Research Article

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Assessing the spatial-temporal clustering of HIV prevalence among adolescents and young adults across countries around the world

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Abstract: To date, HIV infection among adolescents and young adults remains a challenging public health issue, especially for countries located in Sub-Saharan Africa but no empirical research known to date has provided a spatial-temporal cluster analyses to assess trends in HIV prevalence among this population. This study attempts fill in the gaps in research by examining how the prevalence of adolescents and young adults aged 15–24 living with HIV are clustered together and estimating the number of individuals infected with HIV and the effectiveness of disease control initiatives. The empirical work of this study is based on the UNAIDS estimates downloaded from the World Bank DataBank and data obtained from the United States Central Intelligence Agency. Findings suggest that trends in HIV prevalence among adolescents and young adults differed by region and the prevalence of HIV infection among these individuals will not surge but will somewhat fluctuate over time. Attempt to end AIDS as a public health threat by year 2030 can remain a challenge if the current antiretroviral therapy (ART) coverage, population growth rates, and AIDS-related death rates were to continue into the next decade.

Keywords: HIV, AIDS, spatial temporal cluster analysis, system dynamics modeling, 95-95-95 goal

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1 Introduction

To date, HIV infection among adolescents and young adults remains a challenging public health issue. In fact, it is estimated that over 30 percent of new HIV infections occurred among those aged between 15 to 24 [1]. Even though incidents of HIV infections decrease by 20 percent among adolescents and young adults between 2010 and 2017, they continue to account for 36 percent of new HIV infections among adults aged 15 and above [2]. Although the number of adolescents and young adults living with AIDS is expected to decrease, attempt to end AIDS as a public health threat by 2030 can be challenging, partly because this segment of the population is expected to continue to grow rapidly (10 percent) from 2010 to 2050 [2]. This is especially so for countries located in Sub-Saharan Africa. In fact, adolescents account for the largest share of new HIV infections in South Africa [3].

The existing quantitative research either focuses on a specific country or region within a country or uses no more than three waves of data [3–9]. Only two studies take the spatial trends in HIV into account focus on more than one country [2,10]. One study attempts to estimate the HIV incidence trends for adolescents and young adults (age 15–24) from 2010 to 2050 for 148 countries by taking demographic projections and recent trends in HIV interventions into account [2]. The other study attempts to compare excess mortality before and after the implementation of antiretroviral therapy (ART) among people living with HIV using longitudinal data from Malawi, South Africa, Tanzania, and Uganda [10].

To fill the gaps in the current body of literature, this study attempts to use spatial-temporal clustering to examine how HIV prevalence trends differ across the 135 countries listed in the World Bank DataBank. This is one of the pioneering studies that seeks to classify and assign the different countries into their distinctive spatial-temporal clusters based on their trends in the prevalence of adolescent boys and young men (ABYM) and adolescent girls and young women (AGYW) with HIV. This study is timely and warranted because adolescents and young adults continue to account for 36 percent of the new infections among those aged 15 [2]. Using more than three waves of the data through spatial-temporal cluster analysis will better assess how the prevalence of HIV among ABYM and AGYW changed over time and the effectiveness of disease control initiatives in each country. By doing so, policy-makers and practitioners can better implement programs to control the AIDS epidemic. By utilizing current trends in the HIV prevalence among ABYM and AGYW, these results illustrate which clusters of countries should be the focus for HIV prevention programming and research in order to achieve the targets outlined by the 95-95-95 goal.

2 Methods

2.1 Definition

For each country, the UNAIDS estimates of HIV prevalence among ABYM and AGYW (i.e. those ages 15–24), ART coverage for people living with HIV, and the number of newly infected adults (age 15 and over) are downloaded from the World Bank DataBank [11–14]. Because the number of newly infected adults refers to men or women aged 15 and over in 2018 [14], the percentage of newly infected men and women in the age range of 15 to 24 is estimated from

$$\left(\frac{\#\ of\ men\ 15\text{–}24}{\#\ of\ individuals\ 15\text{–}24 + \#\ of\ individuals\ 25\text{–}54 + \#\ of\ individuals\ 55\text{–}64 + \#\ of\ individuals\ 65\ and\ over}\right) * \#\ of\ newly\ infected\ cases\ for\ individuals\ aged\ 15\ and\ over$$

and

$$\left(\frac{\#\ of\ women\ 15\text{–}24}{\#\ of\ individuals\ 15\text{–}24 + \#\ of\ individuals\ 25\text{–}54 + \#\ of\ individuals\ 55\text{–}64 + \#\ of\ individuals\ 65\ and\ over}\right) * \#\ of\ newly\ infected\ cases\ for\ individuals\ aged\ 15\ and\ over.$$

The estimated number of ABYM and AGYW in 2017 and 2018 in the age range of 15 to 24 for countries with relative high HIV prevalence are obtained from the 2017 and 2018 World Fact Book of the United States Central Intelligence Agency [15]. The rates of population growth from the 2017 to 2018 for each of these countries are estimated as

$$\left(\frac{Est.\#\ of\ people\ aged\ 15\text{–}24_{2018} - Est.\#\ of\ people\ aged\ 15\text{–}24_{2017}}{Est.\#\ of\ people\ aged\ 15\text{–}24_{2017}}\right) * 100\%.$$

Data pertaining to the 2018 estimated number of deaths due to HIV/AIDS for men or women aged 15 and over for each of these countries are obtained from the UNAIDS [16]. Because of that, three steps are involved in the calculation of the death rates associated with AIDS for each country for men and women in the age range of 15 to 24. First, the percentage of men and women in this age range is first estimated as

$$\frac{\#\ of\ men\ 15\text{–}24}{\#\ of\ men\ 15\text{–}24 + \#\ of\ men\ 25\text{–}54 + \#\ of\ men\ 55\text{–}64 + \#\ of\ men\ 65\ and\ over}$$

and

$$\frac{\#\ of\ women\ 15\text{–}24}{\#\ of\ women\ 15\text{–}24 + \#\ of\ women\ 25\text{–}54 + \#\ of\ women\ 55\text{–}64 + \#\ of\ women\ 65\ and\ over}.$$

Then, this percentage is multiplied by the total number of deaths due to AIDS for men or women 15 and over obtained from the UNAIDS in order to get the number of deaths due to AIDS for men or women within this age range. Finally, the number of deaths due to AIDS for men or women within this age range is divided by the number of men or women in the 15–24 age range to get the percentage of deaths due to AIDS for men or women in this age range.

2.2 Analyses

Analyses are conducted using the R Statistical Computing Software. Spatial-temporal cluster analysis proceeds in three steps. The dissimilarity measures / distances among the HIV prevalence trends of these countries are calculated using the dynamic time warping (DTW) metric. DTW is an appropriate metric for the purposes of this study because it seeks to compare two time series by identifying the best alignment that minimizes the dissimilarities or distances between them in a given distance matrix.

After that, the Elbow Method, Silhouette Analysis, and the Calinsky Criterion are used to determine the optimal number of clusters. The Silhouette Analysis suggests two as the optimal number of clusters while the Calinsky Criterion suggests ten as the optimal number clusters for ABYM and nine optimal clusters for AGYW. When the Elbow Method is used to determine the optimal number of clusters, it seems that there is an "elbow" at two clusters even though the total within-clusters sum of squares change slowly and remain less changing after 9 or 10 clusters.

