The geography of measles vaccination in the African Great Lakes region

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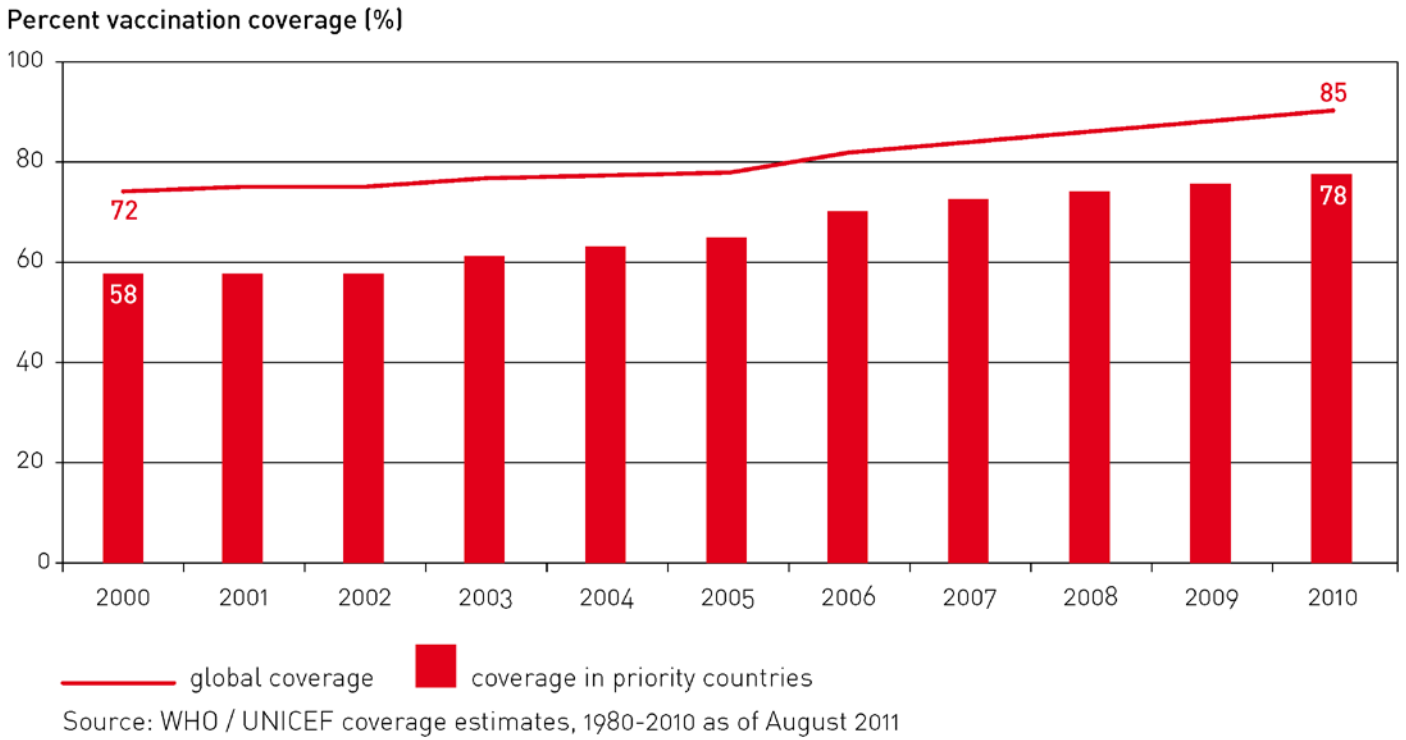
Measles control and elimination

- Measles control is one of the most cost-effective public health interventions
- Substantial gains made in measles vaccination coverage over recent decades

Figure 2: 1st Dose Measles Coverage Globally and in 47 Measles Priority Countries 2000-2010

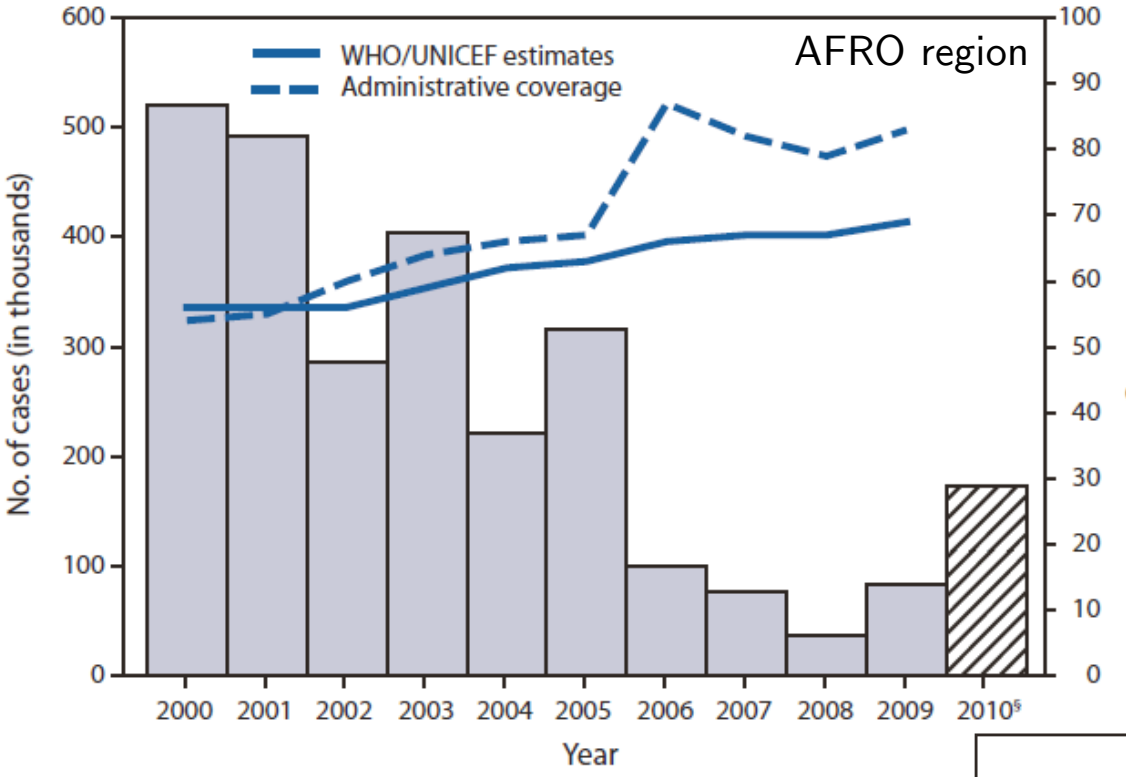


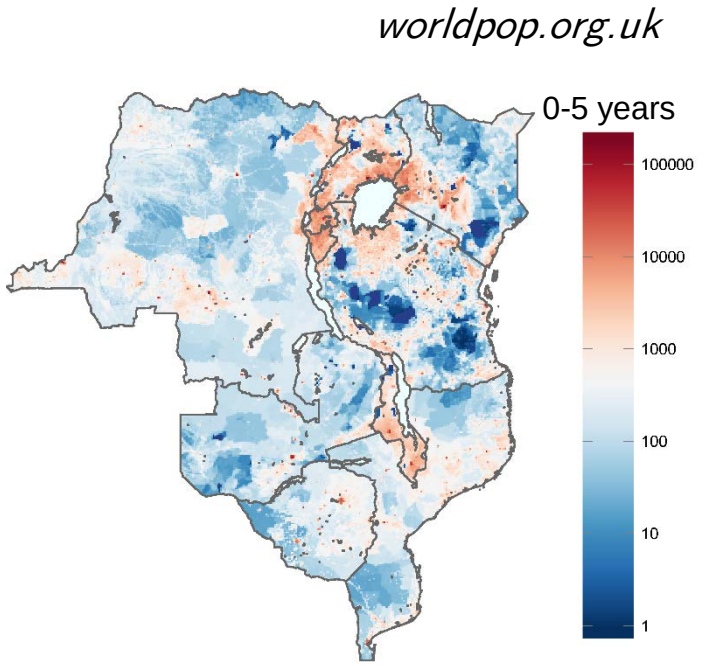
Source: WHO / UNICEF coverage estimates, 1980-2010 as of August 2011

