the control of COVID-19 infection	WHO [55]
Place for handwashing	Infection	Hand washing is recommended by WHO for the control of COVID-19 infection	WHO [56]
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 [56]
Comorbidities indicators			
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 [22]
DM	Severity	Death from COVID-19 was associated with DM (HR 1.50, 95%CI: 1.40-1.60) 1.50	Williamson E [40]
BMI	Severity	Death from COVID-19 was associated with higher BMI (HR 1.27, 95%CI: 1.18-1.36)	Williamson E [40]
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 [22]
HIV prevalence	Severity	Mortality from COVID-19 was associated with immunosuppression (HR 1.69, 95%CI: 1.21-1.34)	Williamson E [40]
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 [22]
Service availability and readiness indicators			
Health care access problem	Death	Healthcare resource availability is associated with COVID-19 mortality	Ji Y [6]
General service readiness	Death	General health service preparedness is essential for combating the COVID-19 pandemic	WHO [57]
ICU availability	Death	Lack of critical care unite increase the risk of death from COVID-19	Murthy S [58]
CRD readiness	Death	Cardiorespiratory disease (CRD) is a risk factor for COVID-19 related death	Zheng Z [22]
TB readiness	Death	TB determinants outcomes of patients with COVID-19	Tadolini M [59]
Diabetes readiness	Death	Diabetes affects the prognosis of patients with COVID-19	Zheng Z [22]

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

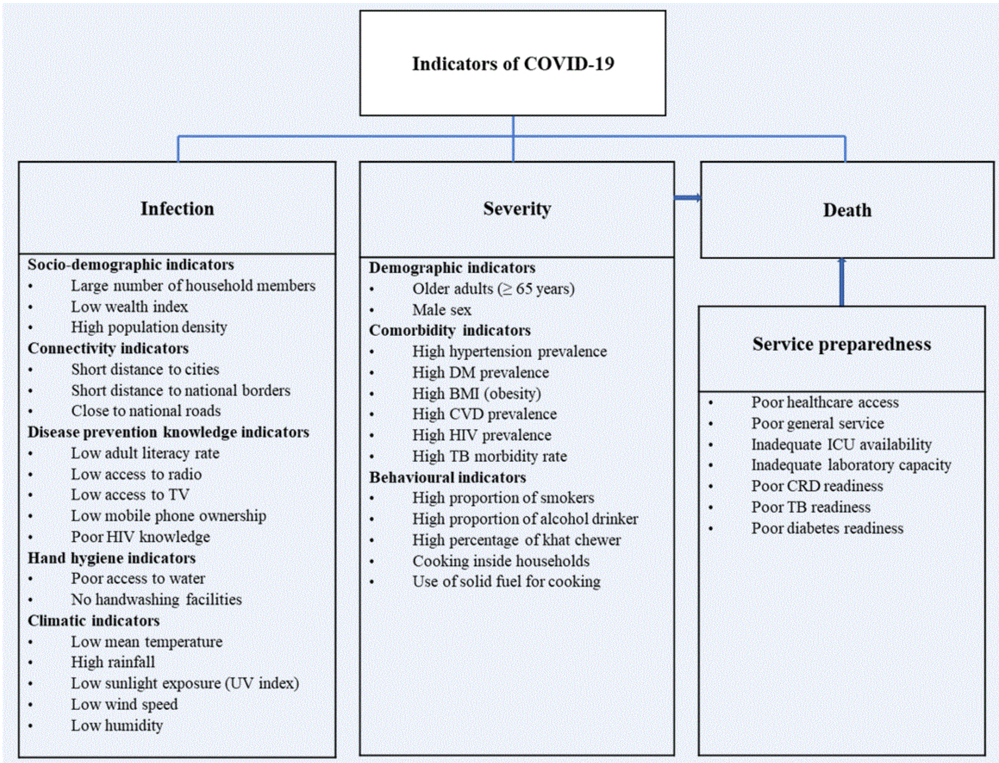


Figure 1: Indicators for the vulnerability of COVID-19 infection, severity, service, preparedness, and related death. DM: diabetes mellitus, BMI: body mass index, CVD: cardiovascular disease prevalence; TB: tuberculosis; HIV: Human immunodeficiency virus; ICU: intensive care unit; CRD: cardiorespiratory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

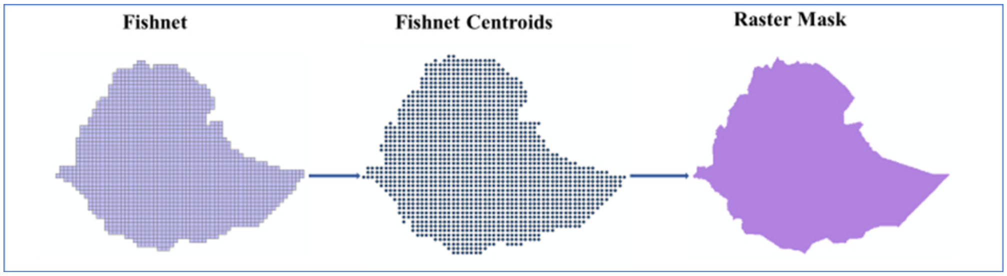


Figure 2: Rectangular polygon (fishnet), fishnet centroids, and raster mask covering the whole territory of Ethiopia.

