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Original Research Report

Epidemiological and spatio-temporal characteristics of COVID-19 in Rwanda

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ABSTRACT

Background: The coronavirus disease 2019 (COVID-19) has taken millions of lives and disrupted living standards at individual, societal, and worldwide levels, causing serious consequences globally. Understanding its epidemic curve and spatio-temporal dynamics is crucial for the development of effective public health plans and responses and the allocation of resources. Thus, we conducted this study to assess the epidemiological dynamics and spatio-temporal patterns of the COVID-19 pandemic in Rwanda.

Methods: Using the surveillance package in R software version 4.0.2, we implemented endemic-epidemic multivariate time series models for infectious diseases to analyze COVID-19 data reported by Rwanda Biomedical Center under the Ministry of Health from March 15, 2020 to January 15, 2021.

Results: The COVID-19 pandemic occurred in two waves in Rwanda and showed a heterogenous spatial distribution across districts. The Rwandan government responded effectively and efficiently through the implementation of various health measures and intervention policies to drastically reduce the transmission of the disease. Analysis of the three components of the model showed that the most affected districts displayed epidemic components within the area, whereas the effect of epidemic components from spatial neighbors were experienced by the districts that surround the most affected districts. The infection followed the disease endemic trend in other districts.

Conclusion: The epidemiological and spatio-temporal dynamics of COVID-19 in Rwanda show that the implementation of measures and interventions contributed significantly to the decrease in COVID-19 transmission within and between districts. This accentuates the critical call for continued intra- and inter- organization and community engagement nationwide to ensure effective and efficient response to the pandemic.

Introduction

In late December 2019, a case of an unidentified disease was reported in Wuhan, China. Subsequently, the outbreak of the disease developed into a global pandemic, which was declared by the World Health Organization (WHO) on March 11, 2020 [1]. This unidentified disease, which manifests as severe pneumonia symptoms with high fever, was named 'coronavirus disease 2019' (COVID-19) by the WHO. COVID-19 is caused by the infection of the human vascular and respiratory systems by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) [2]. This type of virus, which is in the same family as SARS-CoV and the Middle East respiratory syndrome has an intermediate host and is then transmitted to humans [3]. Since its emergence to date (January 15, 2021), the COVID-19 pandemic has disrupted living standards at individual, societal, and worldwide levels, and caused 2,039,464 deaths out of 95,520,875 cases in 191 countries/regions [4].

The first case of COVID-19 in Africa was reported on February 14, 2020 in Egypt. It was expected that the outbreak of the disease would critically affect the continent due to the fragile healthcare infrastructure of most African countries, the concomitant presence of non-communicable and communicable diseases in several regions in the continent, and the household socio-demographic characteristics of numerous African populations [5]. However, effective lockdown measures, contact tracing and tracking procedures, and increased COVID-19 testing, in addition to the warmer climatic conditions and the young population structure of the continent, contributed to the control of the epidemic [6,7].

In Rwanda, the first case of COVID-19, which was that of an Indian

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citizen who arrived in the country on March 8, 2020 from Mumbai, India, was reported on March 14, 2020. After two months, imported cases (returning residents, travelers, and cross-border truck drivers and their assistants) contributed two-thirds of the total 289 confirmed cases. As of January 16, 2021, the disease had killed more than 140 people out of 10,850 confirmed cases. Rwanda had managed to bring the outbreak under control in the previous wave, which occurred in mid-August, by strengthening the intra- and inter-organization leadership and coordination capabilities of various stakeholders and partners, reinforcing epidemiological surveillance in the health facilities of all districts, augmenting entry-point screening, boosting national reference laboratory abilities, enhancing infection prevention and control practices through district rapid response teams, managing confirmed cases properly, upsurging risk communication and Rwandan community engagement, and ensuring the provision of operational support and logistics [8]. However, the current wave, which began in late November 2020, is particularly worrisome because it is spreading quickly in many districts of the country. It took only a month for the number to rise from 6000 to 10,000, marking the fastest pace of the pandemic in the nation.

It has been over a year since the outbreak of COVID-19, and the world is experiencing the third wave of the pandemic. In addition, a mutant COVID-19 strain was reported in the United Kingdom in December 2020 and is now spreading rapidly around the world. The number of confirmed cases is increasing every day, with higher increases recorded among elderly patients and/or those with underlying health conditions [9]. Fortunately, COVID-19 vaccines have been developed by various pharmaceutical companies, and vaccination has already begun in developed countries such as the United States, Canada, and the United Kingdom. However, the end to this global nightmare cannot be predicted yet.

Understanding the epidemic curve and spatio-temporal dynamics of COVID-19 is fundamental for the comprehension of its epidemiological characteristics, identification of clusters, and development of effective public health plans and responses as well as resource allocation. Although COVID-19 epidemiological models have been developed in various studies [10–14], and the spatio-temporal dynamics of the disease have been assessed [15–20], to our knowledge, little attention has been paid to African countries individually. Additionally, seeing the irregular spatial distribution of COVID-19, we intended to comprehend its diffusion within and across districts, as well as the evolution of the phenomenon over time in Rwanda. Hence, the endemic-epidemic multivariate time series model using autoregressive, spatio-temporal, and endemic components was applied to understand the spatio-temporal transmission of the disease. Furthermore, no country has been declared as the unanimous frontrunner in the control of the pandemic to date. However, some countries, including Rwanda, have managed the pandemic better than others. Using the available data collated by each country over nine months until January 9, 2021, and after having at least 100 confirmed COVID-19 cases, Lowy Institute declared Rwanda as the first in Africa and the sixth worldwide in the proper handling of the pandemic [21].