- All WHO regions currently target measles elimination by 2020

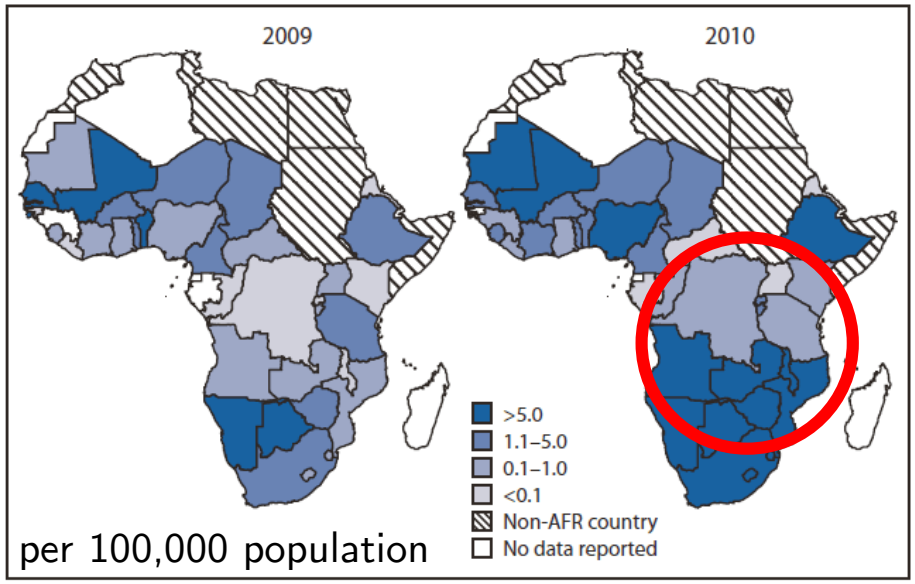
Global M&R Strategic Plan (2012)

Recent resurgence of measles in sub-Saharan Africa





Despite overall national coverage levels, clustering of low vaccination areas may allow for pockets of susceptibility



MMWR (2011)

A shifting focus

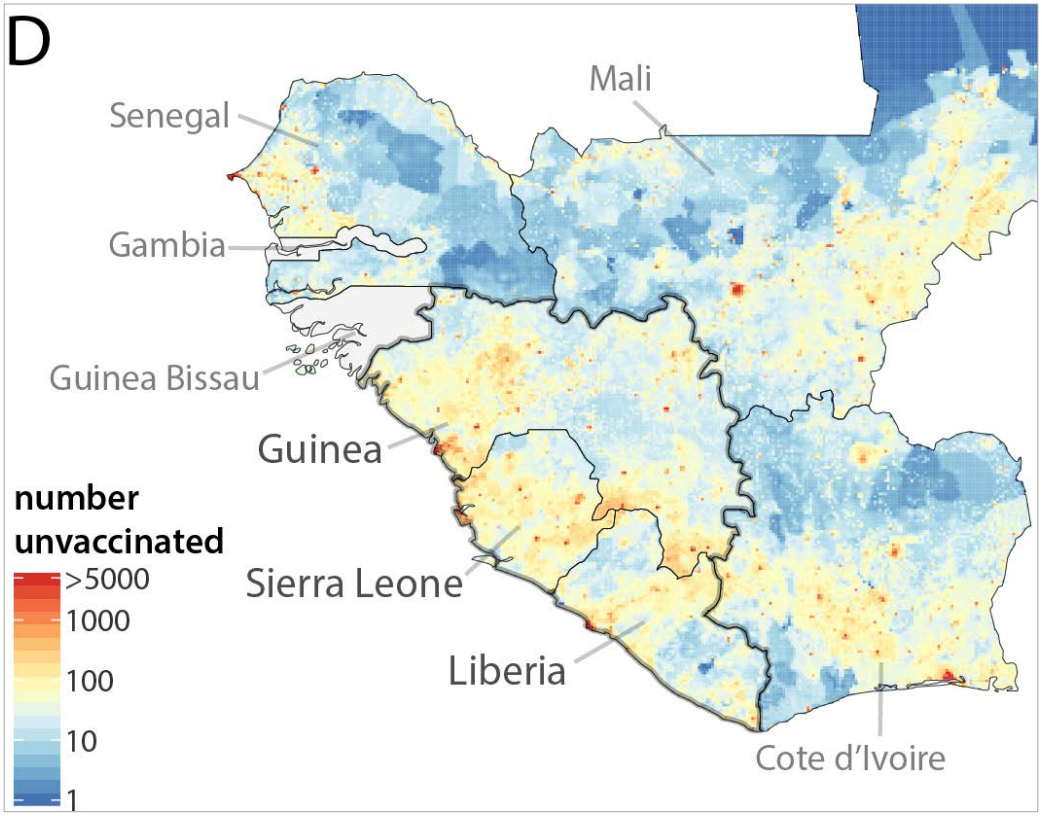
- A milestone for 2015: to increase routine coverage with MCV-1 for children aged 1 year to **at least 90% nationally**, and **at least 80% in every district** by every member state (World Health Assembly, 2010)

- Patches of unvaccinated people living in close proximity are more likely to sustain a measles epidemic, compared to the same number of unvaccinated people evenly distributed throughout a country

- The degree to which susceptible children cluster spatially is a key question for targeting control measures

Wallinga, Heijne, Kretzschmar (2005) *PLOS Med*

Spatial clustering of susceptibility to vaccine-preventable diseases



- Disruption in health care services associated with the West African Ebola epidemic → large connected cluster of children unvaccinated against measles

- In general, decrease in vaccination coverage affects potential for:
  - Continuing circulation of virus (countries nearing elimination)
  - Outbreaks after re-introduction (countries that have achieved elimination)