165x44mm (150 x 150 DPI)

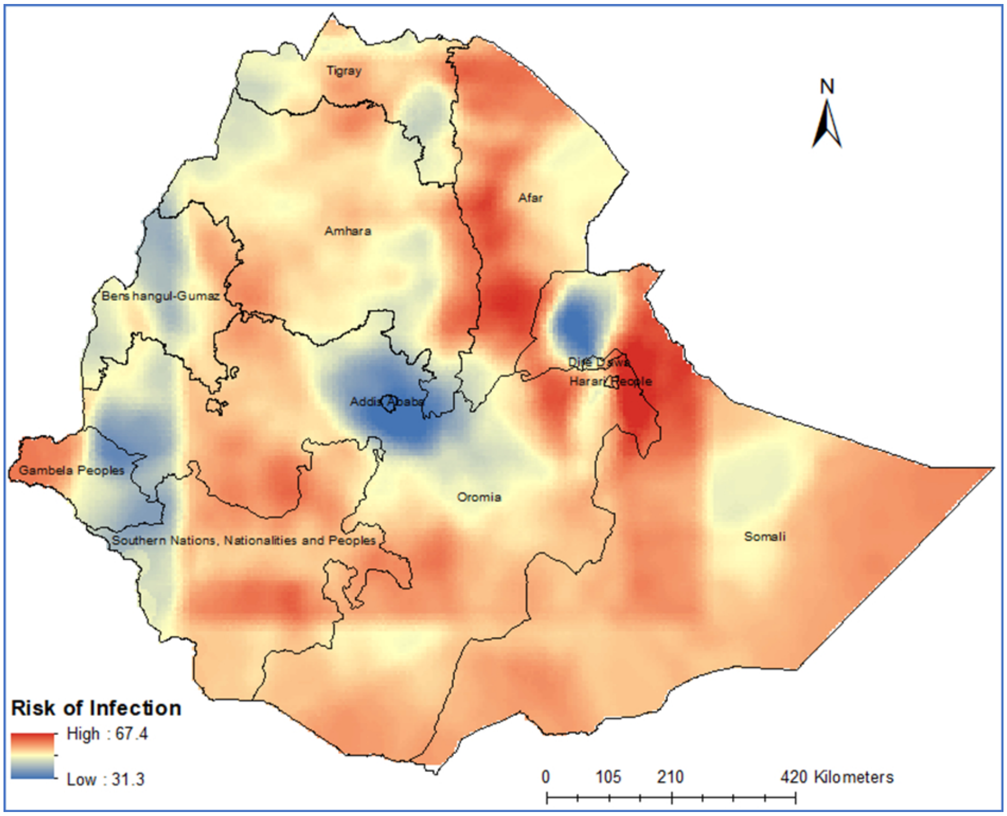


Figure 3. Vulnerability map to COVID-19 infection in Ethiopia.

249x201mm (96 x 96 DPI)

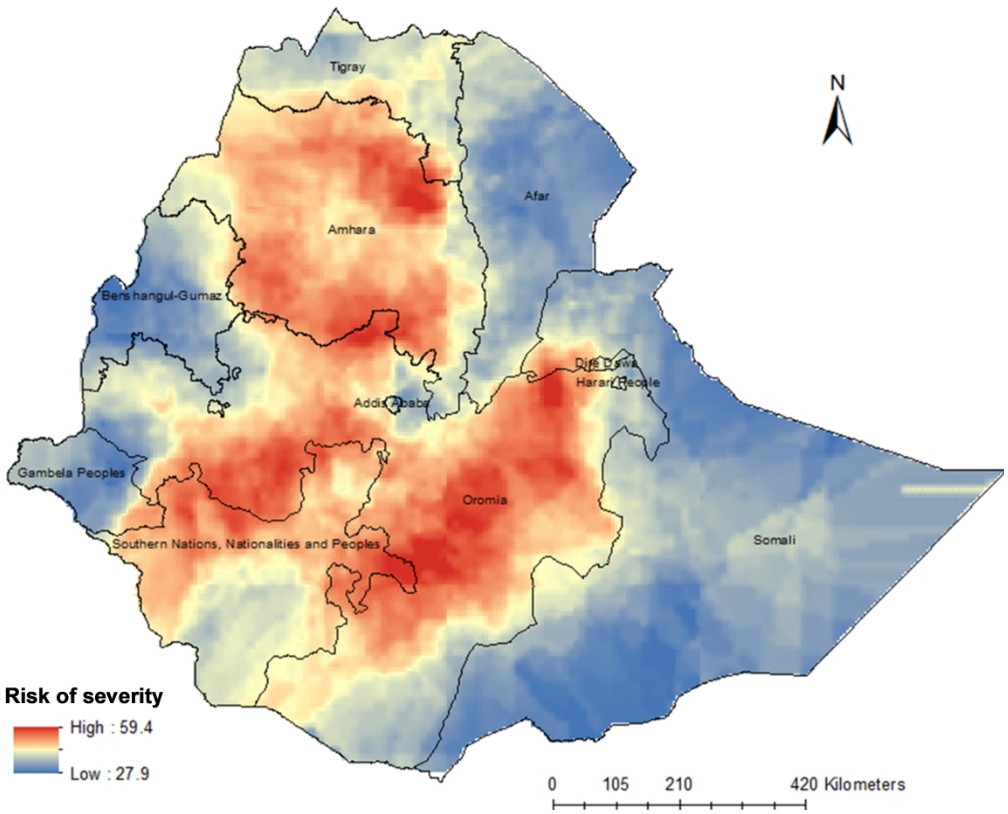


Figure 4. Vulnerability map to COVID-19 severity in Ethiopia.