In the present study, we aimed to statistically assess the epidemiological dynamics and spatio-temporal patterns of the COVID-19 pandemic in Rwanda. Using incidence maps, we modeled the spread of COVID-19 after discussing the timely policy response vis-a-vis COVID-19 in Rwanda.

Materials and methods

Study area and data source

Rwanda is located in Central Africa, immediately south of the equator between latitude 1°4′ and 2°51′S and longitude 28°63′ and 30°54′ E. According to the 2012 Fourth Rwanda Population and Housing Census, the country is subdivided into four (Northern, Southern, Eastern, and Western) geographically centered provinces plus Kigali city (the capital, in the center). These provinces are further split into districts (30), the most important administrative regions of Rwanda's decentralization system, sectors (416), cells (2148), and villages (14,837), which cover a 26,338 km^2 area that houses 10,515,973 inhabitants [22].

For the analysis, we used COVID-19 data accumulated from March 15, 2020 to January 15, 2021, a total of ten months. We used the time-series models of cumulative and daily numbers of confirmed COVID-19 cases and deaths provided by the Rwanda Biomedical Center (RBC) under the Ministry of Health [23]. RBC revises and updates the data every day after amending for probable errors, and the data is posted on the RBC website and the official Twitter account of the Ministry of Health. Regarding the population data, the 2012 Fourth Rwanda Population and Housing Census, which is the most recent, was used. For the report of COVID-19 data, Kigali city, which includes the Gasabo, Kicukiro, and Nyarugenge districts, was considered one district named 'Kigali'. Therefore, the map included 28 districts.

Statistical analysis

We implemented the endemic-epidemic multivariate time series models for infectious diseases proposed by Held et al. [24] and expanded as developed diversity forms in several papers [25–28]. The composition of the equation represents the model with count data for the number of new cases $y_{a,\,t}$, from areal units $a = 1, \ldots, A$ at time series $t = 1, \ldots, T$, which has a negative binomial distribution with mean $\mu_{a,\,t}$ and over-dispersion parameter $\psi_a > 0$, where

$$\mu_{a,t} = \lambda_{a,t} y_{a,t-1} + \varphi_{a,t} \sum_{r \neq a} w_{r,a} y_{r,t-1} + \nu_{a,t}, \lambda_{a,t}, \varphi_{a,t}, \nu_{a,t} > 0 \quad (1)$$

and the conditional variance of $y_{a,\,t}$ is $\mu_{a,\,t}(1 + \psi_a \mu_{a,\,t})$. The weights $w_{r,\,a}$ are assumed to be known and they determine how cases between other regions are related. We define the weight as 1 if area *r* is the first-order neighborhood with area *a,* and 0 otherwise. This number reflects the geographical information only so that the weight is not time-dependent.

According to Held et al. [24], the first two terms capture occasional outbreaks in area *a*. The first component, which is called 'within-epidemic', describes the effect of the disease's temporal dynamics to the expected number of infections within the district *a*. It contains the number of infections recorded in the same district on the previous day (*time t* − *1*) $y_{a,\,t-1}$, which affects the mean of the distribution $\mu_{a,\,t}$ based on the value of the multiplicative coefficient $\lambda_{a,\,t} > 0$ and this $\lambda_{a,\,t}$ varies among the districts by means of a random effect which allows for heterogeneous behavior in the evolution of the infections [26].

The second component, which is called 'between-epidemic', models the effect of neighboring districts by counting in the average incidence of infections $y_{r,\,t-1}$ of districts *r* on the previous day (*time t* − *1*) which are neighbors of district *a*. The weighted average of incidence rates introduced into the model as the coefficient $w_{r,\,a}$ is positive if either district *a* and district *r* have the same border or if both share a border with the same district, while $w_{r,\,a}$ is zero otherwise. The multiplicative coefficient $\varphi_{a,\,t}$, which determines the magnitude effect of the average incidence rate of the neighboring districts on the expected number of infections $\mu_{a,\,t}$, differs among districts in line with the population and unobserved heterogeneity in the transmission of the virus [26].

The last component $\nu_{a,\,t}$, which is called the 'endemic component', describes a stable temporal pattern and district-wise contribution to the number of infections, once the within-epidemic and between-epidemic effects are accounted for, while heterogeneity among districts is brought into the model by means of a random effect [28].

The proportions of within-epidemic (autoregressive), between-epidemic (spatio-temporal), and endemic components are the average of $\lambda_{a,\,t} y_{a,\,t-1}/\mu_{a,\,t}$, $\varphi_{a,t} \sum_{r \neq a} w_{r,a} y_{r,t-1}/\mu_{a,t}$, and $\nu_{a,\,t}/\mu_{a,\,t}$ over time, respectively. The three averaged proportions are provided in Fig. 4. In Fig. 5, the within-epidemic component,$\lambda_{a,\,t} y_{a,\,t-1}$ is marked in blue, and the between-epidemic component $\varphi_{a,t} \sum_{r \neq a} w_{r,a} y_{r,t-1}$ is marked in orange, and the endemic component $v_{a,\,t}$ is marked in gray.