Takahashi et al (2015) *Science*

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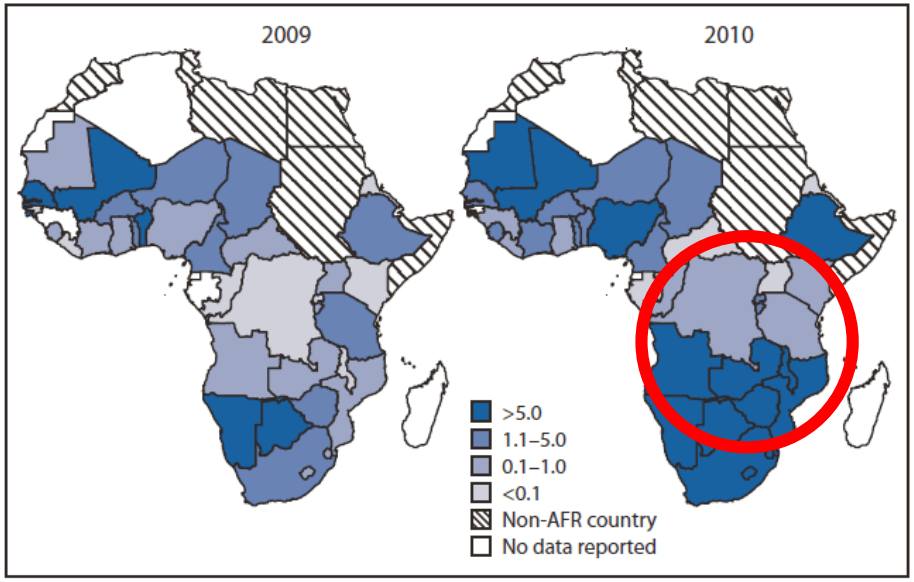
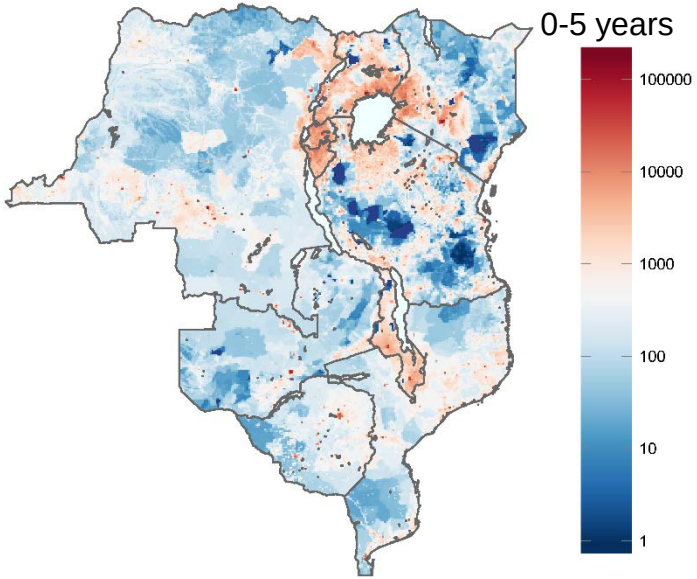
2. Identify foci for elimination efforts
3. Inform the spatial scale at which vaccination policy could be effectively implemented