Finally, hierarchical agglomerative clustering is performed using the *hclust* function to classify and assign the different countries into their distinctive spatial-temporal clusters based on their longitudinal changes in HIV prevalence from 1990 to 2017. The *cutree* function is used to separate observations into ten groups for ABYM and nine groups for AGYW.

The Susceptibility, Infected, and Recovered (SIR) model within system dynamics modeling (SDM) is used to project the number of HIV infections by taking the ART coverage, population growth rates, and death rates associated with AIDS into account. SDM is limited to ABYMs and AGYW's living in countries assigned to clusters characterized by relatively high HIV prevalence in recent years. This deterministic epidemic model assumes that the population is fixed, the only way an individual can leave the susceptible state is to become infected. The model also assumes that the spread or transmission of a given disease is proportional to the size of the population based on the law of mass action from chemistry [17,18] that states that the rate of chemical reactions is proportional to the concentration of reactants [19]. In other words, this model assumes that infection rate is proportional to the product of susceptible and infected individuals [18] or the number of people in a population [20]. This mass-action model also assumes that the population in that country are homogeneously mixed [20] and infected individuals coming into random contact with other individuals within the same country [17,21]. Previous researchers have used the SIR model to assess the effectiveness of counselling and ART to control HIV infection [21–24]. Their findings suggest that the effectiveness of counseling and ART and the proportion of infected people receiving ART prevention are instrumental in the control and prevention of HIV/AIDS [21–24].

The time horizon for observing the system behavior is defined as ten years and the time step for the simulation runs is defined as one year. The flows of individuals between the susceptibility (S) and infected (I) states are described by the following ordinary differential equations (ODEs):

$$\frac{dS}{dt} = -\beta SI - (ART * I) + (popgrowth * I) - DI$$

$$\frac{dI}{dt} = \beta SI - (ART * I) + (popgrowth * I) - DI$$

where β is the transmission rate parameter and is defined as the effective contact rate divided by the individuals susceptible (S) to HIV infection. Effective contact is the likelihood of an interaction leading to an infection or the frequency of contact sufficient to lead to transmission between an infected and a susceptible individual [25]. S refers to the initial number of susceptible individuals and I refers to the initial number of infected individuals. *ART* refers to the rate at which infected individuals received antiretroviral therapy, *popgrowth* refers to the population growth rate, and D refers to the death rates associated with AIDS.

Because the number of individuals at-risk of HIV infection is not reported by the government agencies or any official sources of these countries, the estimated population aged 15 to 24 in 2017 is used as the initial number of individuals susceptible to HIV infection (S). The initial values for Infected (I) is set to be the number of people with infected with HIV in 2017. The rate of change in the number of people infected with HIV is formulated as

$$1 + \frac{(\#Infected_{2018} - \#Infected_{2017})}{\#Infected}.$$

The optimal and appropriate values for β's are obtained through the validation process that compares the simulated new number of HIV infections for 2018 with the new number of HIV infections reported by the World Bank DataBank. ART coverage in 2018 and rate of population growth from 2017 to 2018 are used as the initial ART coverage and population growth rate for the time horizon for observing the system behavior. The goal is to gauge what the future number of HIV infections will look like if the ART coverage, population growth rate, and the death rates associated with AIDS remains the same from 2018 onwards.

3 Results

3.1 Adolescent boys and young men (ABYM)

Spatial temporal cluster analysis yields 10 clusters for ABYM (Table 1, Figure 1). The cluster results will not be discussed in numerical order, but the severity of the epidemic in each cluster varies. The majority (60.44 percent) of these countries (81 out of 134) are assigned to the first cluster, characterized by *very low* percentages of men ages 15–24 with HIV (slightly above 0 to no greater than 0.5 percent) during 1990–2017 (figure provided upon request). Several other countries are assigned to the second cluster, characterized by *low* percentages of young men with HIV (slightly above 0 to about 1.5 percent) during 1990–2017 (top panel of Figure 2).

Countries assigned to the fourth cluster experience a peak in HIV prevalence either from the early to the mid-1990s (i.e. Bahamas), from 1998 to 2000 (i.e. Nigeria) or during the early 1990s (i.e. Uganda) (bottom panel of Figure 2). Nevertheless, HIV prevalence declined thereafter in Bahamas and Nigeria. In Uganda, HIV prevalence drastically declined from the early 1990s until the late

Table 1: Cluster by country for ABYM (Cl. denotes cluster)

Country	Cl.	Country	Cl.	Country	Cl.
Albania	1	Gabon	2	Norway	1
Algeria	1	Gambia	1	Pakistan	1
Angola	1	Georgia	1	Panama	2
Argentina	1	Ghana	2	Papua New Guinea	1
Armenia	1	Greece	1	Paraguay	1
Australia	1	Guatemala	1	Peru	2
Austria	1	Guinea	2	Philippines	1
Azerbaijan	1	Guinea-Bissau	5	Portugal	1
Bahamas	4	Guyana	5	Qatar	1
Bahrain	1	Haiti	2	Romania	1
Bangladesh	1	Honduras	2	Russian Federation	1
Barbados	5	Hungary	1	Rwanda	2
Belarus	1	India	1	Senegal	1
Belize	5	Indonesia	1	Serbia	1
Benin	2	Iran	1	Sierra Leone	2
Bolivia	1	Ireland	1	Singapore	1
Botswana	6	Italy	1	Slovak Republic	1
Brazil	1	Japan	1	Slovenia	1
Bulgaria	1	Kazakhstan	1	Somalia	1
Burkina Faso	3	Kenya	7	South Africa	8
Burundi	2	Kuwait	1	South Sudan	5
Cabo Verde	1	Kyrgyz Republic	1	Spain	1
Cambodia	2	Lao PDR	1	Sri Lanka	1
Cameroon	5	Lebanon	1	Sudan	1
Central African Republic	7	Lesotho	8	Suriname	2
Chad	2	Liberia	3	Tajikistan	1
Chile	1	Lithuania	1	Tanzania	7
Columbia	2	Luxembourg	1	Thailand	3
Comoros	1	Madagascar	1	Togo	2
Congo Dem. Rep.	2	Malawi	7	Trinidad and Tobago	2
Congo Rep.	2	Malaysia	2	Tunisia	1
Costa Rica	1	Mali	2	Uganda	4
Cote d’Ivoire	2	Mauritania	2	Ukraine	2
Cuba	1	Mexico	1	Uruguay	1
Cyprus	1	Moldova	1	Uzbekistan	1
Czech Republic	1	Mongolia	1	Vietnam	1
Denmark	1	Montenegro	1	Zambia	9
Djibouti	2	Morocco	1	Zimbabwe	10
Dominican Republic	5	Mozambique	9		
Ecuador	1	Myanmar	2		
Egypt	1	Namibia	9		
El Salvador	1	Nepal	1		
Equatorial Guinea	5	Netherlands	1		
Eritrea	1	New Zealand	1		
Estonia	1	Nicaragua	1		
Eswatini	10	Niger	1		
Ethiopia	2	Nigeria	4		
France	1	North Macedonia	1		

