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# The health impact of free access to antiretroviral therapy in South Africa

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ABSTRACT

Since 2004 the South African government has rolled out free antiretroviral therapy (ART) at public health care facilities nationwide. No prior studies have estimated the impact of the ART rollout on health and survival using a longitudinal household survey with national coverage. We match household member deaths and self-assessed health from a large national longitudinal survey to community-level ART availability in clinics to estimate the reduction in mortality and morbidity attributable to ART availability between 2006 and 2016, using a difference-in-difference model. Our analysis focuses on black Africans aged 25–49 because this demographic group represents more than two-thirds of all South African HIV cases. We find that the rollout of free ART has reduced annual mortality by 27% and decreased the likelihood of reporting poor health by 36% for black Africans aged 25–49. These estimates amount to annual reductions in this demographic category of 31% in annual mortality and 47% in individuals reporting poor health. Our findings confirm that making ART treatment freely available nationwide has had a dramatic impact in terms of both prolonged survival and improved health, with most of these gains concentrated in the high HIV prevalence group of black Africans aged 25–49.

## 1. Introduction

The human immunodeficiency virus (HIV) pandemic has caused tremendous human suffering and loss of life. It is one of the most devastating global pandemics the world has seen since 1900, causing more than 36 million deaths to date with only the Spanish flu claiming more lives (WHO, 2021).

HIV compromises the immune system by infecting white blood cells which help the body to fend off infections. If HIV is not treated, people living with HIV are exposed to life-threatening cancers or opportunistic infections (WHO, 2021). A list of twenty of these life-threatening infections define the most severe and last stage of HIV, which is also known as acquired autoimmunodeficiency syndrome (AIDS). Patients typically die within 2 years of entering the AIDS phase (Poorolajal et al., 2016)., The introduction of antiretroviral therapy (ART) in 1996 marked a radical improvement to the prospects of people living with HIV. It represents one of the largest population health gains in recent history resulting from the successful rollout of a new medical treatment (Forsythe et al., 2019). Without treatment, someone with HIV tend to die within 10 years, but on ART they can have a normal life expectancy (Poorolajal et al., 2016; Sabin et al., 2013). For instance, a 35-year-old HIV-positive person who is successfully treated[1] is expected to live to the age of 80 (May et al., 2014). Globally, more than 27 million people were on ART in 2020 (WHO, 2021).

Against this background, this study considers the population impact of ART on mortality and self-reported health in South Africa. South Africa has the largest share of the world's HIV cases: it is home to 7.5 milion people living with HIV, which represents one in five of the global HIV burden (Simelela et al., 2015; UNAIDS, 2019).

By 1997 HIV prevalence was increasing rapidly in South Africa and it was clear that ART can help to curb the spread and the mortality impact of the disease (GBD, 2015) but it was rolled out to public health care facilities only from 2004. It has been estimated that this delay in the introduction of ART caused as many as 330 000 unnecessary deaths (Chigwedere et al., 2008). At first the provision of ART was almost entirely hospital-based because of accreditation requirements but these requirements were abandoned in 2010. Subsequently, all public health facilities were allowed to distribute antiretroviral medication.

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[1] The authors define successful treatment as achieving viral suppression and a $CD4^+$ cell count of at least 350 cells/μl within 1 year of starting ART. CD4s are white blood cells and a count of these cells provides an indicator of immune system health and in the context of HIV disease progression.

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Initially, eligibility was restricted to HIV patients with CD4 counts[2] below 200 cells/μL. As of 2010, eligibility was expanded to CD4 counts below 350 cells/μL and all pregnant women living with HIV were put on ART for life.[1] In 2016 the government moved to universal testing and treatment. The number of patients on treatment increased in response to the expansion of eligibility for and availability of ARTs: in 2018 an estimated 7.7 million people were living with HIV in South Africa and 4.6 million of them were receiving ART (UNAIDS, 2019)[2] By comparison, 1.85 million people were receiving ART in 2011 and an estimated 47 500 in 2004 (Johnson, 2012).

