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Short communication

POLICI: A web application for visualising and extracting yellow fever vaccination coverage in Africa

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ABSTRACT

Recent yellow fever (YF) outbreaks have highlighted the increasing global risk of urban spread of the disease. In context of recurrent vaccine shortages, preventive vaccination activities require accurate estimates of existing population-level immunity. We present POLICI (POpulation-Level Immunization Coverage – Imperial), an interactive online tool for visualising and extracting YF vaccination coverage estimates in Africa.

We calculated single year age-disaggregated sub-national population-level vaccination coverage for 1950–2050 across the African endemic zone by collating vaccination information and inputting it into a demographic model. This was then implemented on an open interactive web platform.

POLICI interactively displays age-disaggregated, population-level vaccination coverages at the first sub-national administrative level, through numerous downloadable and customisable visualisations. POLICI is available at https://polici.shinyapps.io/yellow_fever_africa/.

POLICI offers an accessible platform for relevant stakeholders in global health to access and explore vaccination coverages. These estimates have already been used to inform the WHO strategy to Eliminate Yellow fever Epidemics (EYE).

1. Introduction

Yellow fever (YF) is a vector-borne haemorrhagic fever caused by the YF virus, of the genus *Flavivirus* endemic to Africa and South America [1]. Recent outbreaks in Angola, Brazil and Nigeria have raised the fear of resurgence and international spread of the disease [2,3].

While no specific treatment for YF exists, a highly efficacious vaccine that confers lifelong protection with a single dose has long been available [4]. Due to the presence of a non-human primate sylvatic reservoir YF cannot be eradicated, but achieving a sufficient population-level vaccination coverage can substantially diminish the probability of an outbreak. In a context of recurrent vaccine shortages [2] preventive vaccination activities need to be prioritized, considering both the local risk of YF and existing population-level immunity.

Due to the lifelong immunity conferred by the vaccine, all previous vaccination activities contribute to contemporary population-level immunity. To estimate the African burden of the disease, Garske et al. [5] systematically collated information on past YF vaccination activities and combined this with demographic information to estimate population-level vaccine-derived immunity coverage in the African endemic zone. This work provided past and future coverage estimates from 1940 to 2050. Following a very similar approach, Shearer et al. [6] produced estimates of coverage from 1970 to 2016 for both Africa and Latin America.

Interpreting vaccination coverage data for public health or policy often requires considering various specific stratifications (by time, location and age group) that static tabular presentations do not effectively communicate. Providing an interactive, user-friendly graphical tool to allow the visualisation and extraction of vaccination coverage estimates will increase the accessibility of this pertinent information to public health decision-makers. Here, we present the POLICI (POpulation-Level Immunization Coverage – Imperial) online tool, developed in the programming language R [7]. We showcase both disaggregated estimates of YF vaccination coverage across the endemic zone of Africa, as well

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as a web-based interface which offers an interactive and accessible way for global and public health professionals to utilise this information without specialist knowledge or software.

2. Methods

The primary aim of this application is to provide an accessible, easy-to-use tool to visualise the coverage of YF vaccination across Africa through time. In order to achieve this, we placed an emphasis on interactivity which we attained by combining the R packages Shiny, Leaflet and Plotly [8], to create interactive maps and graphs in order to allow the user to customise plots of population-level vaccination coverage, and to download the underlying datasets.

2.1. Demographic data

As previously described [5], we used UN World Population Prospects (UN WPP) data [9] to inform the size of any annual birth cohorts between 1940 and 2050 for 34 African countries considered endemic or at risk for YF. We furthermore aggregated gridded population estimates from LandScan 2015 [10] to the province or district (first and second sub-national administrative unit, respectively), and scaled the national population size through time with the proportion of the population estimated for each province or district to achieve higher spatial resolution, assuming the national age distribution throughout.