eyer et al. [27] proposed the decomposed Eq. (1) in log-linear types in all three different components:

$$log(\lambda_{a,t}) = \gamma_a^{(\lambda)}, \tag{2}$$

$$log(\varphi_{a,t}) = \gamma_a^{(\varphi)}, \tag{3}$$

$$log(v_{a,t}) = \gamma_a^{(v)} + log(e_{a,t}), \tag{4}$$

Where $\lambda_{a,\,t}$ is the autoregressive effect in area a and $e_{a,\,t}$ is the population fraction in area a at time t. The three components $\{\gamma_a^{(\lambda)}, \gamma_a^{(\varphi)}, \gamma_a^{(v)}\}$ in Eqs. (2) to (4) describe areal unit-specific intercepts following normal distributions which are represented by $\{\gamma_a^{(\lambda)} \sim^{iid} N(\gamma^{(\lambda)}, \sigma_\lambda^2), \gamma_a^{(\varphi)} \sim^{iid} N(\gamma^{(\varphi)}, \sigma_\varphi^2), \gamma_a^{(v)} \sim^{iid} N(\gamma^{(v)}, \sigma_v^2)\}$ [28]. According to Giuliani et al. [26], Eq. (2) is the epidemic component that describes autoregression within the geographical regions only. Eq. (3) is the epidemic component that describes autoregression with neighboring provinces that may be affected by other regional characteristics [24,27]. Eq. (4) is about the endemic component which consists of the random intercept and the offset.

We implemented the formulas for data analysis using the multivariate “hhh4” model in the surveillance package in R software version 4.0.2 [27].

Results

Descriptive analysis of COVID-19 policy responses over time

Fig. 1 shows the policy response to the COVID-19 outbreak over time in Rwanda, starting from the beginning of the pandemic. To limit the transmission of COVID-19, the Rwandan government set up a multidisciplinary team in late January 2020 to elaborate preventive and responsive measures, continuously communicate risk, and engage the community. After the first confirmed case was reported, the Rwanda government through the Ministry of Health initially implemented preventive measures for a two-week period to further curb the transmission of COVID-19. The measures included the closure of all schools and higher education institutions, worship places, and nightclubs; postponement of large gatherings; restriction of unnecessary movements; and the use of the 114 toll-free number to report suspected COVID-19 symptoms. After observing the rise in the global trend of the pandemic a week later, new measures, including the closure of all borders except for goods and cargo and mandatory 14-day quarantine for all returning Rwandan citizens and legal residents, were implemented in addition to the previous ones. Social distancing was also reinforced through various measures, including restriction of public transportation and non-essential travel between cities, and closure of shops, markets, bars, and non-essential businesses. With the aid of the police force, these lockdown measures were maintained until May 3, 2020 when the full lockdown ended and curfew measures were established. In June 2020, domestic travel and international tourism for visitors with charter flights resumed nearly in all provinces except Rubavu and Rusizi districts. International flights resumed on August 1, 2020. Since then, the Rwandan government has continued to lift or reinstate lockdown/restrictions periodically in different districts and villages based on the results of continuous risk assessment.

To halt the first wave of the outbreak, which occurred in mid-August and mostly in Kigali city, mass gatherings and public transport between Kigali and other districts were proscribed. After a remarkable decline in cases, transport between all districts and provinces was resumed on September 25, 2020 and schools resumed in November 2020 based on