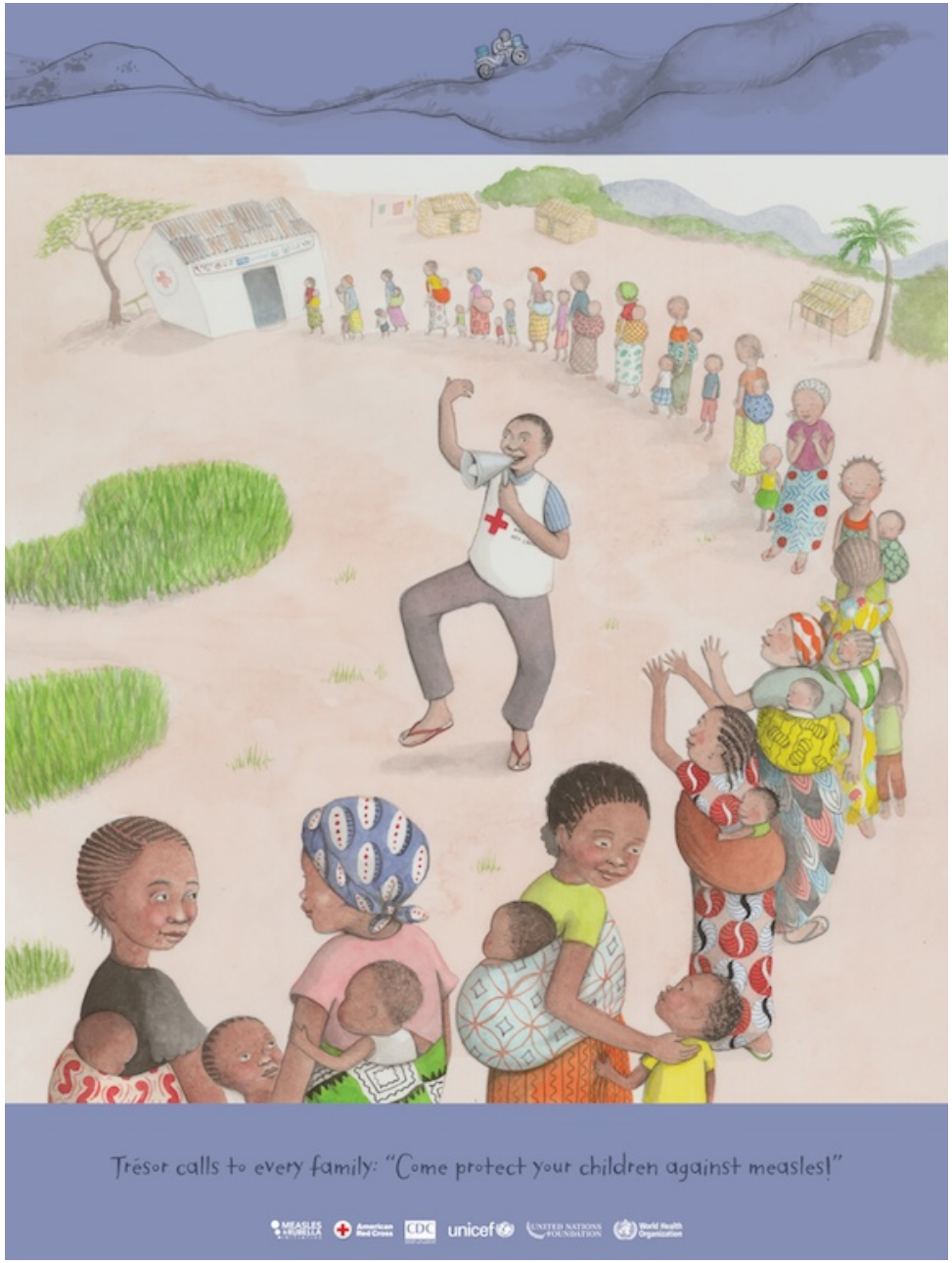
worldpop.org.uk



Takahashi et al (2017) Accepted

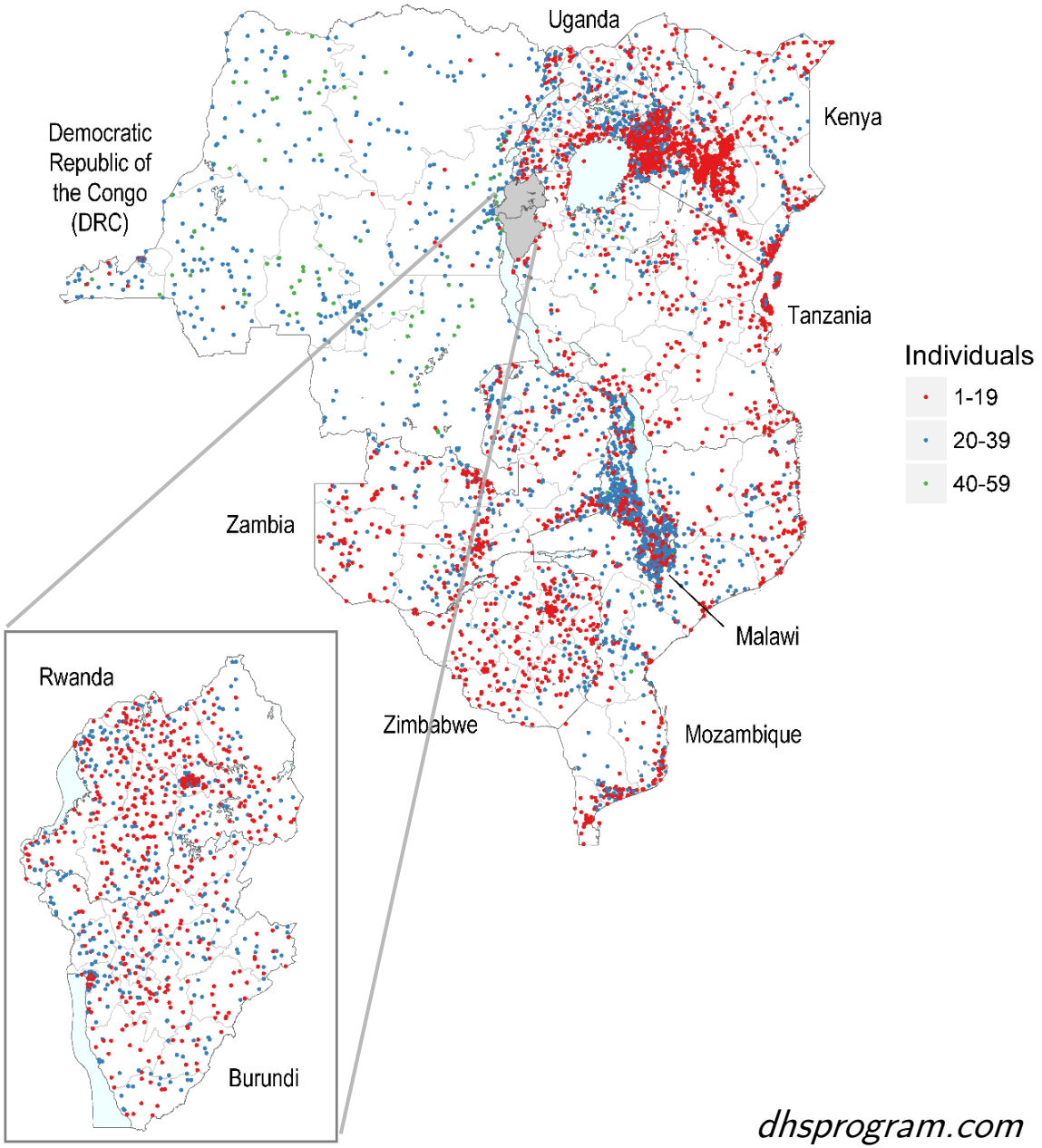
Delivery of measles vaccination

- Routine immunization (local health centers) target children at 9 months of age for MCV-1
- Supplementary immunization activities (SIAs) are periodically conducted to reach those missed by routine immunization
  - National
  - Sub-national



Demographic and Health Surveys (DHS), 2009-2014

Country	DHS survey start date	DHS survey end date	Children in survey, 6-60 months
Burundi	08/2010	01/2011	6,661
DRC	08/2013	02/2014	14,321
Kenya	05/2014	10/2014	18,311
Malawi	06/2010	09/2010	16,379
Mozambique	05/2011	12/2011	9,369
Rwanda	09/2010	04/2011	7,883
Tanzania	12/2009	05/2010	6,592
Uganda	06/2011	12/2011	6,580
Zambia	08/2013	04/2014	11,659
Zimbabwe	09/2010	03/2011	4,494



dhsprogram.com

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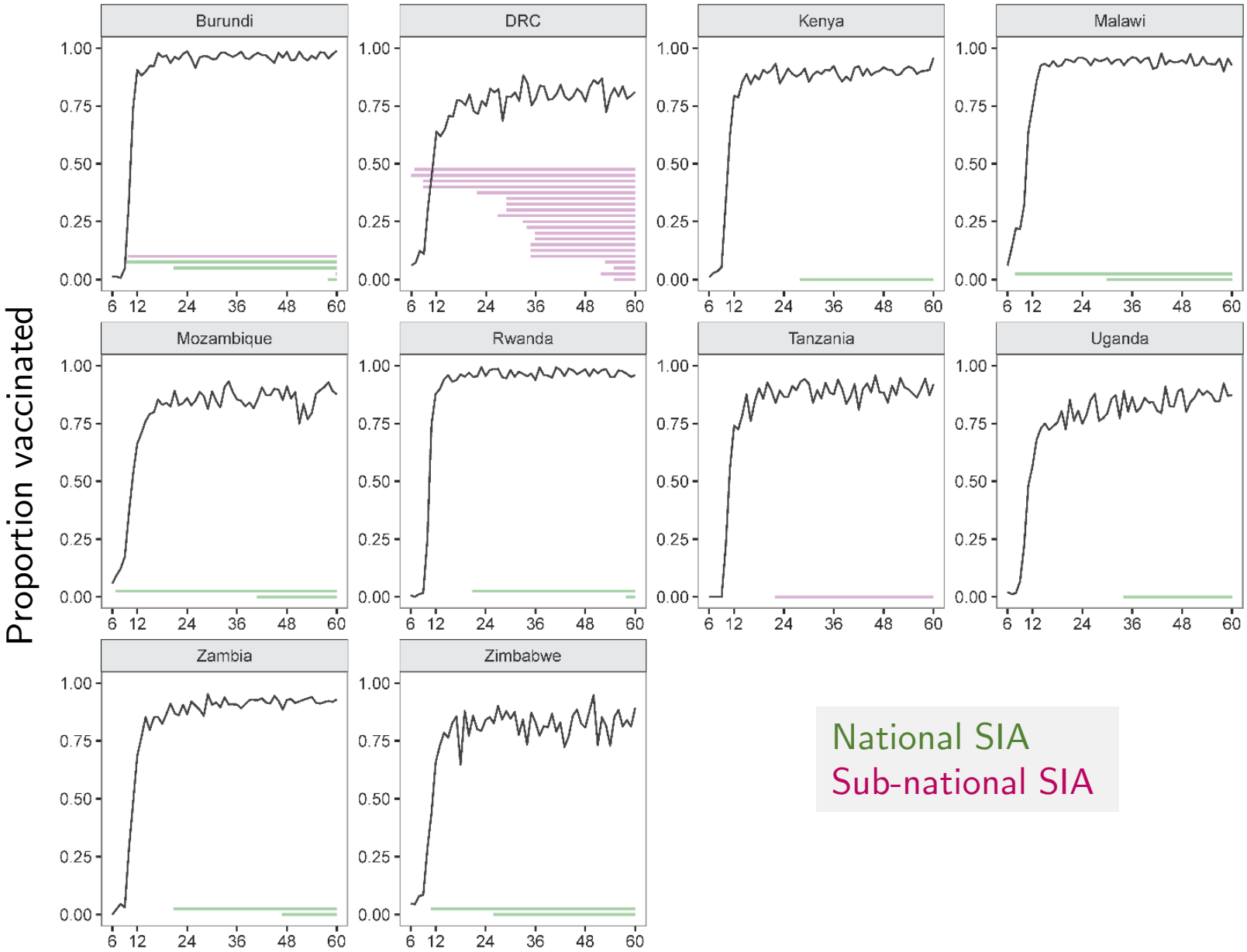

dhsprogram.com

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Estimating vaccination coverage, by country