2.2. Vaccination data

YF vaccination activities were collated from various sources on (i) historical large-scale vaccination activities 1940–1960s [11], (ii) outbreak response campaigns since 1970 reported in the WHO Weekly Epidemiological Record [12], and WHO Disease Outbreak News [13], (iii) routine infant YF immunization as reported by the WHO/UNICEF Estimates of National Immunization Coverage (WUENIC) [14], and (iv) preventive mass vaccination campaigns conducted as part of the Yellow Fever Initiative (YFI) [15]. We compared the resulting list of activities with data from the WHO International Coordinating Group (ICG) on Vaccine Provision and resolved any discrepancies. By drawing vaccination coverage activities from a wide variety of sources, including the grey literature, and validating these with the help of the ICG, our dataset represents a very robust and inclusive catalogue of previous vaccination activities in Africa.

Vaccination activities were resolved to the district level while recording the magnitude of the activity (coverage achieved, target population or doses administered), as well as the age groups targeted.

2.3. Estimation and visualisation of population-level vaccination coverage

The completeness and available detail of information regarding vaccination activities was highly variable. When provided, we used information on the coverage achieved in a specific area, either estimated through post-campaign surveys or administratively reported (with a preference given to the former as this is generally considered as more reliable). In the absence of information on coverage, we estimated the coverage by dividing the number of doses administered by the population size of the area targeted.

We assumed that all targeted age groups had an equal chance to receive vaccination, and we used a variety of approaches to combine subsequent vaccination activities targeting the same subpopulations dependent on the situation and available information.

As a default we assumed no correlation between subsequent vaccination activities, so the combined coverage from two subsequent activities was calculated as

$$vc_{combined} = 1 - \frac{(1 - vc_1)}{(1 - vc_2)}. \quad (1)$$

This approach was applied when precise geographic information on the target area and magnitude of the campaign were provided. In some cases, in particular for large preventative campaigns that were performed in stages over several years, information was only available at the scale of the overall target area, and no further information was available regarding the sequence of implementation across sub-areas. We assumed that subsequent campaigns would target those previously unvaccinated, and therefore the resulting coverage was given as

$$vc_{combined} = vc_1 + vc_2(1 - vc_1). \quad (2)$$

For routine infant immunization we used WUENIC data and assumed vaccination of the yearly cohorts at 1 year of age for the entire respective country without subnational heterogeneities and without prior coverage of the respective cohort.

Combining routine immunization and campaigns, we calculated the achieved vaccination coverage by age and province for each year between 1940 and 2050 by incorporating information on YF vaccination activities into our demographic model. For onward projection after 2017, we assumed that routine infant immunization coverage was maintained at the 2017 levels, with no further vaccination campaigns. For each province, time-varying population-level vaccination coverage was calculated by aggregating the age-specific vaccination coverage for all age groups.

To disseminate these estimates the online tool is made available at https://polici.shinyapps.io/yellow_fever_africa/.

3. Results

To illustrate the usage of the POLICI app we will explore the history of vaccination coverage of Benin.

The history of vaccination activities in Africa since vaccine development has been varied. From the 1940s to 1960s, populations under French control in West Africa benefitted from compulsory mass vaccination campaigns. While there is only limited information on the distribution of doses during that time, this likely achieved a coverage of over 80% in most targeted countries by 1960 (Fig. 1, tab Endemic Zone, year = 1960).

This was highly effective in preventing yellow fever outbreaks, but following the withdrawal of France from West Africa in the 1960s these activities ceased. Susceptible populations grew through the accumulation of unvaccinated birth cohorts. In Benin the vaccination coverage reached a low of around 19.4% by 1996 (tab "Country maps", select "country" = "Benin", year = 1996). From 1985 to 2005, YF incidence gradually increased with 3 outbreaks recorded between 1985 and 2005 in Benin [1]. Subsequent vaccination activities were largely restricted to outbreak response campaigns of limited scope. This is directly observable in Benin where a limited reactive vaccination campaign in the provinces of Atakora and Borgou during 1997 only managed to raise coverage to an average of 32.9% across these provinces (Fig. 2).

Since the late 1980s, the YF vaccine has been adopted into the national Extended Programmes of Immunization in an increasing number of countries, covering 23 African countries by 2016 [14]. However, routine vaccination only targets new birth cohorts and therefore has a slow effect on increasing vaccination coverage. Variable routine coverage achieved over time leaves a clearly visible signature in the age distribution of vaccination (tab "Age Distribution", country = "Benin", year = 2009) (Fig. 2).