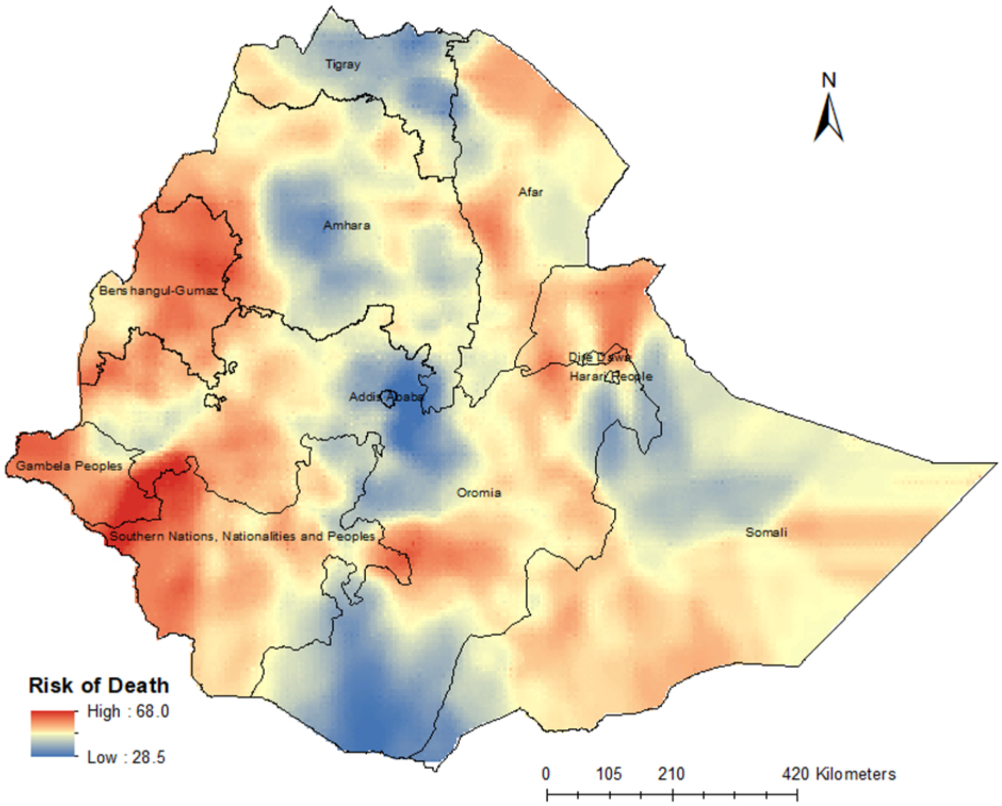


Figure 5. Vulnerability map to death from COVID-19 in Ethiopia.

248x200mm (96 x 96 DPI)