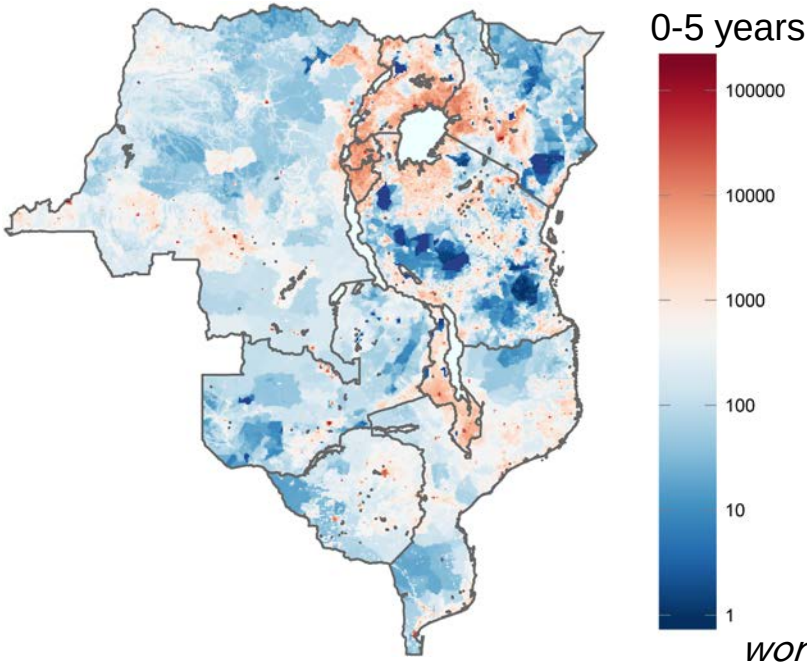
- Logistic regression in a GAM: vaccination status of child i, with covariates for location, survey age, and eligibility for sub-national SIA j (from DHS)

$$logit(v_i) = s(long_i, lat_i) + s(age_i) + \sum_j c_{ij}$$

- Overlay 10 km x 10 km grid across the country, and interpolate expected value at each grid cell (outcome: predicted coverage at a given age)

- Grid cells with $< 80\%$ coverage at a certain age is defined as a 'coldspot' for that age

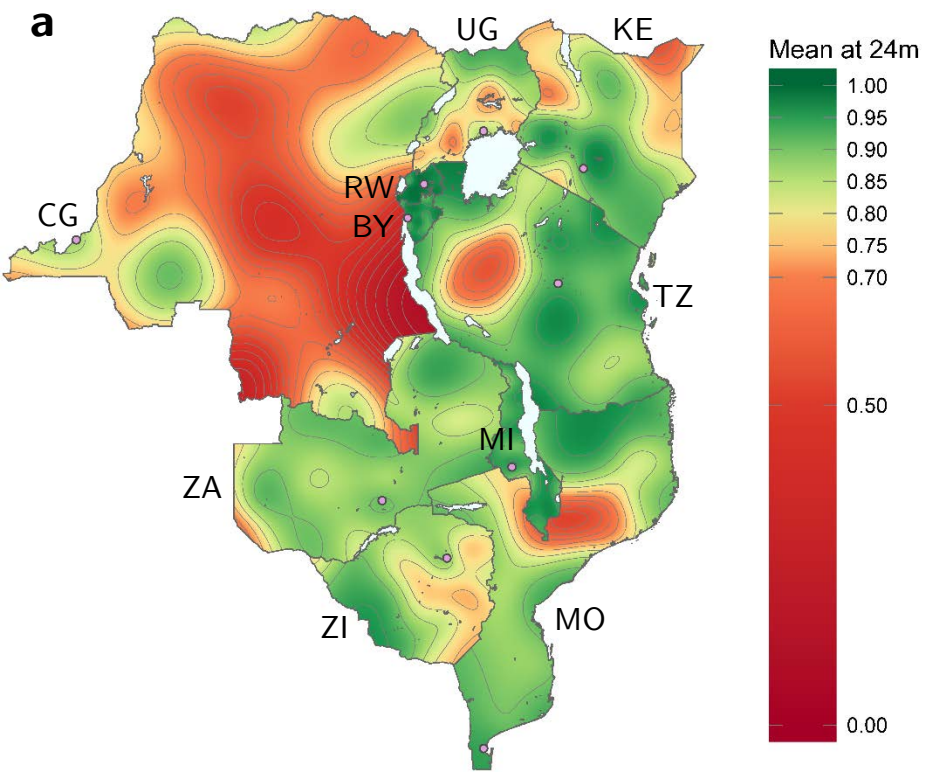
- Combine with age-structured, spatial information on population size (from WorldPop)