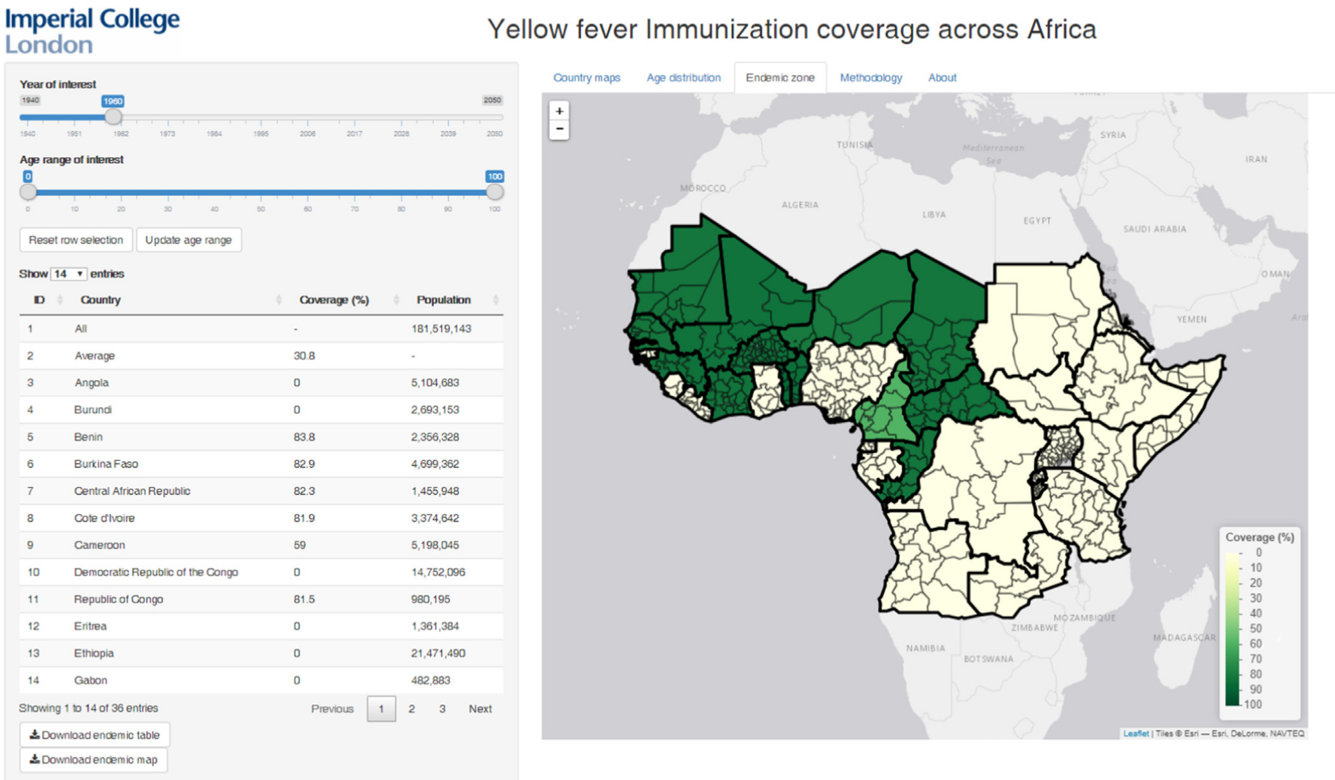


Fig. 1. “Endemic zone” tab showing a table and map of the vaccination coverages at the country level across the African endemic zone.