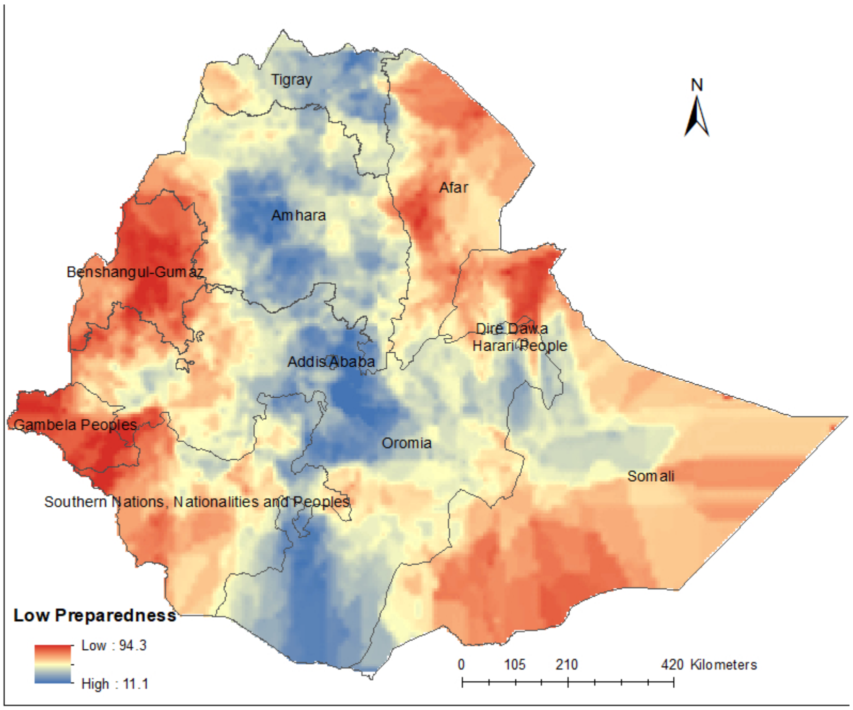
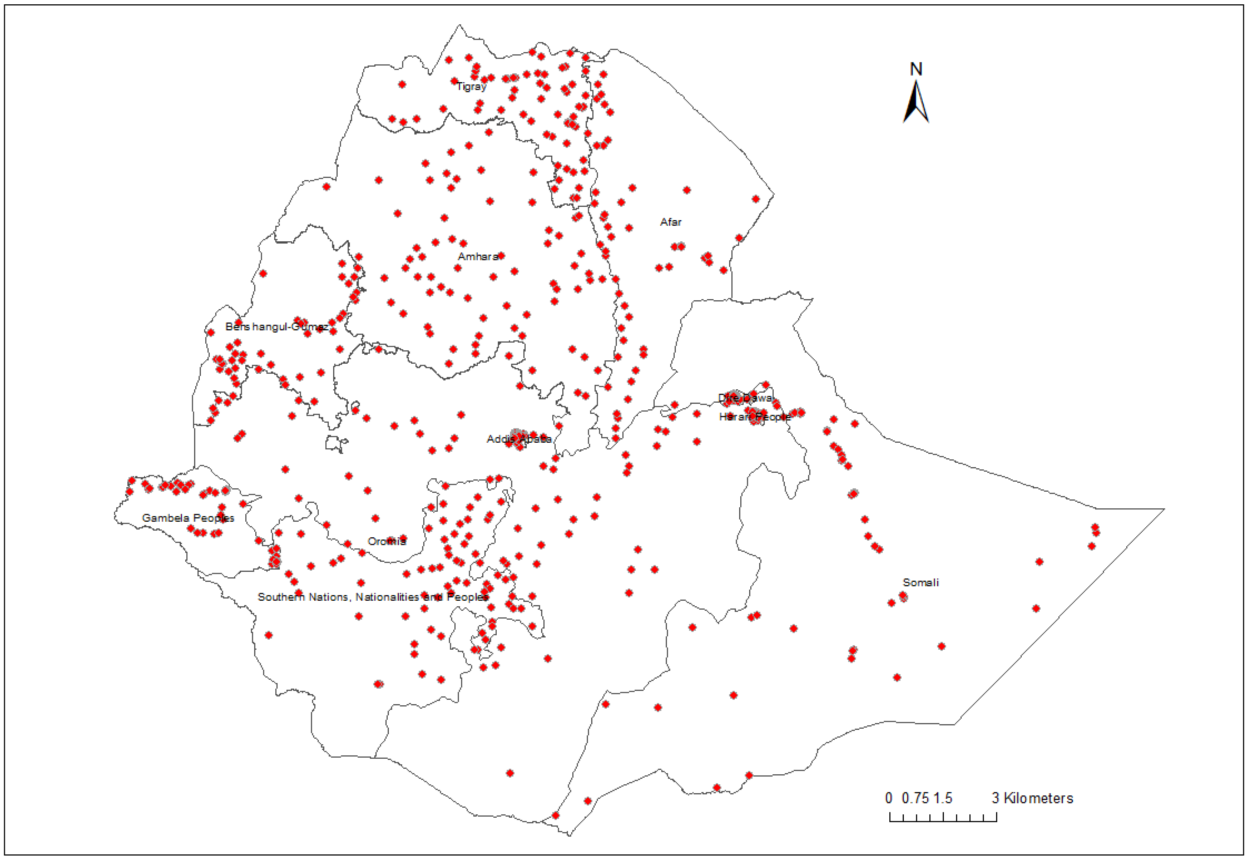


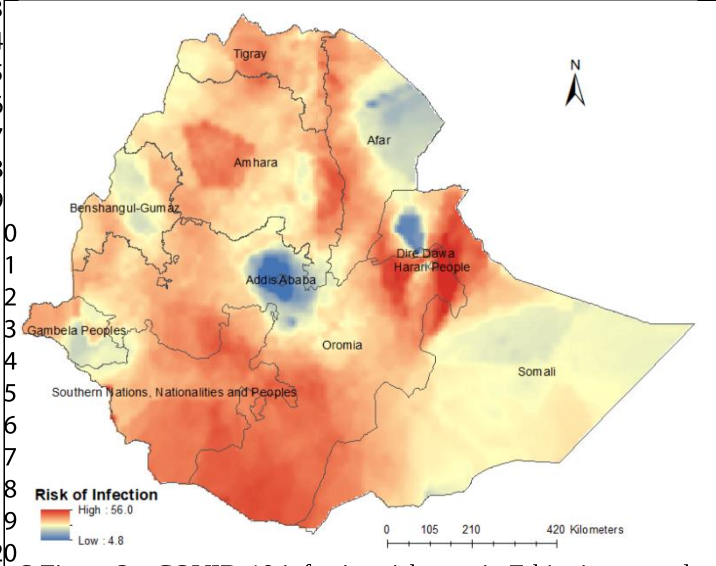
Figure 6. Vulnerability map to service preparedness for COVID-19 in Ethiopia.