worldpop.org.uk

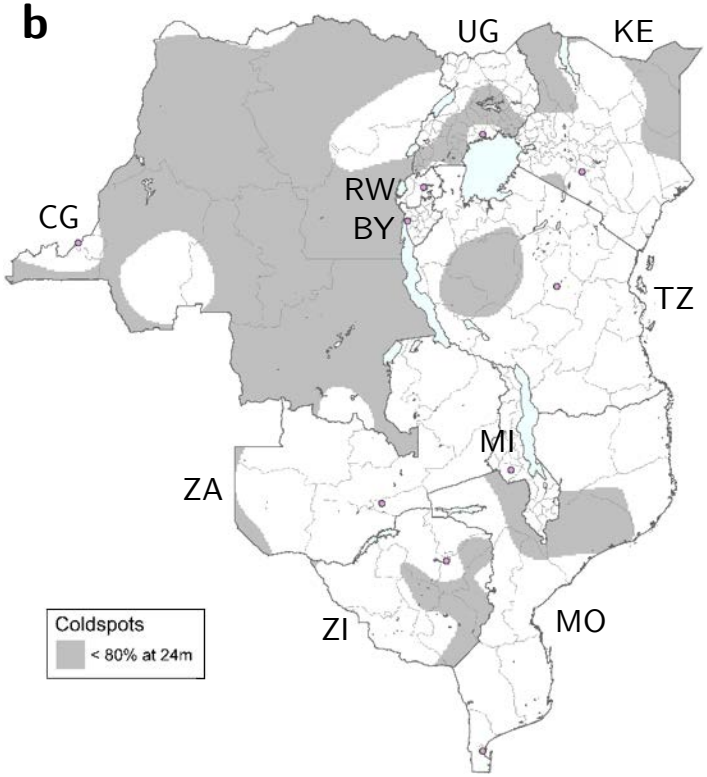
Maps: vaccination coverage

Coverage



a. Mean proportion of children 24 months of age who are vaccinated

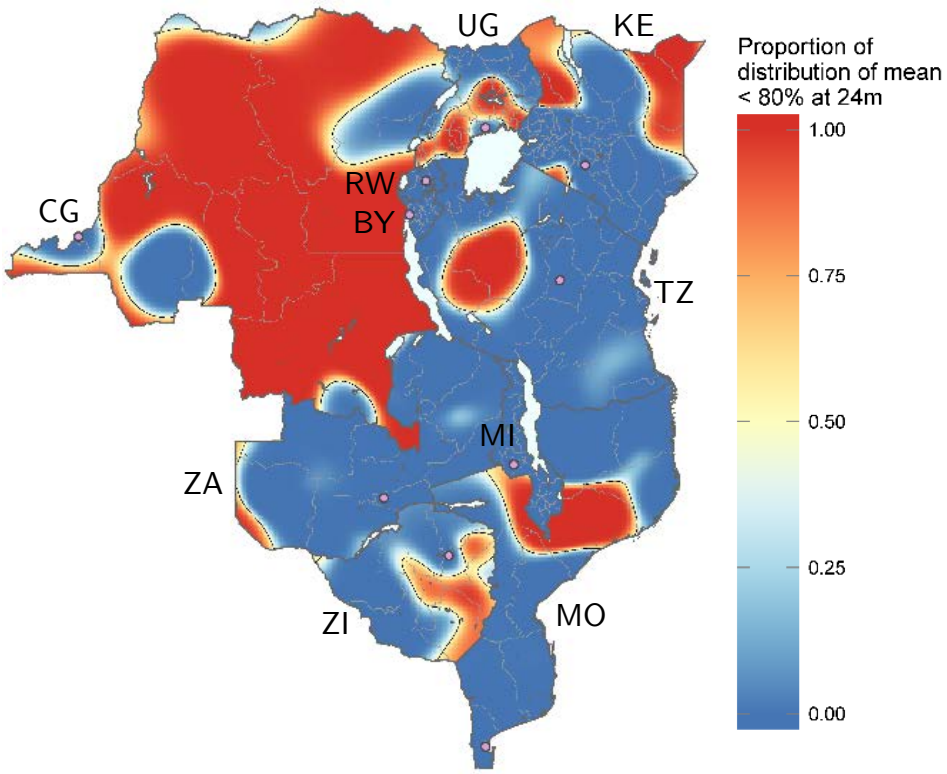
Coldspots



b. Grid cells with $< 80\%$ estimated coverage for children 24 months of age

Map: uncertainty

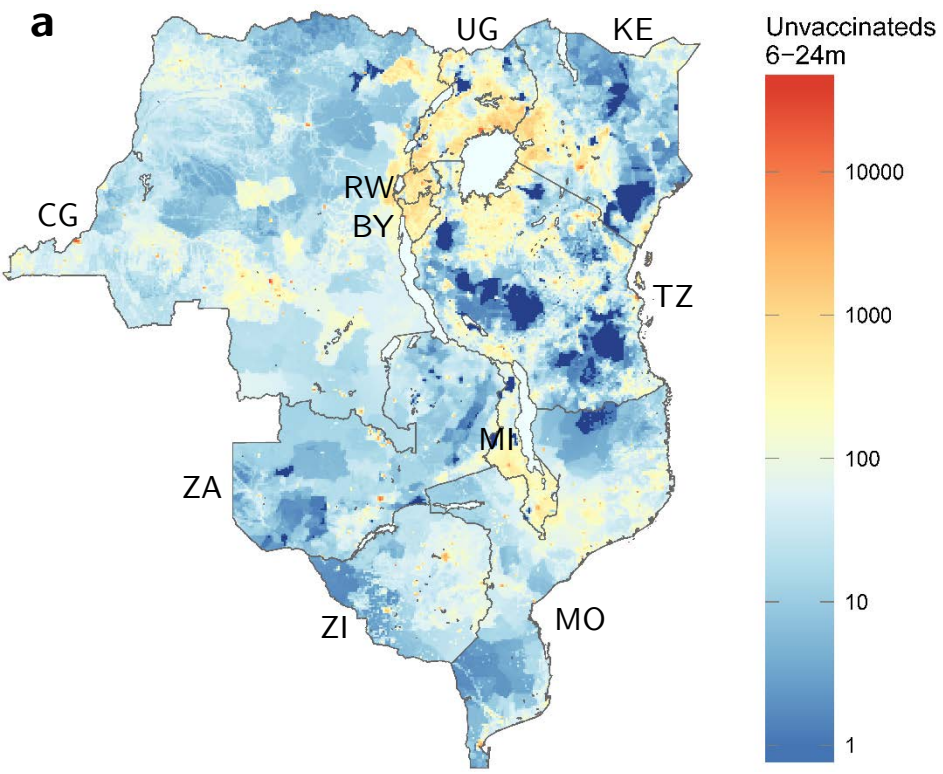
Coldspots boundaries



Proportion of the distribution of estimated mean measles vaccination coverage at 24 months of age that is $< 80\%$