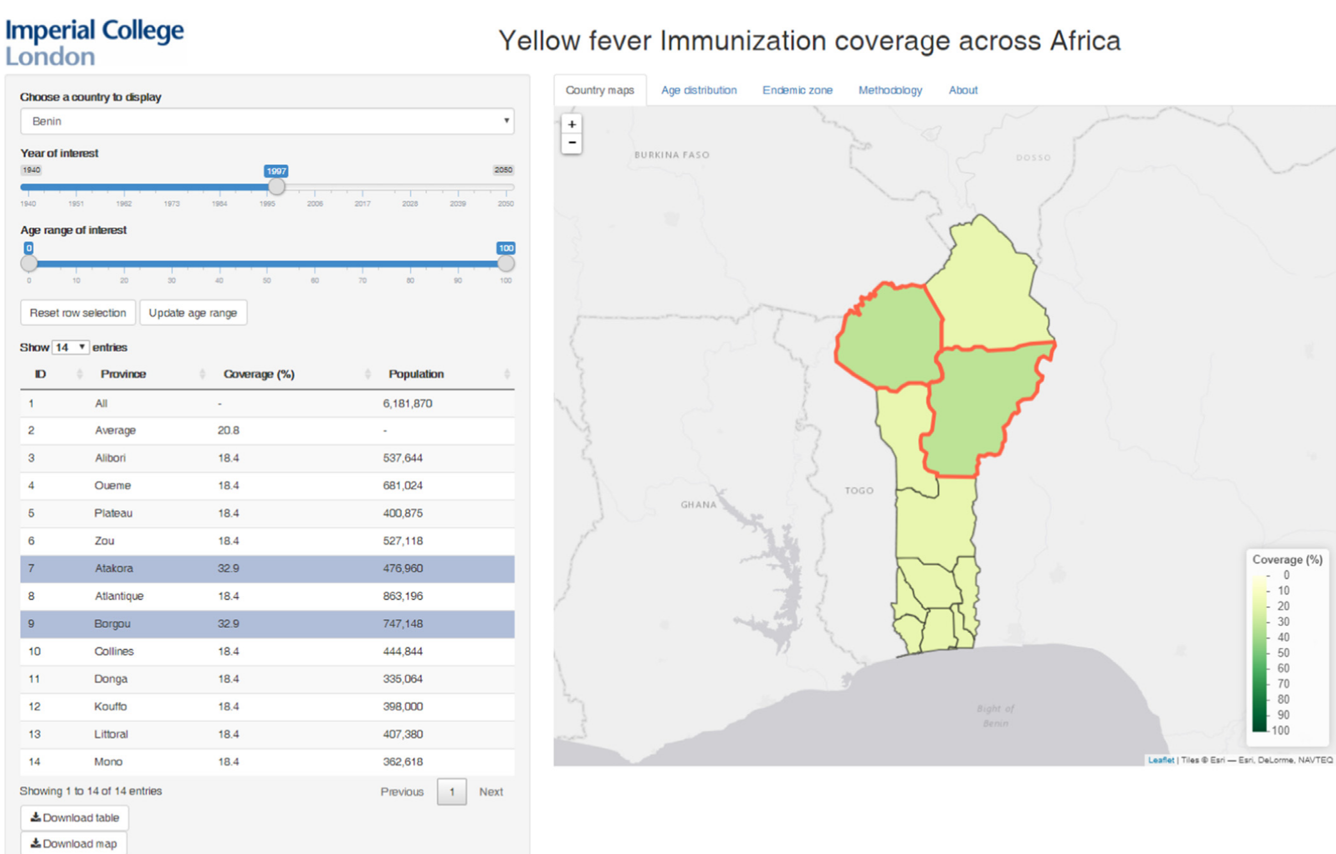


Fig. 2. “Country maps” tab showing a table and map of the vaccination coverage at the province level in Benin 1997 with two provinces highlighted, and the country average.

This haphazard implementation of YF vaccination created a patchy pattern of coverage both geographically and demographically, with low coverage across most of the endemic zone by 2005. To combat the occurrence of large outbreaks, the YFI was launched in 2006 as a collaboration led by WHO and UNICEF with support from Gavi, the Vaccine Alliance [15]. Several large-scale preventive vaccination campaigns were conducted in West Africa, dramatically reducing the burden in the 14 countries targeted by the YFI, though coverage remains patchy in countries that have not been targeted (tab "Endemic zone", year = 2017). The effect of this can be directly observed in Benin, where in 2009 a campaign boosted population-level vaccination coverage to a country-level average of 92.3% (tab "Country maps", country = Benin, year = 2010).