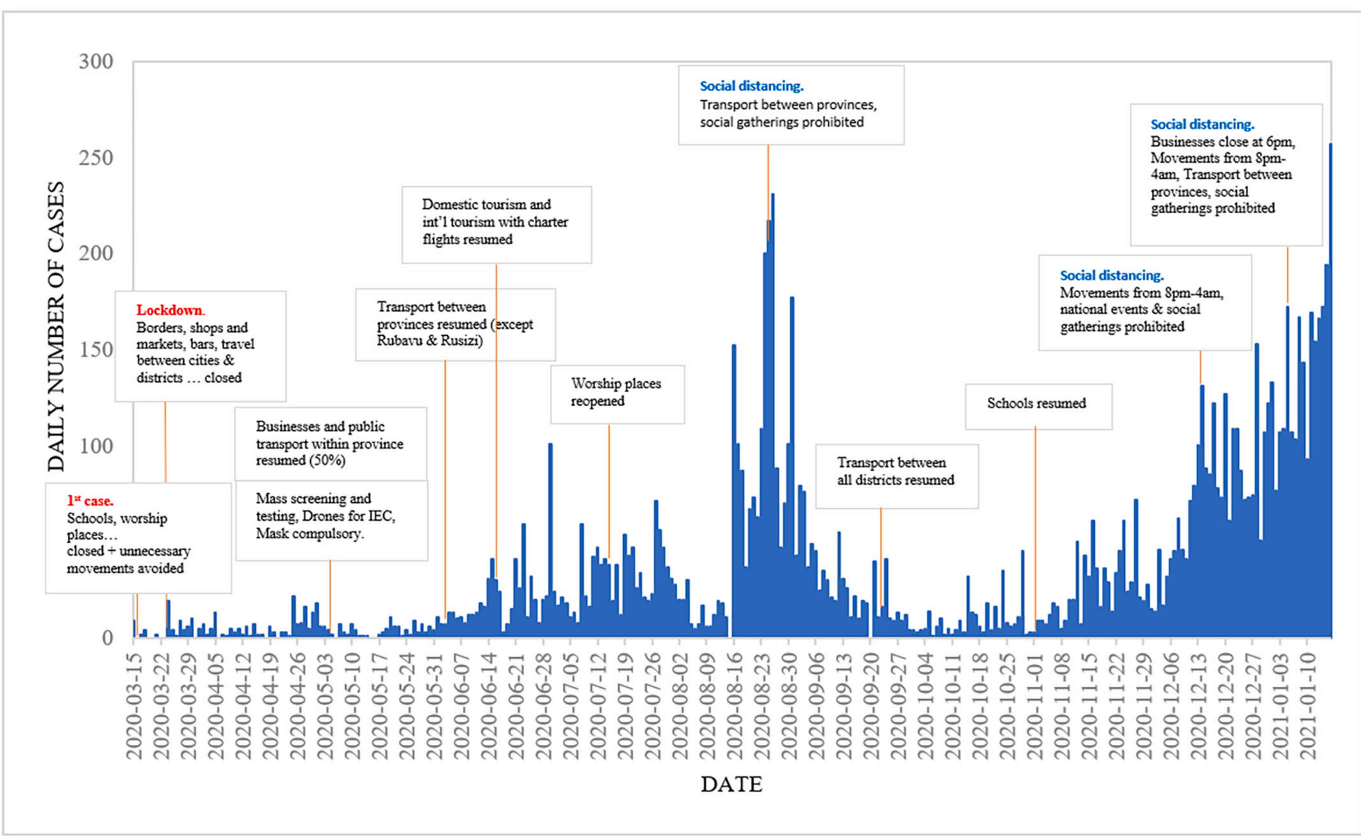

Fig. 1. Daily COVID-19 confirmed cases in Rwanda with various policy interventions from March 15, 2020 – January 15, 2021. In addition to lockdown and other preventive measures including social distancing, ban on social gatherings, and transports between provinces and/or districts prohibition have been of great effect in the control of the COVID-19 pandemic in Rwanda.

levels of education. Following the rise in COVID-19 cases and deaths in late November 2020, the government tightened existing health measures to further contain the spread of the disease. In mid-December 2020, all national events were postponed, and all social gatherings were prohibited in public and private settings. Specific measures were implemented in Musanze district, which was experiencing an unusual upsurge in COVID-19 cases for the three weeks. In the first week of January 2021, in addition to the existing measures, public and private transportation to and from Kigali city, and between different districts, was prohibited except for medical and essential services. In addition, all business establishments were directed to close operations by 6 pm daily for two weeks. Upon assessment of the continued unprecedented rise in cases, deaths, and transmission rates in communities, especially in Kigali city, the capital was put under lockdown, and citizens in the other parts of the country were urged to significantly diminish social interactions and limit movements to only those for essential services.

General description of the epidemic curve in Rwanda

From March 15, 2020 to January 15, 2021, the number of confirmed cases recorded in Rwanda was 10,573 (male: 6777; female: 3796). The COVID-19 epidemic curve and its respective time-varying reproduction numbers (Rt) are depicted in Fig. 2, whereas the geographical distribution of the cumulative COVID-19 incidence is presented in the map in Fig. 3. Since the report of the first confirmed COVID-19 case, Rwanda has experienced two waves of the pandemic. The first wave occurred in mid-August 2020 and hit its peak on August 26, 2020. This wave mostly occurred in the central part of the country (capital: Kigali city) and the southwestern part of the country (Rusizi District). The outbreak in Kigali city was related to two big markets in Kigali (Kigali city market and Nyabugogo market), whereas that in Rusizi District was related to the movement of truck drivers to/from Bukavu and the daily commute of Rwandans to Bukavu, a city in the neighboring Democratic Republic of Congo. Other increases in cases recorded in the country, especially in the capital city, were related to villages under lockdown, high-risk isolated clusters, and the Kigali Transit Center cluster. After a two-month period

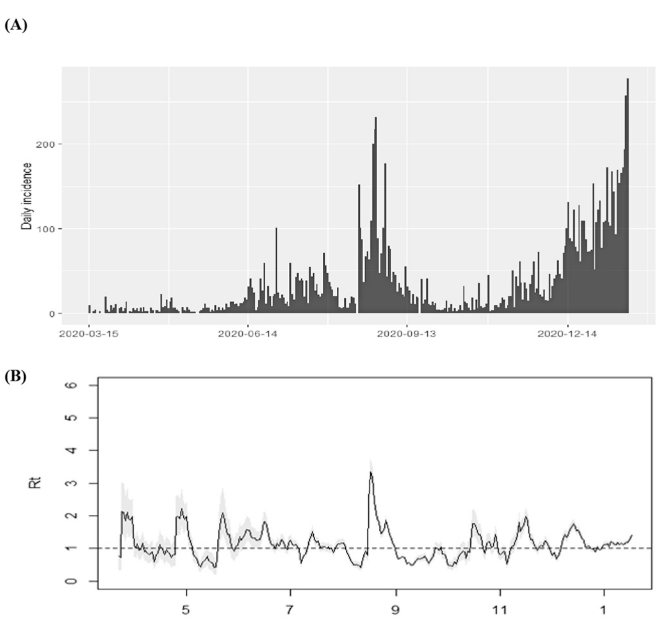

Fig. 2. Epidemic curve of COVID-19 confirmed cases in Rwanda from March 15, 2020 – January 15, 2021. (A) Daily incidence cases due to COVID-19. (B) The basic reproduction number (R_t) of COVID-19. Rwanda experienced two waves of the COVID-19 pandemic in mid-August and late November 2020 respectively.

of remarkable decrease in cases since late November 2020, the country started experiencing the second wave of the pandemic owing to the fact that people started to let their guard down and stopped adhering to health measures and guidelines.