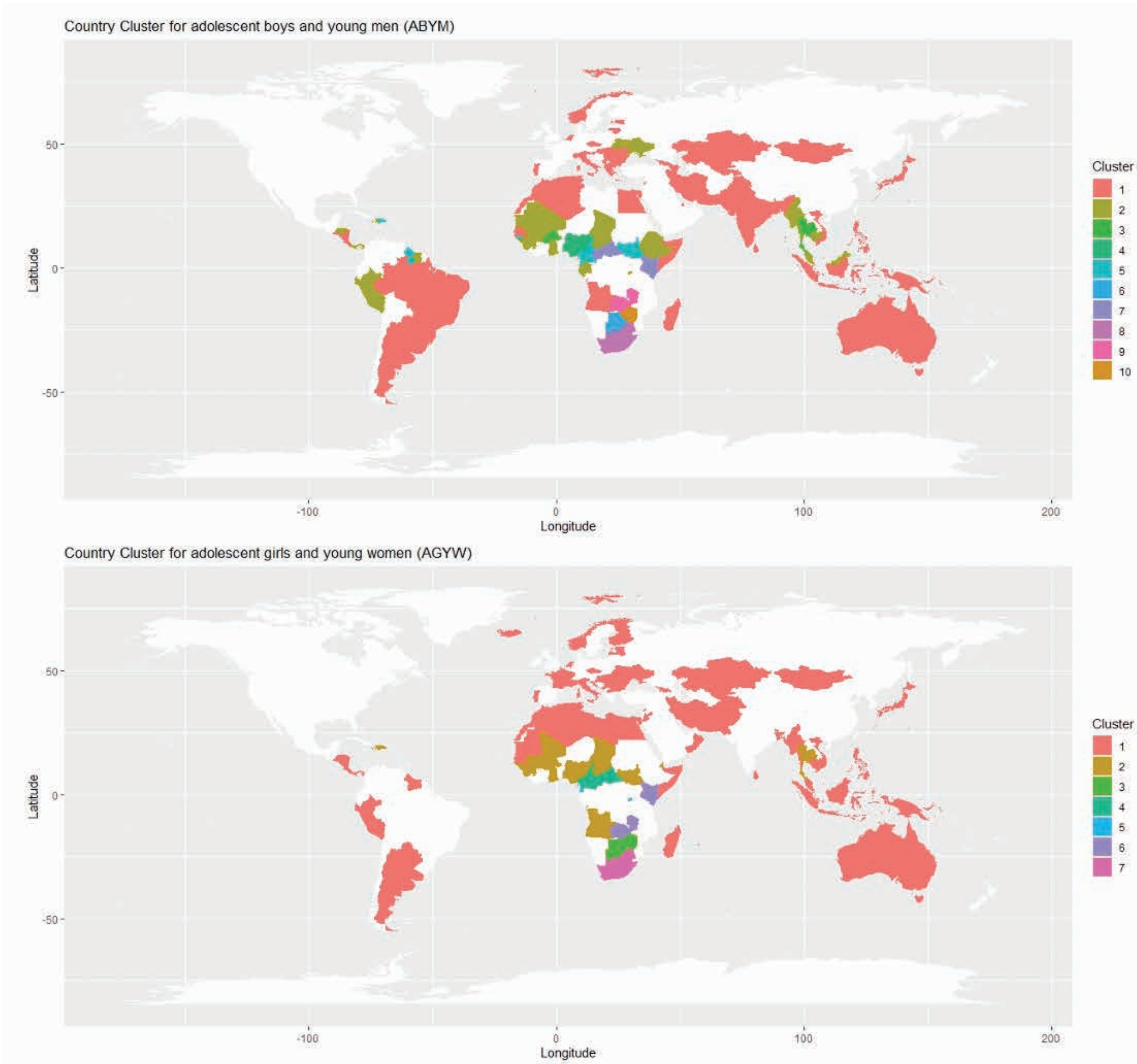

Figure 1: Cluster for ABYM (top) and AGYW (bottom). Note: White indicates that cluster assignment is not available because HIV prevalence data is not available for that country.

1990s, somewhat increased thereafter until 2010, and declined again afterwards. In general, these countries have *moderately low* HIV percentages of young men with HIV during the period of observation. During the peak, the percentages of young men with HIV for these countries range between 2 to 2.5.

Countries assigned to the fifth cluster (i.e. Barbados, Belize, Cameroon, Dominican Republic, Equatorial Guinea, Guinea-Bissau, Guyana, and South Sudan) have *moderately low* HIV prevalence (between 0 to 1.5 percent) for their younger male populations (bottom panel of Figure 2). Some of these countries experience a slight increase in HIV prevalence over time (e.g. Barbados, Belize, Guyana, and South Sudan). There is a noticeable increase in HIV prevalence in Equatorial Guinea over time. In Cameroon, Dominican Republic, and to a lesser extent, in Guinea-Bissau, the HIV prevalence peaked around year 2000 and declined thereafter.

Burkina Faso, Liberia, and Thailand are assigned to the third cluster, characterized *moderate* HIV prevalence with a peak during the 1990s and drastically declined thereafter (top panel of Figure 3). During the period of observation, the HIV prevalence of these countries ranges from 0.5 to slightly above 3. Countries assigned to the seventh cluster are also characterized by *moderate* HIV prevalence (e.g. Central African Republic, Kenya, Malawi, and Tanzania). The HIV prevalence for these countries