210x296mm (96 x 96 DPI)

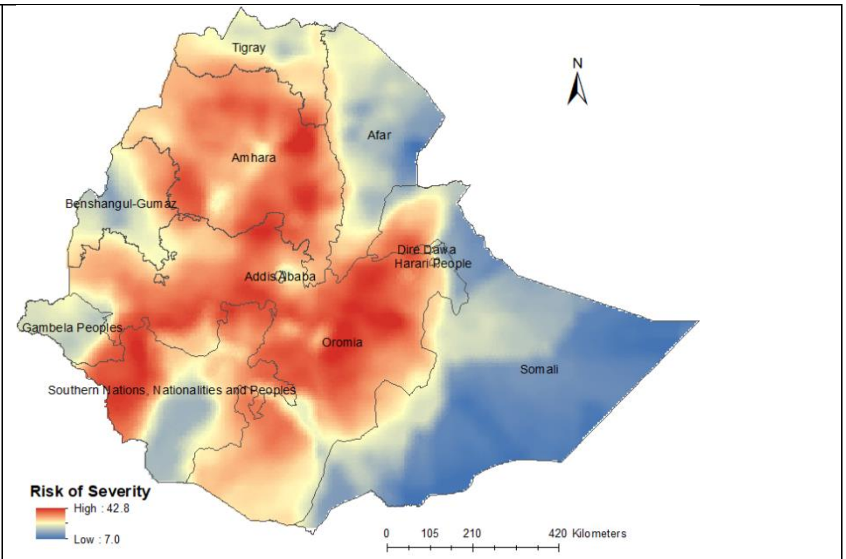
Supplemental Information



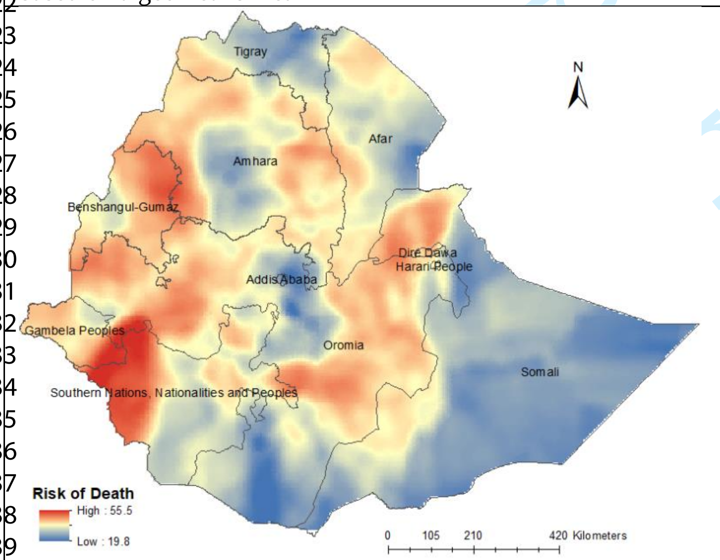
Supplemental Figure 1: A map showing the distribution of the Ethiopia Demographic and Health Survey (EDHS 2016) datapoints.



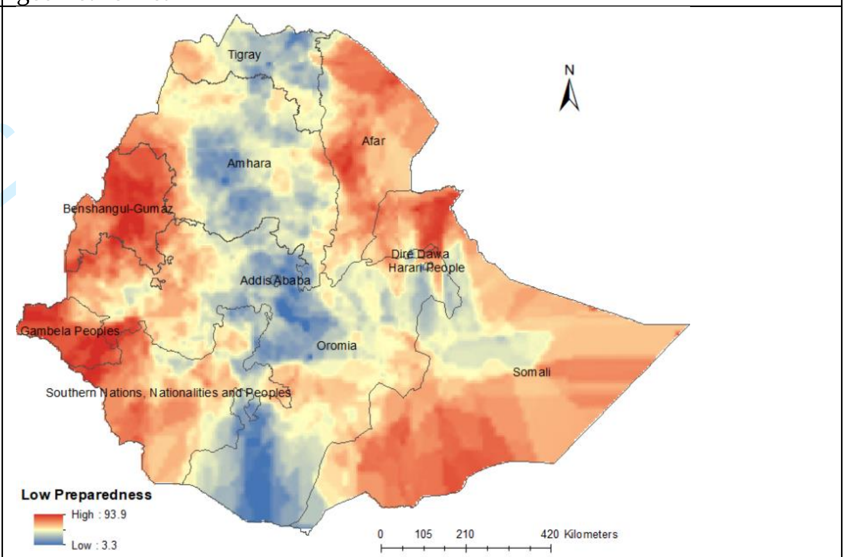
S Figure 2a. COVID-19 infection risk map in Ethiopia, created based on a geometric mean