Fig. 3 shows the countries in Africa and the geographical distribution of the cumulative incidence of COVID-19 in Rwanda. The figure displays a clear heterogeneous spatial pattern, with the central region in Kigali city (Gasabo, Kicukiro, and Nyarugenge districts) having the highest cumulative incidence in the country (5.4 cases per 1000 people), followed by Rusizi (southwest region) (2.4 cases per 1000 people) and Rubavu (northwest region) (1.5 cases per 1000 people) districts. These districts are the most affected boroughs, whereas Rutsiro, Nyaruguru, and Ruhango districts tend to have low incidence compared to other districts. The detailed number of confirmed cases in each district is presented in the supplementary table (Table S1).

Table 1 presents the number of confirmed cases according to age group and the absolute sex-specific COVID-19 mortality burden according to age group. The burden of cases/deaths refers to the number of cases/deaths of a given sex or age group in a total number of cases or deaths. Regarding the number of confirmed cases, people in their 20s and 30s account for more than the half of the total burden of COVID-19 infection in Rwanda. This is because the demographic structure of Rwanda shows that there are considerably more young people in the country than the elderly. It is remarkable that the total burden of COVID-19 decreases with increasing age. Regarding the number of deaths, the male burden in the total number of COVID-19 deaths is approximately three times higher than the burden of females (74.6% vs. 25.4%). Adding to the fact that men have weaker immune systems than women [29], another plausible reason for this statistic is that males tend to be more exposed to the virus due to daily-life socio-economic aspects like employment exposures than their counterparts. The results also showed that people aged 60 years and above account for more than half of the total burden of COVID-19 deaths in Rwanda. This is similar to the reported results of COVID-19-related mortality in several other countries, which indicate that the mortality rate is high among the elderly [30]. The results of the present study are similar to those of some previous studies [31–33], which indicated higher odds of morbidity and mortality among males than females. The number of confirmed cases and deaths per million people was 1005.4 and 13.1, respectively, whereas the number of confirmed cases as a proportion of tests was 1.3 in 74.6 tests per thousand people.

Spatio-temporal endemic-epidemic modeling

Fig. 4 presents the estimated expected number of infections of three components, a) within-epidemic effect (autoregressive), b) between-epidemic effect (spatio-temporal), c) endemic effects. The figures show that only a few districts mostly affected by the pandemic (Kigali, Rusizi, and Rubavu), are principally influenced by the epidemic transmission within the area (map (A) on the top). In a few districts that adjoin the capital city, Kigali, the transmission of COVID-19 is explained by the epidemic tendency from neighboring districts (map (B) in the middle), whereas the infection did trail the endemic pattern in essence in the majority of the remaining districts (map (C) at the bottom).

In order to check the goodness-of-fit, we used *probability integral transformation (PIT)* and we found out that it is close to a uniform distribution [34]. We have selected the best prediction performance as our model and we reported further details in supplementary figure (Fig. S2). The point and 95% confidence intervals estimate of each parameter are as follows: within-epidemic (−1.05, 95% CI: −1.50 to −0.59), between-epidemic (−4.58, 95% CI: −5.62 to −3.54), endemic (0.93, 95% CI: 0.23 to 1.63), and overdispersion parameter (6.60, 95% CI: 6.00 to 7.19).

Fig. 5 portrays the estimated average number of cases according to the model, accompanied by the observed number of cases in the Rwandan districts. It shows consistency with the results shown in Fig. 3 and relates to the policy intervention outlined in Fig. 1. First, the Kigali