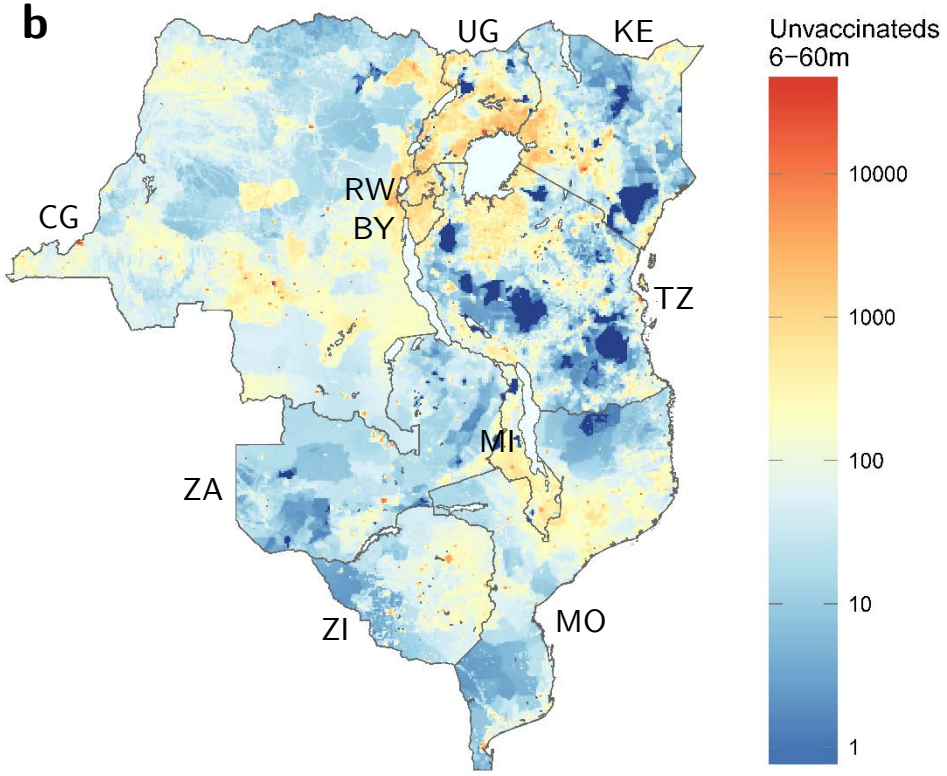
Maps: density of unvaccinated children

Unvacc: 6 million



a. Number of children 6-24 months of age per grid cell who are unvaccinated

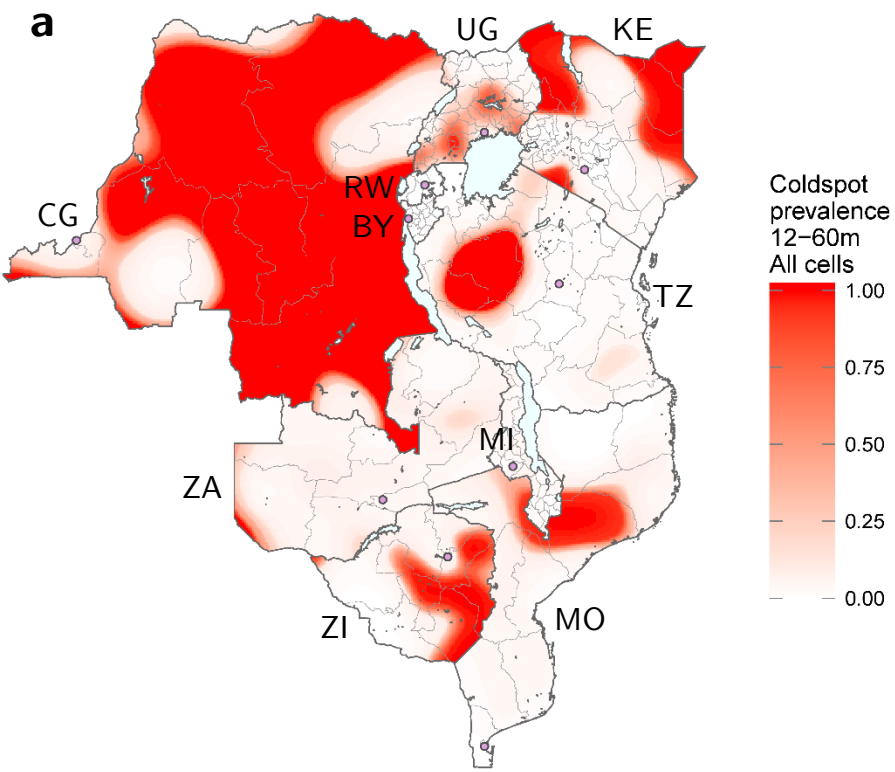
Unvacc: 10 million



b. Number of children 6-60 months of age per grid cell who are unvaccinated

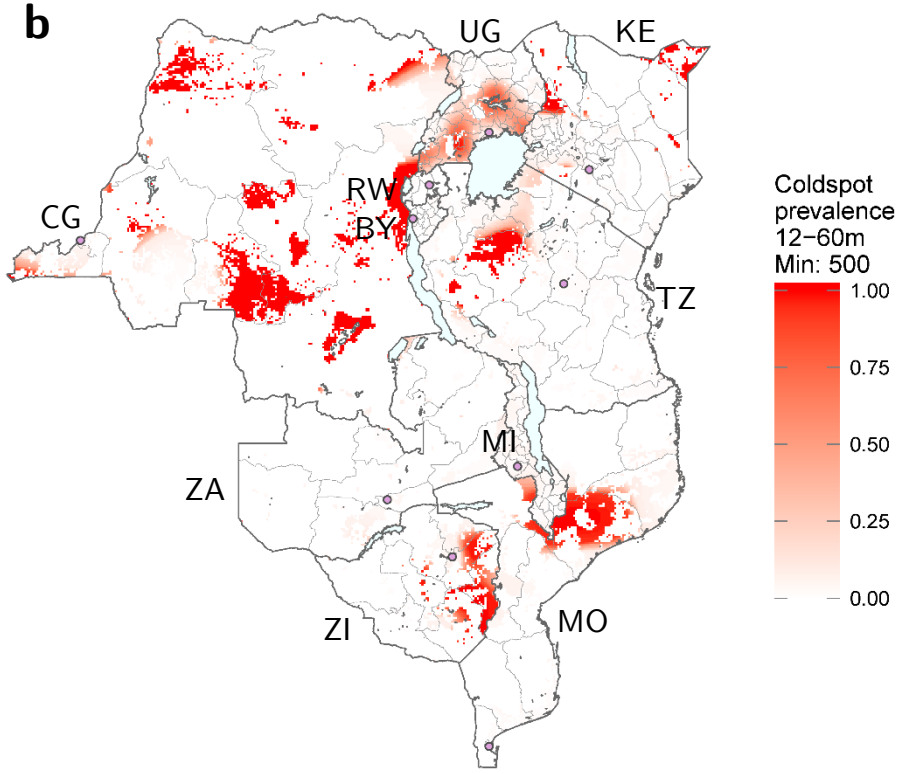
Maps: vaccination coverage by age + population density

Long-term coldspots



a. Proportion of monthly age cohorts that each grid cell exists as a 'coldspot' between 12-60 months of age (49 total age cohorts), showing all cells

Long-term, high-density coldspots



b. Same as left, but showing only grid cells with at least 500 children under 60 months of age

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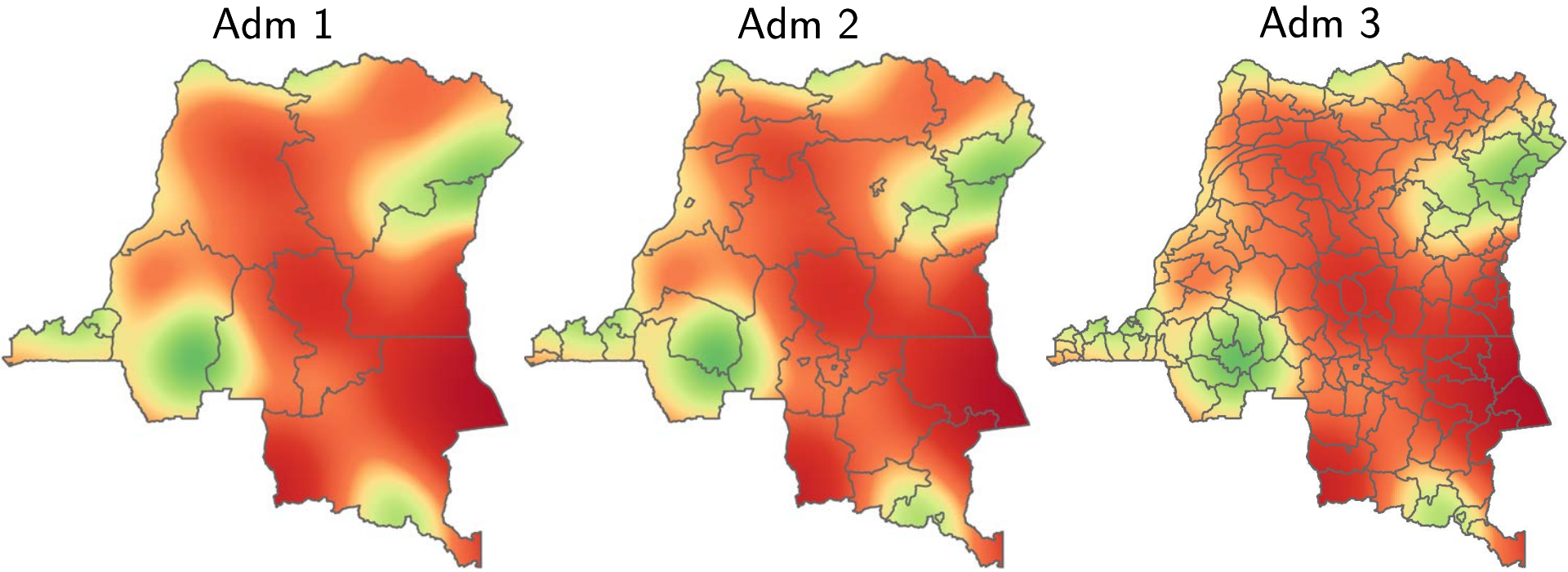
Spatial variation within countries – DRC



$$logit(p_k) = \mu + (1|\alpha_{1k}) + (1|\alpha_{2k}) + (1|\alpha_{3k}) + \epsilon_k$$

σ_ℓ^2: variance of α_ℓ

$$\text{ICC}_\ell = \frac{\sigma_\ell^2}{\sigma_1^2 + \sigma_2^2 + \sigma_3^2 + \sigma_\epsilon^2}$$