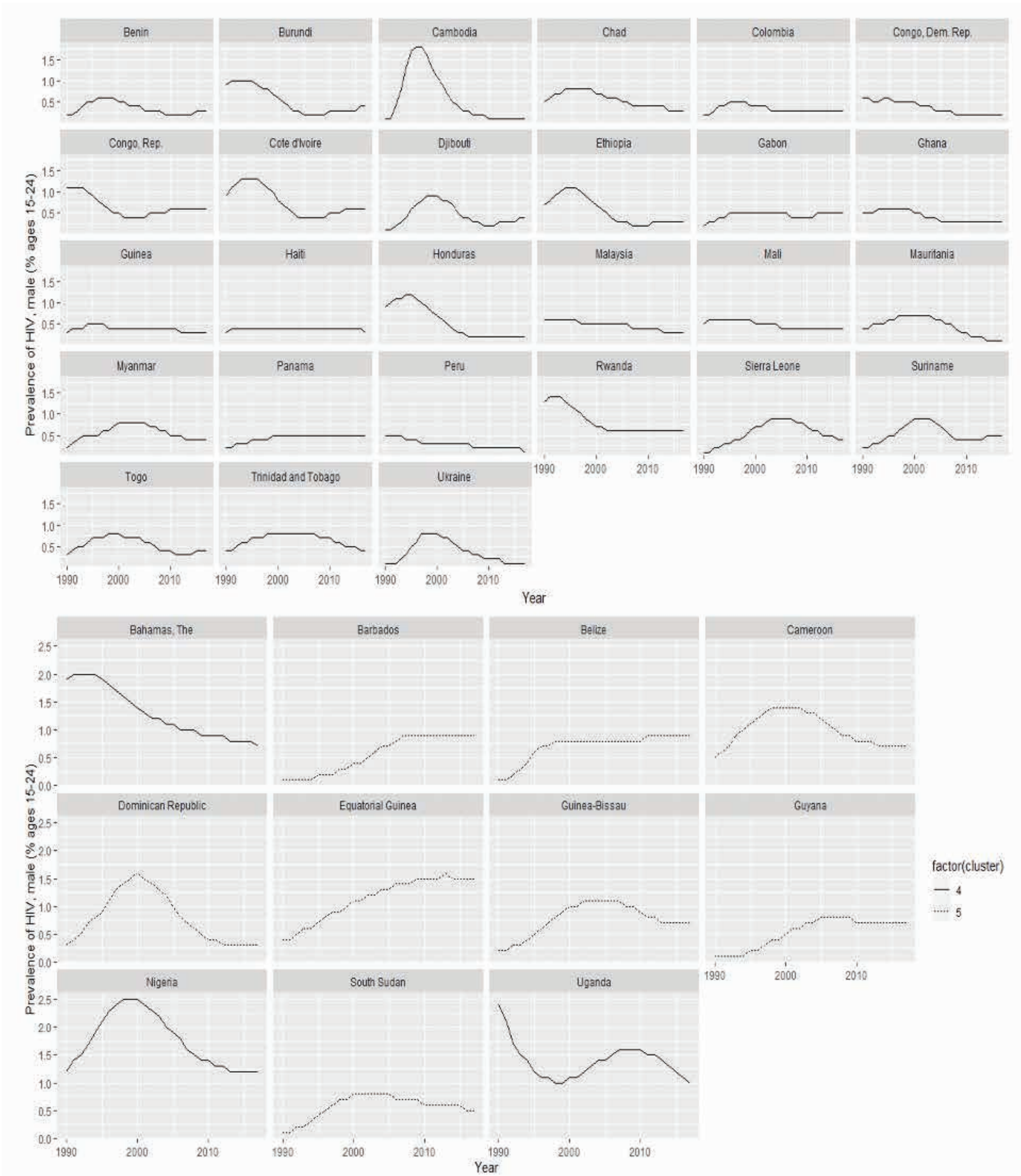

Figure 2: Countries with low (Cluster 2, top) and moderately low (bottom) percentages of ABYM with HIV.

peaked around the mid-1990s and declined thereafter (top panel of Figure 3).

Lesotho and South Africa are assigned to the eight cluster. As shown in the middle panel of Figure 3, in Lesotho, the percentages peaked in 1998 and 1999 (6.4 percent) and gradually declined with slight fluctuation thereafter. Similarly, the middle panel of Figure 3 also shows that in South Africa, the percentages of young men with HIV peaked between 1999 and 2001 (5.5 percent) and gradually decline thereafter.

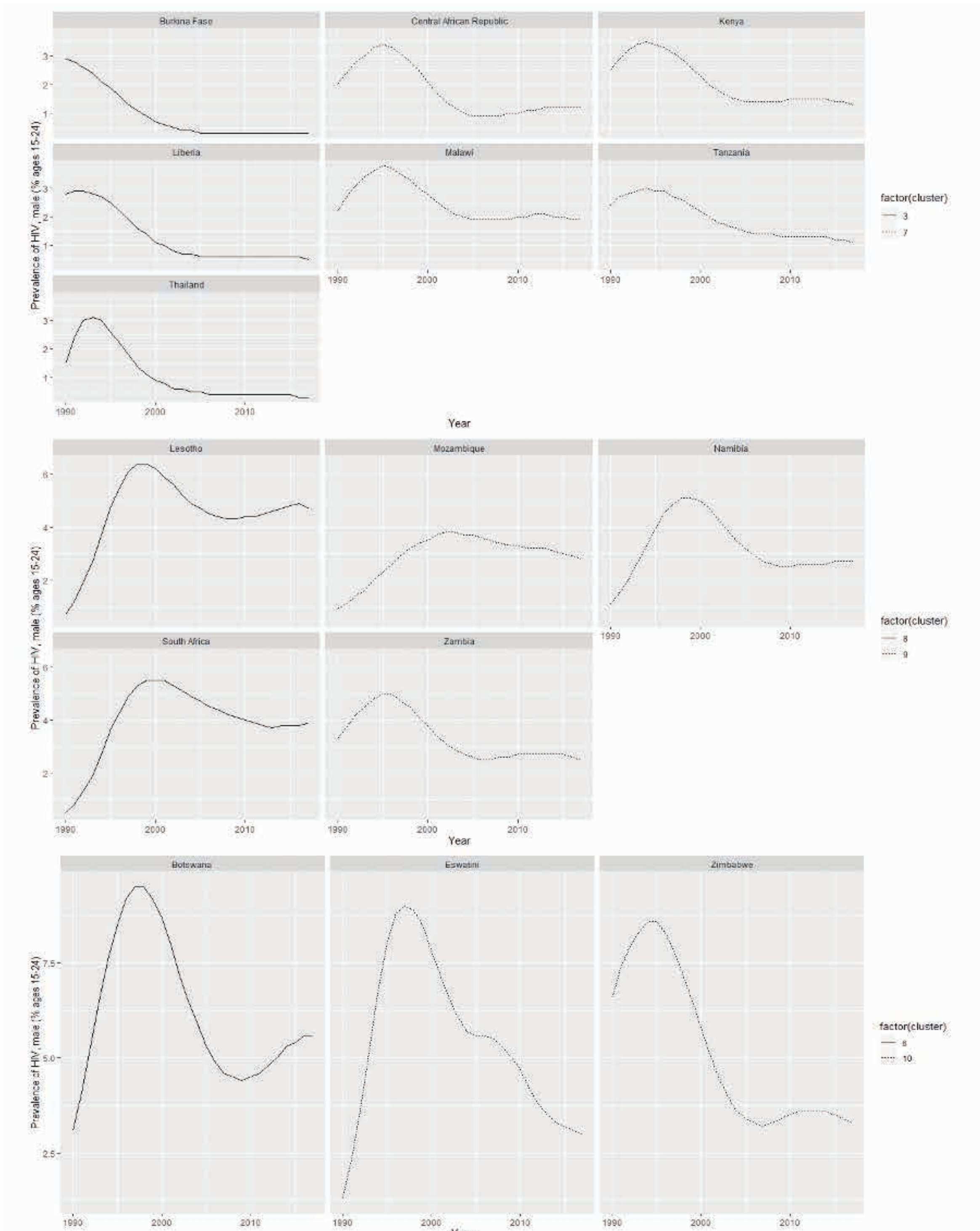

Figure 3: Countries with moderate (top), moderately high (middle), and high (bottom) percentages of ABYM with HIV.

Mozambique, Namibia, and Zambia are assigned to the ninth cluster. As shown in the middle panel of Figure 3, in Mozambique, the percentages of young men with HIV peaked in 2002 and 2003 (3.8 percent) and gradually declined thereafter. The middle panel of Figure 3 also shows that in Namibia, the percentages peaked in 1998 and 1999 (5.1 percent) and gradually decline thereafter. In Zambia, the prevalence peaked in 1995 and 1996 (5 percent) and slightly declined and remained relatively stable thereafter (middle panel of Figure 3).

Eswatini and Zimbabwe are assigned to the tenth cluster. As illustrated in the bottom panel of Figure 3, there is a drastic increase in the percentages of young men with HIV in Eswatini from the early 1990s until a peak is reached between 1996 to 1998 (8 to 9 percent) and after that, the percentages drastically declined thereafter. Likewise, in Zimbabwe, the percentages of young men with HIV drastically increased and peaked in 1994 and 1995 (8.6 percent). The percentages drastically declined until 2007 and slightly fluctuated thereafter (bottom panel of Figure 3). Botswana is assigned to the sixth cluster. As illustrated in the bottom panel of Figure 3, it is one of the countries with the highest percentages of young men with HIV. These percentages peaked between 1996 to 1999 (i.e. more than 9 percent for Botswana), drastically declined until 2009, and gradually increased thereafter (bottom panel of Figure 3).