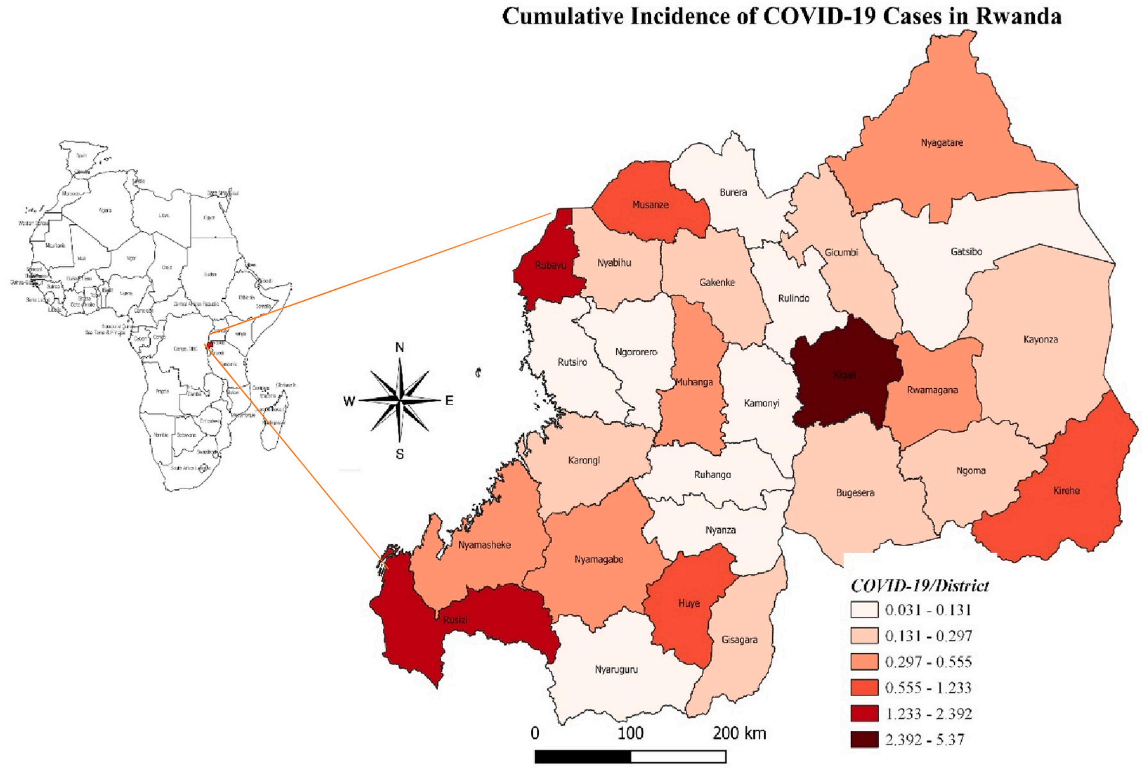

Fig. 3. Left. Map showing the location of the countries in Africa and the red area indicates Rwanda location. Right. Cumulative incidence of COVID-19 cases per 1000 people by district in Rwanda, March 15, 2020 –January 15, 2021. Kigali city, Rusizi, and Rubavu had the highest COVID-19 cumulative incidence in the country whereas Rutsiro, Nyaruguru, and Ruhango districts had the lowest cumulative incidence. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Number of COVID-19 confirmed cases and deaths and their absolute burden in Rwanda.

Age group(yrs)	Number of confirmed cases (% share)[a]	Number of death (% share)[a]	
		Males	Females
<20	1292 (12.2)	0 (0.0)	2 (1.4)
20–29	3094 (29.3)	3 (2.2)	3 (2.2)
30–39	3071 (29.0)	5 (3.6)	2 (1.4)
40–49	1754 (16.6)	17 (12.3)	8 (5.8)
50–59	814 (7.7)	20 (14.5)	3 (2.2)
60–69	355 (3.4)	23 (16.7)	7 (5.1)
70–79	133 (1.3)	21 (15.2)	5 (3.6)
80+	60 (0.6)	14 (10.1)	5 (3.6)
	10,573	103 (74.6)	35 (25.4)
Confirmed cases per million people			**1005.4**
Confirmed deaths per million people			**13.1**
Confirmed cases as a proportion of tests			**1.3**
Test per thousand people			**74.6**

[a] Note: Percentages of share representing the absolute burden of age group-specific and sex-specific in total number of COVID-19 cases or deaths.

city, Rusizi, and Rubavu districts experienced the domination of epidemic components within the area of the contagion. This is in agreement with the special local lockdown and quarantines the Rusizi and Rubavu districts and various villages in Kigali city experienced from the start of the pandemic compared with the rest of the country and in line with the fact that these districts were the most affected by the disease outbreak. Second, Gicumbi, Rwamagana, and Musanze districts borrowed the component related to the epidemic component from neighboring areas. For convenience, we presented six districts with characteristics of geographical and spatio-temporal effects in Fig. 5. The graphs for the other Rwandan districts are presented in the supplementary figure (Fig. S1).

Discussion

The world is currently experiencing the third wave of the COVID-19 pandemic, which will be recorded as a major disaster for modern humans. Transmission of COVID-19 is unpredictable and continues to show repeated increases and decreases. In this study, we statistically analyzed COVID-19 data collated over 10 months in Rwanda by modeling COVID-19 epidemiological dynamics and spatio-temporal patterns, resulting in the observation of differences in the time- and space-specific dynamics of COVID-19. Our results revealed that the districts most affected by the disease were predominantly influenced by the epidemic infections within the area, whereas few districts that are neighboring to the capital city were affected by the epidemic effect from neighboring districts; the majority of the remaining districts followed the endemic trend. This evidence is in harmony with the health measures and interventions implemented to curb the spread of the disease.

The first wave of the pandemic, which occurred in mid-August, hit mostly Kigali city, and given the social distancing measures implemented during that period, the capital city experienced endogenic transmission and a remarkable reduction in the number of confirmed cases. Rusizi District was also affected by this wave. The government prohibited both public and private transportation to and from the district and public transport within the district to control the infection. This isolation resulted in a reduction in the number of confirmed cases and the predominance of epidemic transmission within the area. Rwamagana and Gicumbi districts experienced the epidemic component by borrowing it from the neighboring Kigali city. However, the two districts experienced the epidemic component within the area after the prohibition of transportation between provinces in late August 2020.