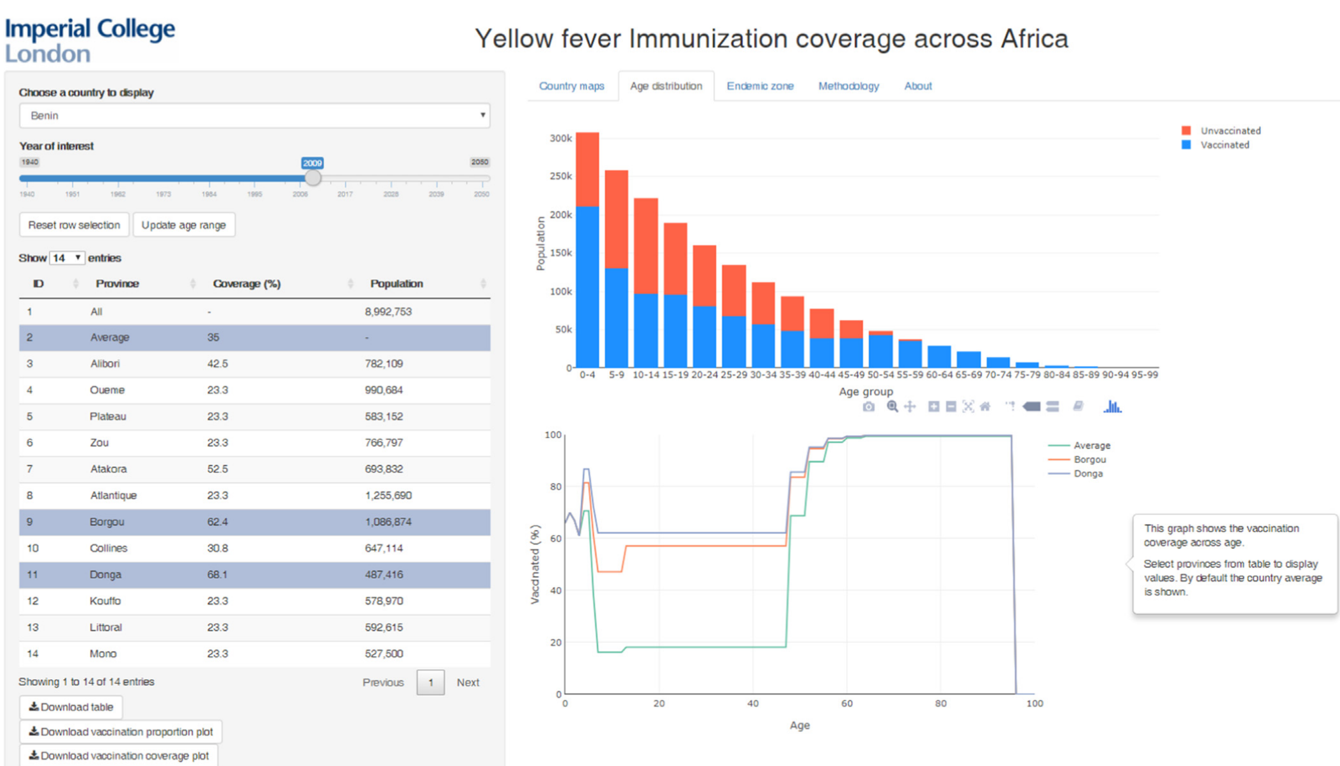
Heterogeneities in coverage complicate the planning of further campaigns as it is usually not possible to distinguish vaccinated and unvaccinated individuals, e.g. based on vaccination cards or registers, and it can be inefficient to target all locations and age groups within a country equally, due to pre-existing immunity. The visualisations available in the tool can serve to highlight areas of concern across the endemic zone as well as at the country level Fig. 3.

4. Discussion

Vaccine-related data such as target population, doses administered, or coverage achieved are typically available at the level of individual vaccination activities. However, the protection of populations afforded by the vaccine depends on the coverage at population level, which is a result of the history of vaccination activities a population was exposed to. We calculate this population-level coverage by consolidating this history in a demographic model. The POLICI tool provides an easy way to visualize these combined estimates, but also to the underlying estimates, interactively across the endemic zone as well as for any sub-geographies or specific age groups at any point in time.