3.2 Adolescent girls and young women (AGYW)

Spatial temporal clustering yields nine clusters for AGYW (Table 2). About 71.11 percent of these countries (96 out of 135) were assigned to the first cluster. These countries are characterized by *very low* percentages of AGYW with HIV (no greater than one percent) during 1990–2017 (figure provided upon request). Slightly over 16 percent of these countries are assigned to the second cluster, characterized by *low* percentages of young men with HIV for these countries were slightly higher (slightly above 0 to slightly 3.6 percent) during 1990–2017 (top panel of Figure 4).

The seven countries assigned to the fourth cluster are characterized by a peak in the percentages of AGYW with HIV around year 2000 (i.e. Cameroon and Gabon), during the early 1990s (i.e. Central African Republic, Congo Republic, Cote d'Ivoire, and Rwanda), or during the mid-1990s (i.e. Tanzania). The percentages of AGYW with HIV for these countries from 1990 to 2017 range from slightly over one to no higher than five percent (bottom panel of Figure 4). Equatorial-Guinea is assigned to the fifth cluster, with a slight and gradual increase in the percentages of AGYW with HIV from 0.5 percent in 1990 to slightly over three percent in 2017 (bottom panel of Figure 4).

Countries assigned to the sixth cluster (i.e. Kenya, Malawi, and Uganda) experience a peak in the percentages of AGYW with HIV during the mid-1990s (slightly over 10 percent for Kenya and Malawi and slightly below 15 percent for Zambia) and a decline thereafter (top panel of Figure 5). For Uganda, the percentages of AGYW with HIV was 9.3 percent in 1990 and gradually declined to 3 percent in 2017. Mozambique and Namibia are assigned to the eighth cluster. The top panel of Figure 5 shows that in Mozambique, the percentages of AGYW with HIV peaked in 2003 and gradually declined thereafter. In Namibia, these percentages peaked in 1999 and drastically declined thereafter. Even though the percentages of AGYW with HIV decline in these two countries, these are still considered *moderately high* in recent years (over 7 percent in Mozambique and close to 5 percent in Namibia) (Figure 5).

Lesotho and South Africa are assigned to the seventh cluster. As illustrated in bottom panel of Figure 5, the percentages of AGYW with HIV peaked around 2000 in Lesotho and slightly after 2000 in South Africa and gradually declined thereafter. Botswana and Zimbabwe are assigned to the third cluster. As illustrated in bottom panel of Figure 5, in Botswana, the percentages of AGYW with HIV peaked between 1997 and 1999 (over 23 percent) and declined thereafter. In Zimbabwe, the percentages of AGYW with HIV peaked between 1993 and 1995 (over 23 percent) and declined thereafter. Nevertheless, the percentages of AGYW with HIV for these two countries are still relatively *high* in recent years (more than 9 percent for Botswana and about 6 percent for Zimbabwe) when compared to countries assigned to the other clusters. Eswatini is assigned to the ninth cluster with percentages of AGYW with HIV peaked in 2000 and declined thereafter (Figure 5).

3.3 System dynamics modeling (SDM)

Findings from SDM suggest that new infections of HIV are estimated to increase (albeit at a declining rate) within the next two years for all the countries assigned to sixth, eighth, ninth, and tenth clusters for ABYM (Figure 6) and for all the countries assigned to third, sixth, seventh, and eighth clusters for AGYW (Figure 7). SDM is not performed for Eswatini as this country experience a drastic decline (about 30.98 percent) in its AGYW population from 2017 to 2018. These two figures also show that these estimated increases in new HIV infections plateaued in the first two years and continually declined thereafter for both ABYM and AGYW.

4 Discussion

Findings from the spatial-temporal cluster analysis demonstrate that trends in HIV prevalence among ABYM and AGYW differ by region. However, despite great effort

Table 2: Cluster by country for AGYW (Cl. denotes cluster)

Country	Cl.	Country	Cl.	Country	Cl.
Afghanistan	1	Gabon	4	Netherlands	1
Algeria	1	Gambia	1	New Zealand	1
Angola	2	Georgia	1	Nicaragua	1
Argentina	1	Germany	1	Niger	1
Armenia	1	Ghana	2	Nigeria	2
Australia	1	Guatemala	1	North Macedonia	1
Bahamas	2	Guinea	2	Norway	1
Bangladesh	1	Guinea-Bissau	2	Oman	1
Barbados	1	Guyana	1	Pakistan	1
Belarus	1	Haiti	2	Panama	1
Belize	2	Honduras	1	Papua New Guinea	1
Benin	1	Hungary	1	Paraguay	1
Bhutan	1	Iceland	1	Peru	1
Bolivia	1	Indonesia	1	Philippines	1
Bosnia & Herzegovina	1	Iran	1	Portugal	1
Botswana	3	Ireland	1	Romania	1
Bulgaria	1	Israel	1	Rwanda	4
Burkina Faso	2	Italy	1	Senegal	1
Burundi	2	Jamaica	1	Serbia	1
Cabo Verde	1	Japan	1	Sierra Leone	2
Cambodia	1	Jordan	1	Singapore	1
Cameroon	4	Kazakhstan	1	Slovak Republic	1
Central African Republic	4	Kenya	6	Somalia	1
Chad	2	Kuwait	1	South Africa	7
Chile	1	Kyrgyz Republic	1	South Sudan	2
Columbia	1	Lao PDR	1	Spain	1
Comoros	1	Latvia	1	Sri Lanka	1
Congo Dem. Rep.	2	Lebanon	1	Sudan	1
Congo Rep.	4	Lesotho	7	Suriname	1
Costa Rica	1	Liberia	2	Syrian Arab Republic	1
Cote d'Ivoire	4	Libya	1	Tajikistan	1
Croatia	1	Luxembourg	1	Tanzania	4
Cuba	1	Madagascar	1	Thailand	2
Czech Republic	1	Malawi	6	Togo	2
Denmark	1	Malaysia	1	Tunisia	1
Djibouti	2	Mali	2	Uganda	6
Dominican Republic	2	Mauritania	1	Ukraine	1
Ecuador	1	Mauritius	1	Uruguay	1
Egypt	1	Mexico	1	Uzbekistan	1
El Salvador	1	Moldova	1	Vietnam	1
Equatorial Guinea	5	Mongolia	1	Yemen	1
Eritrea	2	Montenegro	1	Zambia	6
Estonia	1	Morocco	1	Zimbabwe	3
Eswatini	9	Mozambique	8		
Ethiopia	2	Myanmar	1		
Finland	1	Namibia	8		
France	1	Nepal	1		