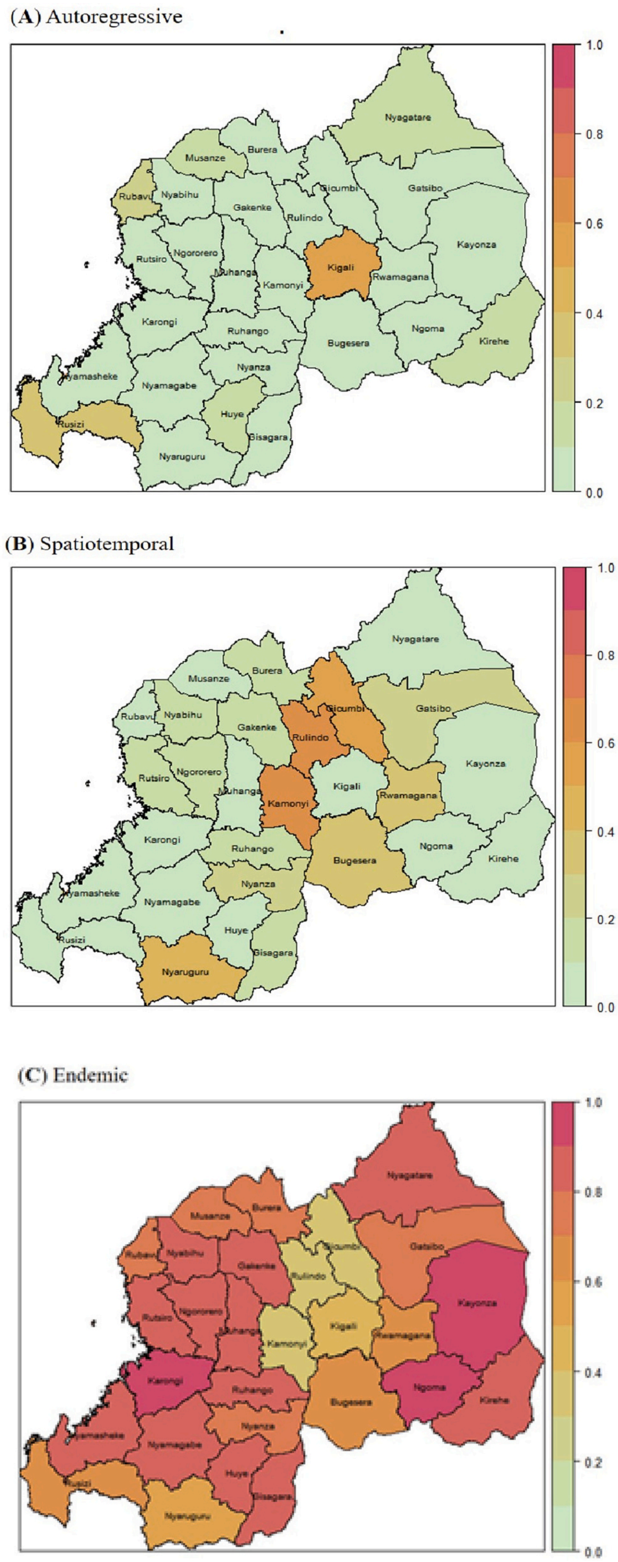

Fig. 4. Maps represent the fitted result of the three components from March 15, 2020 – January 15, 2021. The legend of color change from green to red represents the low to the high role of the component. (A) Within-epidemic effect is observed in a few districts most affected by COVID-19 (B) Between-epidemic effect is experienced in a few districts around Kigali (C) Endemic effect is detected in the majority of the remaining districts. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Musanze district presents a particular case owing to the influence of the epidemic component from neighboring areas. This may be caused by edge effects due to the boundary of the district with the geographical border of the Republic of Uganda. However, the district also experienced an epidemic effect within the area after health measures and guidelines were strengthened.

The second wave of the pandemic started in late November and hit many districts of the country, mostly due to a two-month period of remarkable decrease in cases that caused people to let their guard down and stop following health measures and guidelines. Kigali continued to experience a major increase in the number of COVID-19 cases. Rubavu district also experienced this wave mostly owing to residents returning from the neighboring Democratic Republic of Congo and contact with infected persons in Musanze district. Another major cause of this wave was the spike in the spread of the disease in prison clusters in the country, including Nyarugenge prison in Kigali, Huye prison in Huye district, and Muhanga and Rwamagana prisons in their respective districts.

After comparing the results of studies that analyzed the current state of the COVID-19 pandemic in Africa using spatial or spatio-temporal analysis, we found that one study demonstrated that climatic conditions (wind speed) have a positive relationship with the spread of COVID-19 using a generalized additive model [6]. Another study showed that the pandemic varies geographically across the continent, with high incidence in neighboring countries specifically in West and North Africa [17]. Those previous studies generally observed the current status of COVID-19 in Africa. Another study indicated that the geographic variability and spatio-temporal spread of COVID-19 were observed in Libya, North Africa [35]. Unlike previous studies, it is meaningful that our study focused on Rwanda and we assessed the current status and pattern of the COVID-19 pandemic considering policy intervention in time and space.

Understanding the epidemic curve and spatio-temporal dynamics of COVID-19 will momentously help public health decision-makers to develop effective public health plans and responses. Our findings are in accordance with the results of the assessment of the measures and interventions implemented to considerably reduce COVID-19 transmission in the community, both within and between Rwandan districts. Additionally, the findings of this study can be used in future research on disease modeling in time and space.

This study has certain limitations, which should be noted. First, although we discussed the policy response vis-a-vis COVID-19 and modeled the spread of COVID-19 in Rwanda, the fact that the number of confirmed COVID-19 cases in Rwanda is generally not as high as that in other countries should be taken into account in the consideration of our results. Thus, we had to model the spread of infections in a few districts that had considerably larger numbers of cases than others. Second, we could not analyze the burden of sex in the total number of cases and conduct a more advanced and detailed analysis because the dataset did not include information on confirmed COVID-19 cases according to sex. Other constraints to consider are the limited information and studies about the status of COVID-19 in the Democratic Republic of Congo, and the effect of the Republic of Tanzania's denial of the existence of COVID-19, and the country's refusal to follow public health measures against COVID-19 and report the number of confirmed COVID-19 cases to neighboring countries, including Rwanda, and to the world [36]. Furthermore, the lack of individual mobility data in the present study was another hindrance to advanced spatio-temporal analyses towards public health response at both individual and population levels [37]. However, this analysis of the effects of the epidemic, endemic, spatio-temporal analyses, and policy intervention in each region in Rwanda is considered significant to understanding and assessing the effectiveness of the implemented policy interventions by the government of Rwanda, modeling the trend of COVID-19 epidemics in time and space by identifying when and which districts are more affected than others and letting public health decision-makers intervene at national and local