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

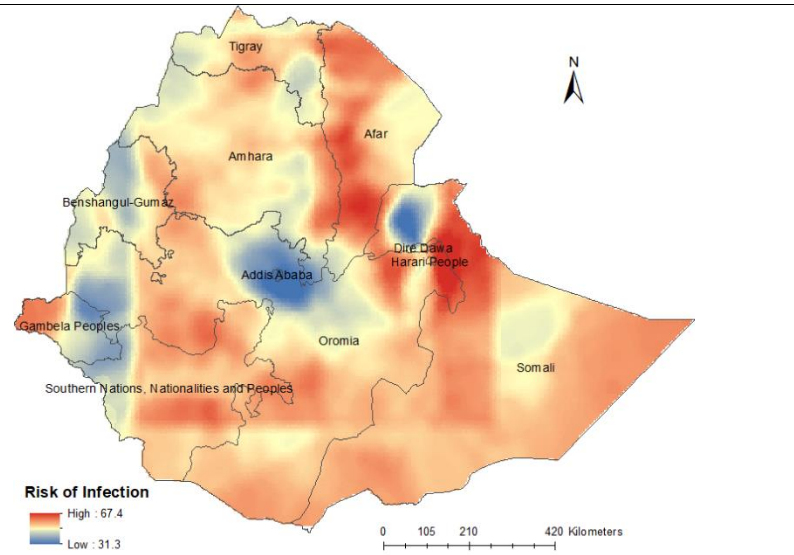


S Figure 2c. Death risk map of COVID-19 in Ethiopia, created based on a geometric mean

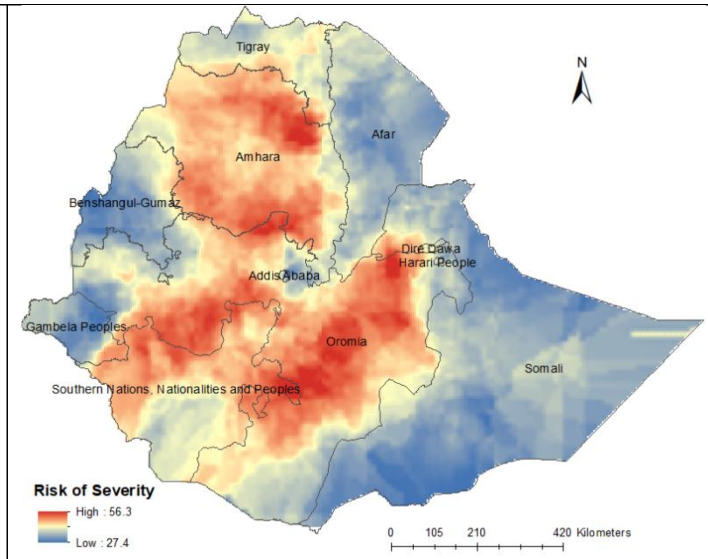


S Figure 2d. Service preparedness map of COVID-19 in Ethiopia, created based on a geometric mean

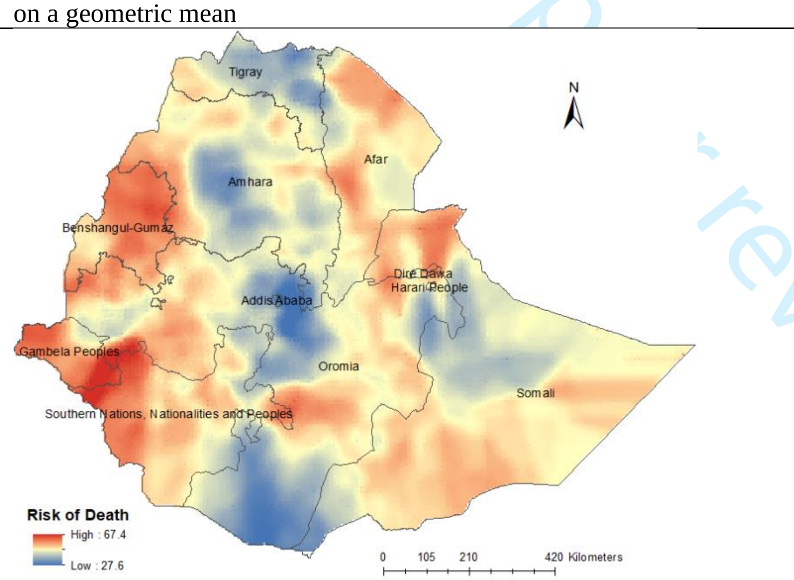
Supplemental Figure 2: Vulnerability maps of COVID-19 infection, severity, preparedness, and death in Ethiopia, created based on a geometric mean as alternative aggregation method.