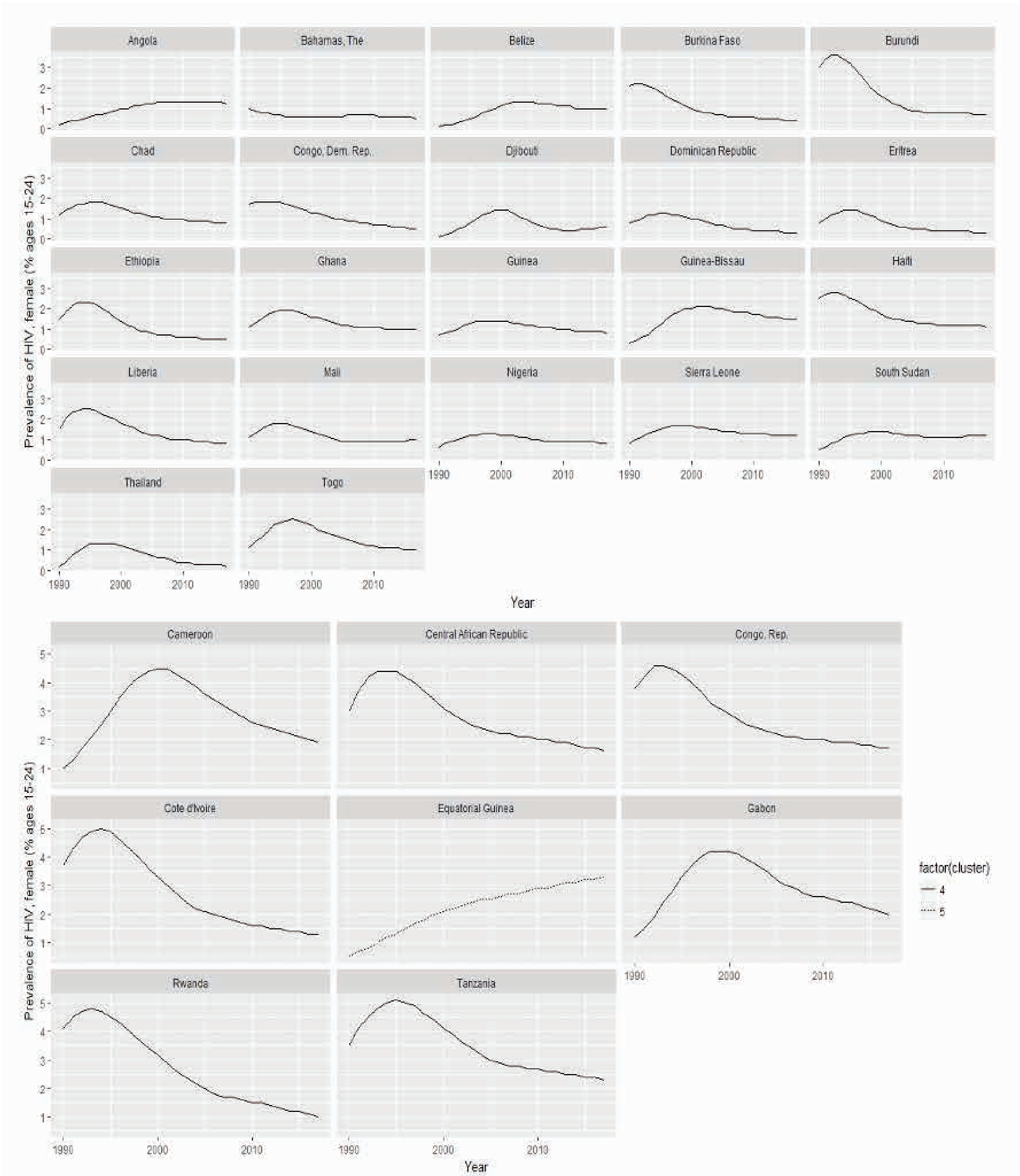

Figure 4: Countries with low (Cluster 2, top) and moderate (bottom) percentages of AGYW with HIV.

to monitor and control the spread of the epidemic, in 2018, HIV prevalence remains relatively high among ABYM living in countries assigned to the sixth, eighth, ninth, and tenth clusters and AGYW living in countries assigned to third, sixth, seventh, eighth, and ninth clusters when compared ABYM and AGYW living in countries assigned to the other clusters. It is also worth noting that during the same year, HIV prevalence remains high for ABYM living in Malawi, a country assigned to the seventh cluster and did not decrease for AGYW living in Mozambique, a

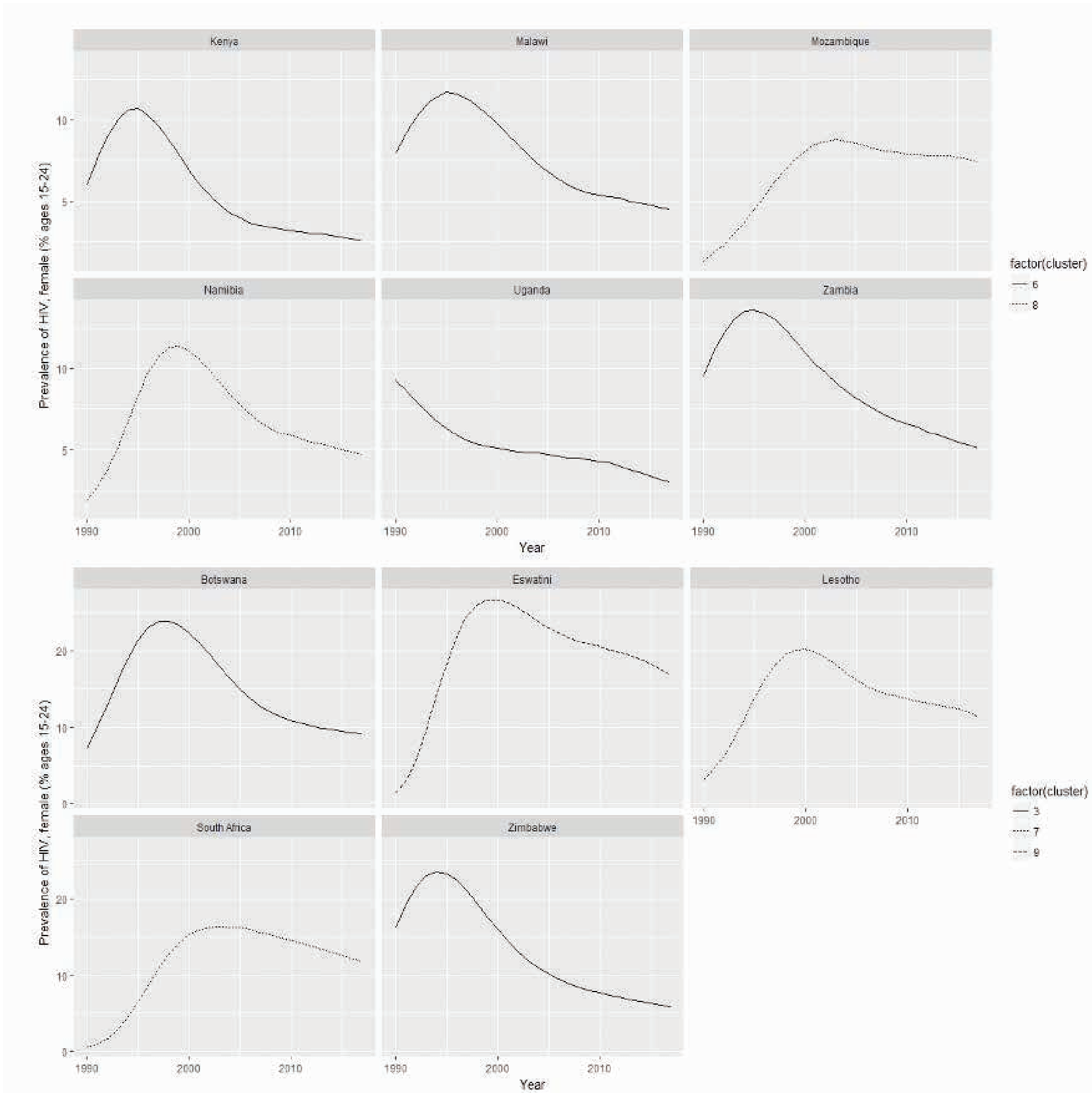

Figure 5: Countries with moderately high (top) and high (bottom) percentages of AGYW with HIV.

country assigned to the eighth cluster, in the last 10 years. All of these countries are located in eastern and southern parts of Africa (i.e. Botswana, Eswatini, Kenya, Lesotho, Malawi, Mozambique, Namibia, South Africa, Uganda, Zambia and Zimbabwe). This finding corroborates with a study that finds extremely high estimated HIV prevalence (more than 10 percent) in 2017 in these countries [6] and a report that compares Swaziland to other Sub-Saharan African countries and finds striking variations in HIV prevalence among adults aged 15 to 49 among these countries [26].