Country	Adm 1 ICC (e.g., provinces) (95% CI)	Adm 2 ICC (e.g., districts) (95% CI)	Adm 3 ICC (e.g., municipalities) (95% CI)	Residual ICC (95% CI)
DRC	0.2404 (0.0000-0.4656)	0.3582 (0.1685-0.5681)	0.2856 (0.1969-0.4422)	0.1158 (0.0867-0.1779)

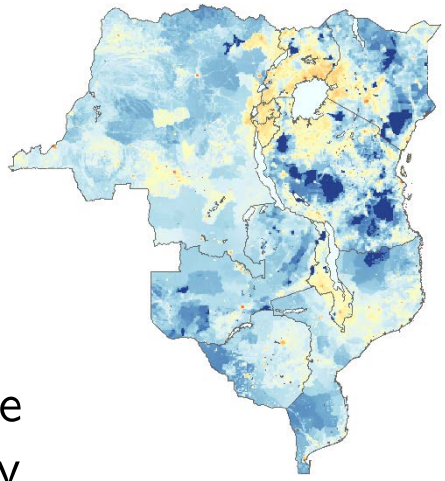
Spatial variation within countries

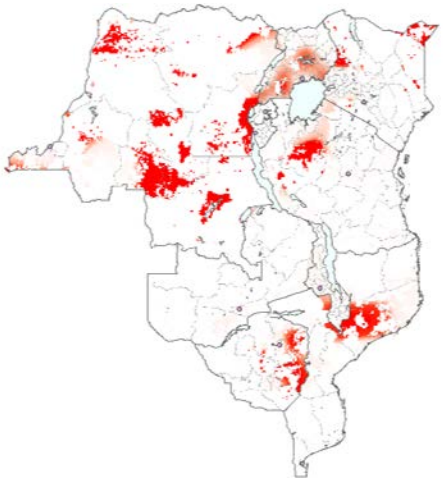
Country	Adm 1 ICC (e.g., provinces) (95% CI)	Adm 2 ICC (e.g., districts) (95% CI)	Adm 3 ICC (e.g., municipalities) (95% CI)	Residual ICC (95% CI)
Burundi	0.5798 (0.3169-0.7058)	0.1668 (0.0891-0.3015)	<0.0001 (0.0000-0.0723)	0.2535 (0.1615-0.4049)
DRC	0.2404 (0.0000-0.4656)	0.3582 (0.1685-0.5681)	0.2856 (0.1969-0.4422)	0.1158 (0.0867-0.1779)
Kenya	0.8271 (0.7478-0.8763)	0.1044 (0.0725-0.1537)	0.0354 (0.0250-0.0530)	0.0331 (0.0241-0.0483)
Malawi	0.5015 (0.3187-0.6203)	0.2759 (0.2013-0.3888)	0.0064 (0.0000-0.0315)	0.2163 (0.1635-0.2998)
Mozambique	0.5506 (0.2213-0.7106)	0.3736 (0.2391-0.6481)	0.0443 (0.0290-0.0811)	0.0315 (0.0209-0.0557)
Rwanda	0.3186 (0.0000-0.5849)	0.4210 (0.2100-0.6896)	0.1468 (0.0842-0.2848)	0.1136 (0.0693-0.2190)
Tanzania	0.7474 (0.6063-0.8253)	0.1364 (0.0895-0.2197)	0.0556 (0.0388-0.0881)	0.0606 (0.0434-0.0948)
Uganda	0.7765 (0.6782-0.8347)	0.1018 (0.0648-0.1583)	0.0404 (0.0281-0.0608)	0.0813 (0.0613-0.1145)
Zambia	0.3469 (0.0679-0.5338)	0.4055 (0.2630-0.5982)	NA	0.2476 (0.1812-0.3769)
Zimbabwe	0.6098 (0.2145-0.7668)	0.2274 (0.1196-0.4874)	NA	0.1628 (0.1008-0.3255)

Conclusions

- Estimated 10 million children unvaccinated against measles in the region between 6-60 months of age

- Numbers of unvaccinated children highlight areas where targeting vaccination efforts may be most cost-effective (left)





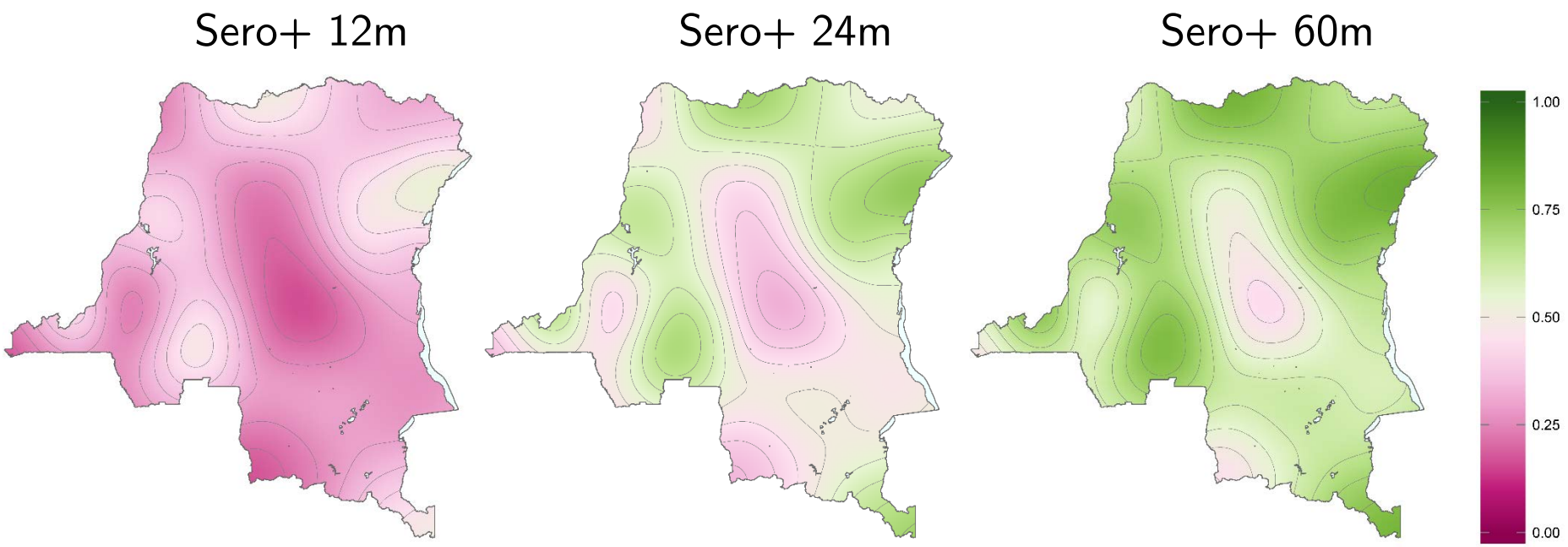
- Areas of high population density + consistently low vaccination coverage pose the greatest risk: if linked, may potentially sustain local transmission (right)

- Targeting of efforts at the largest sub-national administrative unit (provinces) would account for majority of sub-national variation in coverage

github.com/sakitakahashi/coldspots

Ongoing work

- But, mapping of susceptible children is complicated by acquisition of immunity via natural infection



Acknowledgements

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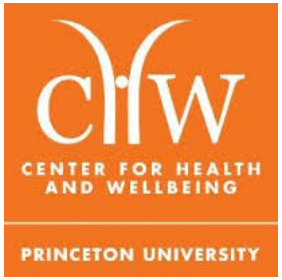
Andy Tatem (Southampton)



Thank you!