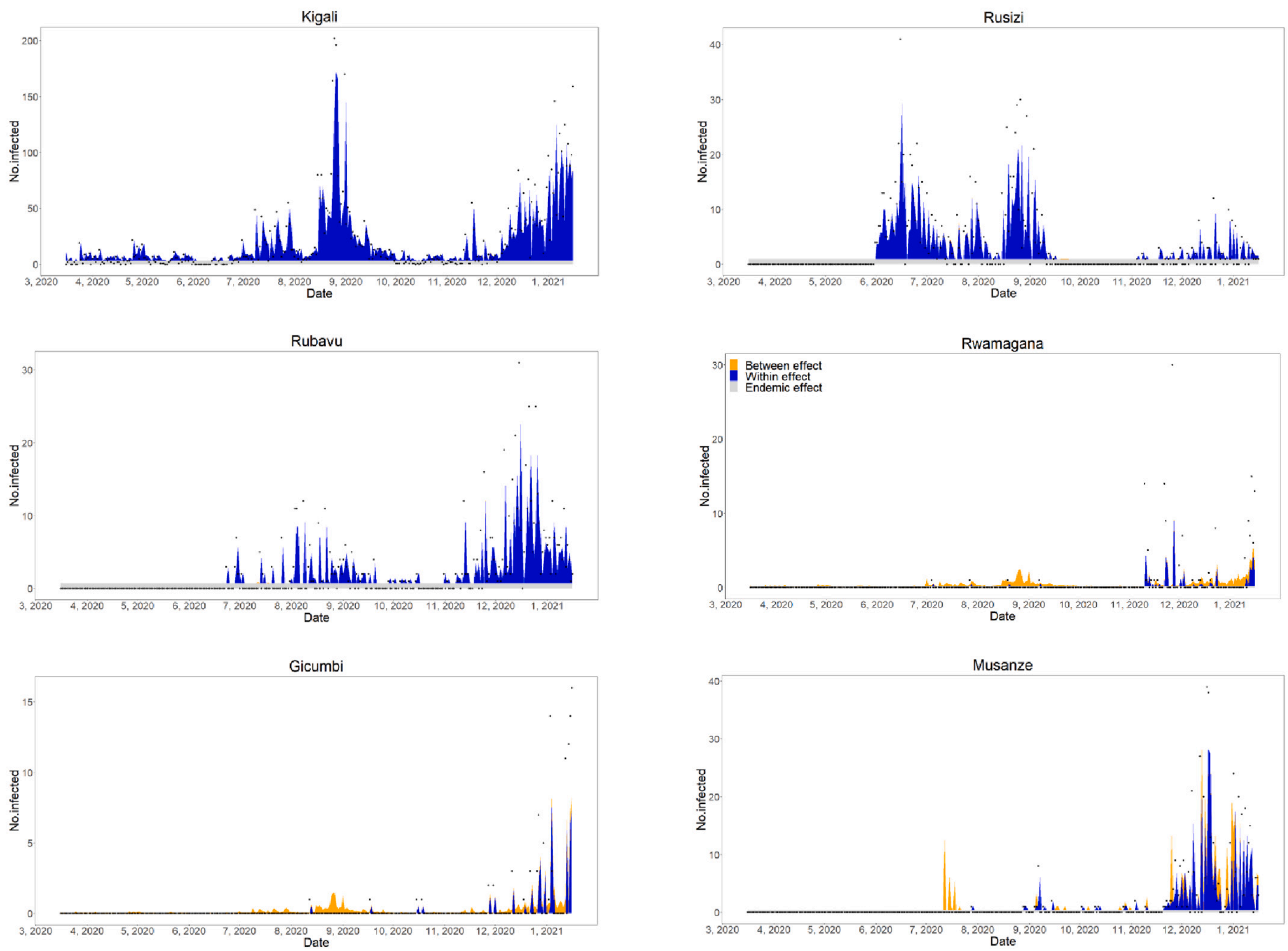

Fig. 5. Plots of three components (spatiotemporal, autoregressive, and endemic) in six districts in Rwanda. The dots represent the number of daily confirmed cases. The blue color represents the within-epidemic component (autoregressive). The orange color characterizes the between-epidemic component (spatiotemporal). The gray color shows the endemic component. Kigali, Rusizi, and Rubavu (districts most affected by COVID-19) experienced the domination of within-epidemic component while Gicumbi, Rwamagana, and Musanze districts showed the between-epidemic component predominance. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

level policies consequently.

Conclusion

In the present study, the analysis of the epidemiological and spatio-temporal dynamics of the COVID-19 pandemic in Rwanda showed that the pandemic is being regulated and controlled to some extent through the government's efforts and the cooperation of the citizens. A week after the first case was reported in Rwanda, the government has implemented total nationwide lockdown until May 3, 2020. Since then, the government continued easing and/or reinstating of local lockdown measures or restrictions, urged mandatory use of face masks in public at all times, and initiated other health measures and guidelines to contain the spread of COVID-19. Nationwide emphasis on vaccination, continued intra- and inter-organization, community engagement, and intervention policy should be crucially accentuated to control and contain this pandemic. Additionally, understanding and modeling the epidemical and spatio-temporal dynamics of COVID-19 can aid public health decision-makers in the allocation of resources and the development of effective public health plans and responses at the local level to ensure effective and efficient response to this pandemic.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloepi.2021.100058.

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