Findings from the spatial-temporal cluster analysis also reveal that the prevalence of HIV infection among ABYM and AGYW will not surge but will somewhat fluctuate over time. This is not surprising in light of a recent study conducted in rural KwaZulu, South Africa that found that the age-standardized HIV incidence rates remained relatively stable from 2004 to 2014 [9]. However, the trends in the prevalence of HIV infections differ by countries based on the country-specific epidemic trends, population growth dynamics, ART coverage, and HIV incidence and deaths related to AIDS. This implies that

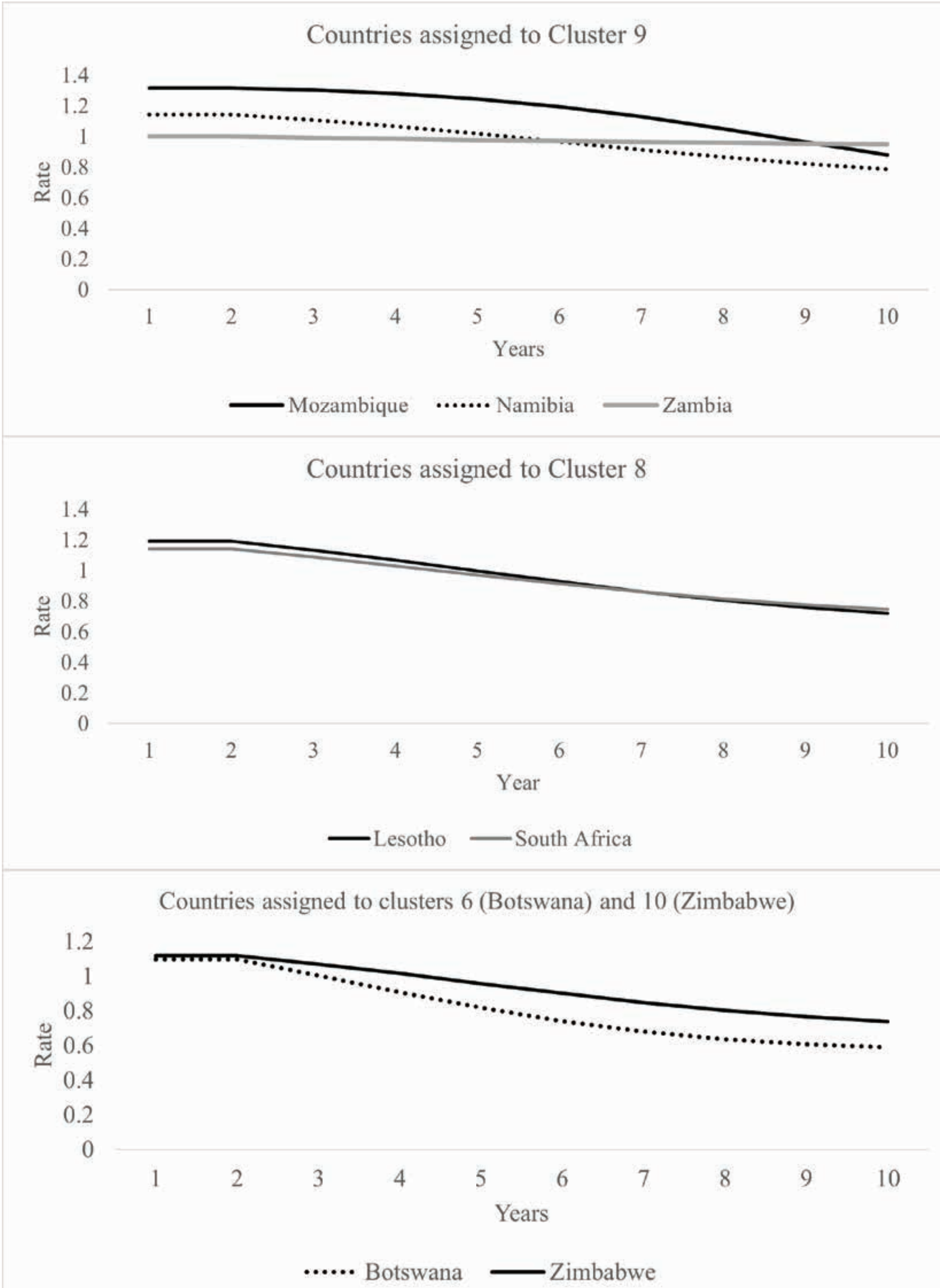

Figure 6: Rate of increase in the number of HIV infections for ABYM.

HIV will remain a challenging public health problem in these countries if HIV testing, ART coverage, and sustainability of treatment and care remain low for adolescents and young adults and if this segment of the population is expected to grow in the near future. This corroborates with an earlier study that finds that whereby population growth among adolescents and young people can pose additional challenge and obstacle to HIV prevention and treatment [2].