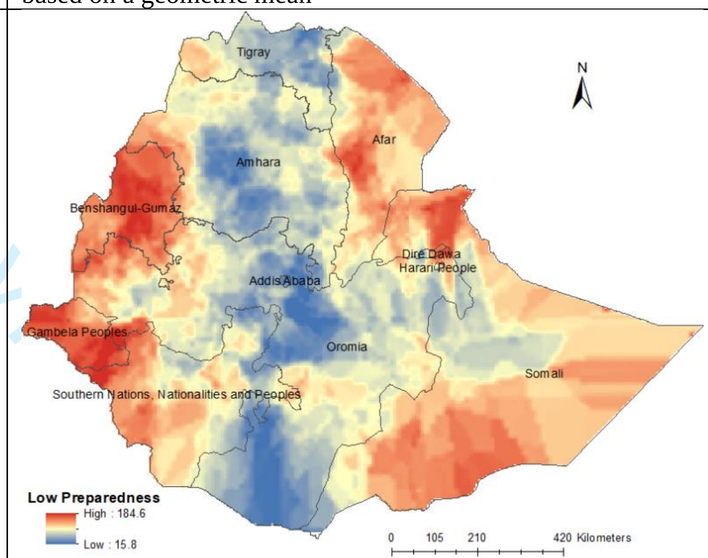
S Figure 3a. COVID-19 infection risk map in Ethiopia, created based on a geometric mean



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

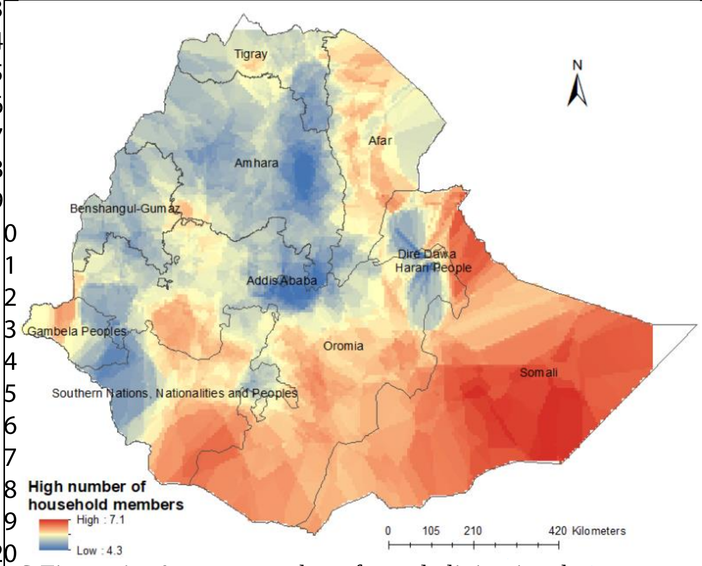


S Figure 3c. Death risk map of COVID-19 in Ethiopia, created based on a geometric mean

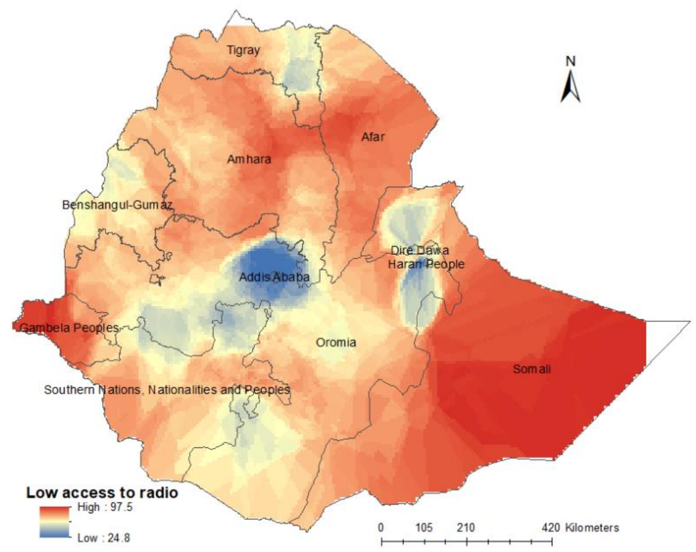


S Figure 3d. Service preparedness map of COVID-19 in Ethiopia, created based on a geometric mean

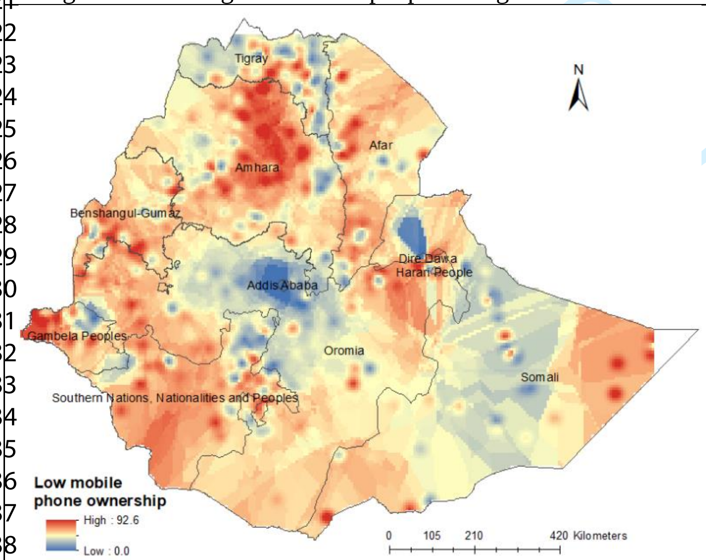
Supplemental Figure 3: Vulnerability maps of COVID-19 infection, severity, preparedness, and death in Ethiopia, created based on a principal component analysis (PCA) as alternative aggregation method.