Our vaccination coverage estimates rely on several assumptions. In the absence of reliable data available in all countries considered, within-country age structures where assumed to be homogeneous and population movements, within and between countries, were neglected. Movement, particularly from rural to urban areas, likely has a substantial impact on "diluting" population-level vaccination coverage especially in countries experiencing high rates of urbanisation, as many of those within the YF endemic zone are [16]. This may result in urban/rural discrepancies between the calculated and actual coverage. Coverage estimates are highly sensitive to uncertainties in population sizes, though quantification of these uncertainties is not currently available. We additionally cannot exclude that some vaccination activities were missed out, or doses wasted, which would translate in under-estimated coverages. Additionally, with the EYE strategy aiming to eliminate epidemic yellow fever by 2030, and increased funding in the area following recent outbreaks our projections are very likely to substantially underestimate future population-level coverage, as they only consider routine-infant immunization. However, this requires a maintained commitment to vaccination - or YF could well re-emerge again as it did in the 80's and 90's across West Africa [1].

Shearer et al. recently published similar estimates of YF vaccination coverage in Africa and Latin America [6]. However, their vaccination coverage is considerably lower than our results in several West and Central African countries. It appears that estimates by Shearer et al do not account for several recent large-scale campaigns in West and Central Africa, mostly performed as part of the YFI since 2006. Overall, these activities represent a total of nearly 31 million doses administered between 2006 and 2016 (See Supplementary Table 1). For example, accounting for these neglected campaigns led us to estimate a country level coverage of 88.5% in Benin in 2016, substantially higher than the 40% upper estimate provided by Shearer et al. [6].



ID	Province	Coverage (%)	Population
1	All	-	8,992,753
2	Average	35	-
3	Alibori	42.5	782,109
4	Oueme	23.3	990,684
5	Plateau	23.3	583,152
6	Zou	23.3	766,797
7	Atakora	52.5	693,832
8	Atlantique	23.3	1,255,690
9	Borgou	62.4	1,086,874
10	Collines	30.8	647,114
11	Donga	68.1	487,416
12	Kouffo	23.3	578,970
13	Littoral	23.3	592,615
14	Mono	23.3	527,500

Fig. 3. The "Age distribution" tab showing the number of individuals vaccinated and unvaccinated by age group and the proportion of each age group vaccinated for the whole country with examples of popups describing the information contained in the plots.

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.vaccine.2019.01.074.

Previous research has found that within infectious disease epidemiology there is a strong interest in dynamic, interactive graphics which allow the user to understand the information, and its place in a wider context [17]. POLICI achieves this through customisable and interactive tables, maps and graphs which allow us to convey this information simply but effectively. Online hosting also allows users to connect remotely and without specialist software, and by facilitating the downloading of plots and tables it allows the information contained within this application to be utilised off-line.

POLICI has already garnered considerable interest from both scientists and decision-makers. It has been used as part of a recent study modelling the 2016 Angola outbreak [18] and been utilised in 2016 by the World Health Organization to inform the reframed global strategy to Eliminate Yellow fever Epidemics (EYE) [19]. While this application is currently limited to Africa, expansion of estimates of YF vaccination coverage across South America is underway. Though historically comprising a smaller burden, and with increased capability to respond to YF, the recent outbreak in the South-East Atlantic Coast of Brazil highlight the need for further information on the underlying population-level coverage to both respond to and protect at risk populations [2].

Furthermore, the online, shiny-based format, allows for regular maintenance, including updates to the vaccination coverages and incorporation of new features. Development is currently underway to expand the tool to include YF vaccination coverage for South America and diversifying the tool to include the 10 diseases covered by the Vaccine Impact Modelling Consortium (VIMC) [20] is being considered.

Resources

https://shiny.dide.imperial.ac.uk/polici/.

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Conflict of interest

The authors declared that there is no conflict of interest.

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Conflict of interests

The authors declare no conflicts of interest.

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