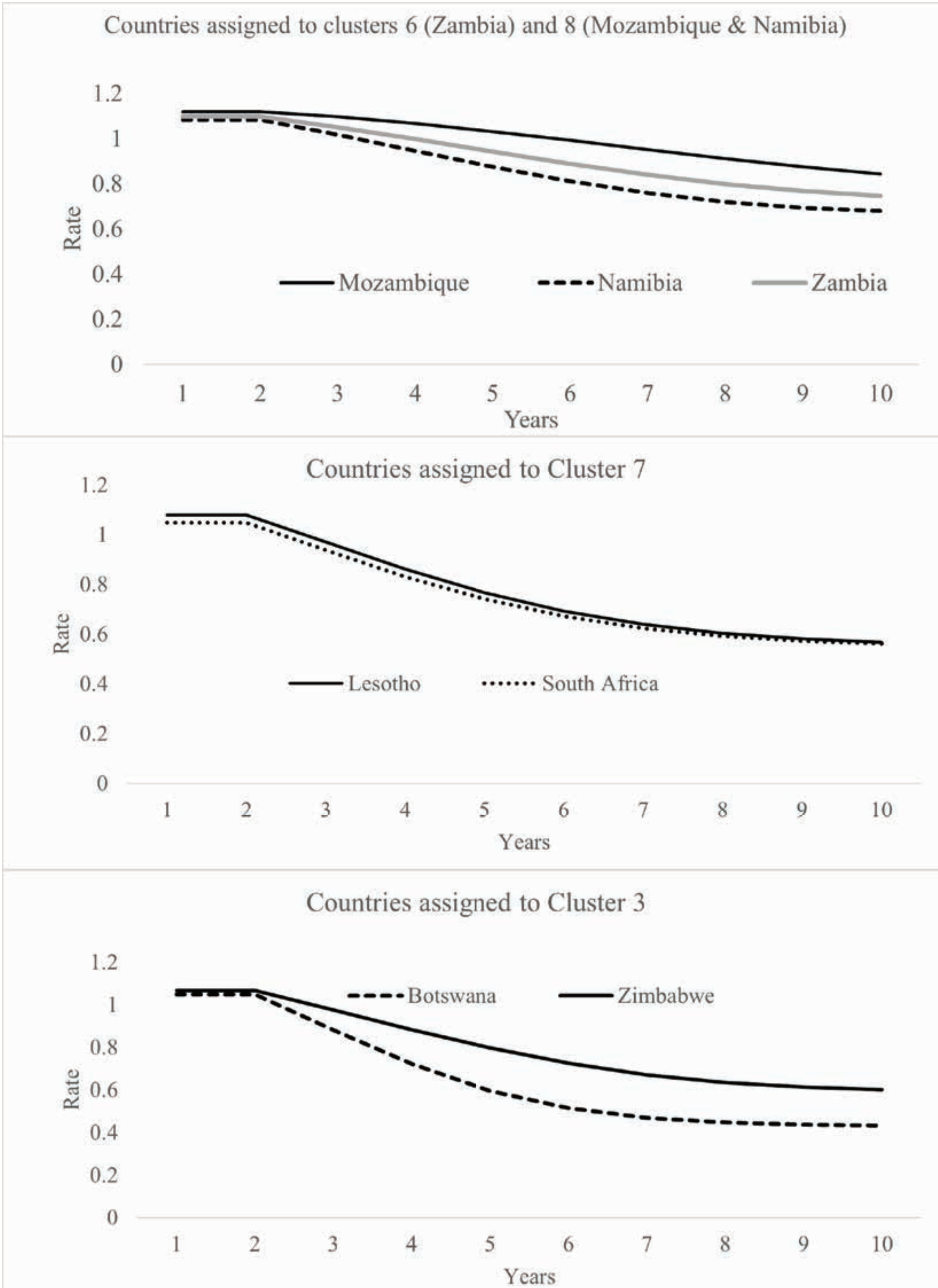

Figure 7: Rate of increase in the number of HIV infections for AGYW.

Another important finding is that the prevalence of HIV infection is considerably higher among AGYW than ABYM (Figures 3 and 4). This finding resonates with a study conducted in Lesotho that found slightly higher HIV prevalence among women aged 15 to 19 but considerably higher among women aged 20 to 24 when compared to their male counterparts [4]. This finding also resonates with a study conducted in rural KwaZulu that find notably higher HIV incidence rates among women aged 15–24 [9]. In fact, HIV prevention challenges are often gendered [2].

Similarly, the calibration of seven of the previous projection models confirms that HIV prevalence will increase among women in South Africa [7]. Relatedly, two recent studies that find that ABYM face different barriers to HIV prevention services compared to AGYW [27,28].

Findings from SDM resonate with the study of Khalifa et al. [2] that projected high population growth and drastic decline in increases in the percentages of new HIV infections among ABYM and AGYW in the eastern and southern parts of Africa by 2050. They also corroborates with projections that HIV prevalence will decline for men and women aged 15 to 24 [7] and another study that find high population growth rates as one of the main factors contributing to spatial clustering of new HIV infections [9]. Inaccessibility to ART and viral suppression are also the main barriers to effective control of the AIDS epidemic [5]. Studies by Johnson et al. [8] and Slaymaker et al. [10] reveal that AIDS-related deaths can be averted with the implementation of the ART. To achieve the global targets of ending AIDS as a public health challenge by 2030, these efforts should prioritize ABYM living in countries assigned to sixth, eighth, ninth, and tenth clusters (Figure 2) and AGYW living in countries assigned to third, sixth, seventh, eighth, and ninth clusters (Figure 4).

4.1 Limitations

There are three interrelated limitations in the analyses that dictate caution in interpretating the findings of this study. First, the system dynamics (SD) models only take ART coverage, population growth, and the number of deaths due to AIDS into account. Other key drivers of HIV such as number of concurrent sex partners, levels of male circumcision, condom and contraceptive use, injection drug use, use of testing and treatment services, sex work, and so forth are not included in SD models. This is because the UNAIDS estimates of the number of sex workers, injection drug users, people receiving pre-exposure prophylaxis, male circumcision performed, and percentages of condom use and male circumcision are neither broken down by age group nor available for each country in the eastern and southern Africa identified by the spatial-temporal clustering [16,29]. Second, because this study is based country-level (aggregated) data, it can be difficult to assess the assumptions under the SIR model. Therefore, it is almost impossible to assess whether this mass-action based model can be used to capture the dynamics of HIV transmission and the effectiveness of disease control in these countries because. It is difficult to determine whether the assumption that HIV infection rate is proportional to the size of the population although the global prevalence of HIV has stabilized over the past two decades [30] and the HIV prevalence for both ABYM and AGYW stabilized from 1990 to 2017 for almost all countries under observation [11,12]. Because there is no publicly available data on the sociodemographic characteristics (e.g. ethnic compositions, income, educational attainment, and so on) for those ages 15–24 for these countries it is hard to ascertain this segment of the population is in fact homogenously mixed. Since we do not have data on how individuals within a given country come into contact with one another, it was almost impossible to ascertain whether and random contact infected and non-infected individuals in that country come into random contact with one another. Therefore, once individual-level data pertaining to the HIV infection rates, sociodemographic characteristics, HIV infection status, and contact records become available, it is worthwhile for future researchers to examine whether each of these assumptions under the SIR model hold to better gauge the extent of HIV transmission and effectiveness of disease control in these countries. Finally, the estimated percentages of population getting tested and treated for HIV/AIDS by the UNAIDS are only available for those 15 and older [16,29]. Because of that, the calculation for the number of deaths due to AIDS among those between ages 15–24 is based on the assumption that the number of deaths is equal in each age group.

5 Conclusions

Overall, the findings suggest that attempts to end AIDS as a public health threat by year 2030 will remain a challenge if the current ART coverage, population growth rates, and AIDS-related death rates were to continue into the next decade. Findings pertaining to the eastern and southern parts of Africa hinges on the possibility that poor care-seeking behaviors [2] like low and sporadic use of condoms and adherence to ART [31], and other social and structural deprivation continued to prevent adolescents' capacity to protect themselves and others from acquiring HIV. Interventions that integrate clinical care and minimizing problems associated with socio-economic deprivations can also improve HIV prevention and priority should be given to adolescents and young adults [31]. Other prevention efforts include abstinence and delaying the onset of sexual intercourse as well as incorporating the ART into the existing needle and syringe programs [1].

In fact, the 2019 World AIDS Day Report by the UNAIDS suggest that on average, about 6,000 women aged 15–24 become infected with AIDS in a given week and in Sub-Saharan Africa, women in this age range are twice as likely to be living with AIDS than their male counterparts [29]. Customized treatment through shared decision making and addressing the structural drivers of HIV testing and transmission within the patriarchy system may also indirectly help reduce and prevent HIV transmission for these individuals especially for AGYWs.

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