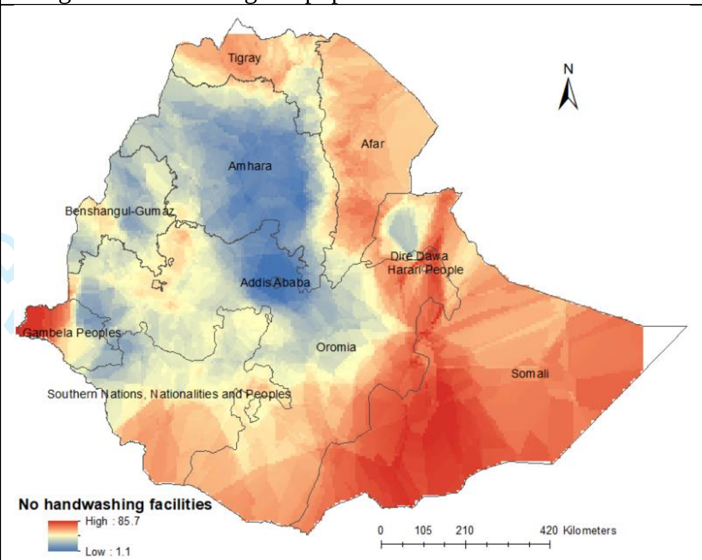
S Figure 4a. Average number of people living in a house



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

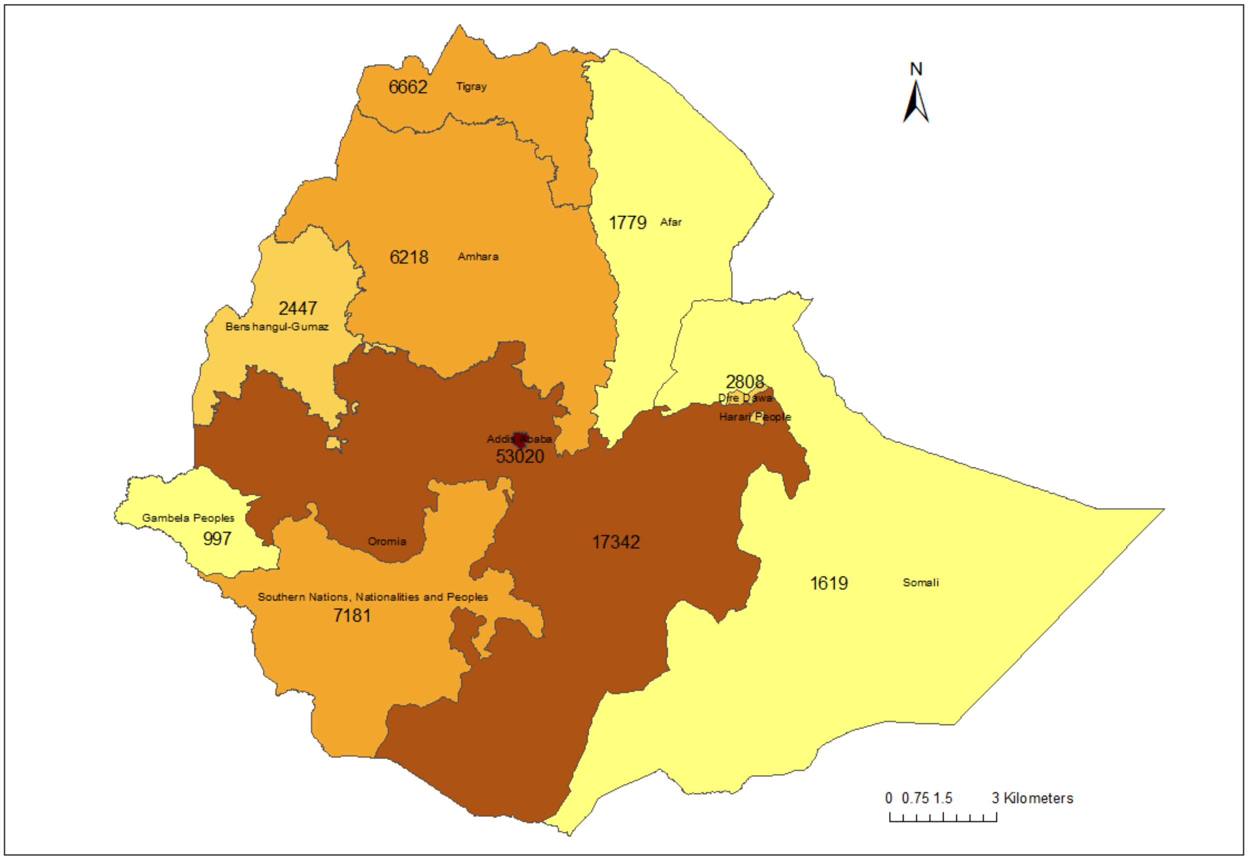


S Figure 4b. Percentage of the population who have not access to mobile phone



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
Title and abstract	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
Introduction			
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
Methods			
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
Results			
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
Discussion			
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
Other information			
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