Despite the scale and coverage of South Africa's ART programme, our systematic literature search found only seven previous studies on the population health impact of ART in South Africa. We conducted a systematic search on 21 February 2020, using PubMed. We used a combination of the following search terms: ART, ARV, antiretroviral; South Africa, SA; inequality, trends; mortality, death, life expectancy; morbidity, disease; burden of disease. No limits were applied to the search. The search was augmented by a manual search in Google Scholar. We excluded studies that considered the impact of ART on ART patients.

The studies fall into three categories: surveillance site studies (Bor et al., 2013; Herbst et al., 2009; Herbst et al., 2011; Reniers et al., 2017); population-level time trends in observational data (Pillay-van Wyk, 2016; Haal et al., 2018); and epidemiological or mathematical models (Johnson et al., 2017). Surveillance site studies have demonstrated that ART can lead to substantial gains in survival (Bor et al., 2013; Herbst et al., 2009; Herbst et al., 2011; Reniers et al., 2017), but lack external validity because the evidence pertains to specific geographic areas and does not represent South Africa's population as a whole. Bor and his co-authors, for instance, warn that extrapolating their demographic surveillance site estimates of life expectancy with ART to country level would not be straightforward (Bor et al., 2013). Time trends in observational data are useful because they showed a dramatic reduction in the mean health and survival of the South African population as the HIV epidemic spread, followed by a post-2006 recovery as ART became more widely available. Given what we know about the high prevalence of HIV and the dramatic impact of ART, it is plausible to attribute most of the observed improvement in health and survival to ART, but the studies warn that such before-after comparisons do not provide causal estimates. Epidemiological and mathematical models have yielded important insights (Johnson et al., 2017), but modellers are aware of the contestability of assumptions about implementation efficacy and patient adherence.

This quasi-experimental study adds to the existing evidence base by assessing the population impact of ART in South Africa on a national level. We judiciously derive estimates for ART availability from facility-level administrative data and link these to community means for mortality and self-assessed health from a national longitudinal survey. This allows us to study the population-level impact of the South African ART programme as it was rolled-out, with outcomes that reflect granular, local-level variation in the behaviour of patients and health workers.

## 2. Methods

### 2.1. Data

We use outcome data from the National Income Dynamics Study (NIDS), a bi-annual longitudinal survey conducted in 2008, 2010, 2012, 2014/5 and 2016/7 a public data set collected by the South African Labour and Development Research Unit (SALDRU, 2018) at the University of Cape Town (UCT). The first NIDS in 2008 had a nationally representative sample of 28 255 individuals and 7305 households.[13] Excluding deaths, 75% of all respondents and 83% of black African respondents had been retained in the sample by the end of the survey. This analysis uses all five waves of the survey in the period 2008–2016. However, because our analysis is performed at cluster or community level, our estimates are less exposed to the perils of individual attrition.

NIDS is an income and expenditure survey, but also contains a module on the health and mortality outcomes of the household members. It is stratified by district council and contains 409 primary sampling units or community clusters. It tracks the deaths of household members over the previous 24 months. Individuals who left the household up to 12 months before the interview date are included in this count. When an individual left the household more than 12 months before that date, their death would be recorded in their last known household. Individuals who moved outside the borders of South Africa were excluded, but this group represented a negligible share of the sample (below 1% in each survey).

We looked at two outcome variables: total non-injury mortality and self-assessed health. Between 2006 and 2016, HIV deaths was one of the largest causes of non-injury mortality and the only major cause of death category displaying a strong downward trend (Pillay-Van Wyk et al., 2016). Total non-injury mortality is calculated from questions regarding deaths in the households over the past two years, excluding injury mortality (i.e. due to violence or accident). To measure self-assessed health we created a dichotomous indicator of poor health, based on respondents' responses to the question "How would you describe your health at present? Would you say it is excellent, very good, good, fair or poor?". Cases where respondents described their health as poor (the lowest category) were coded as 1 and all other cases as 0.

In our model, we aggregate our data to cluster level and estimate by weighted least squares by weighting the clusters in proportion to their sample size in the first period. We have 10 years of observations for mortality and 5 years of observations for morbidity." We include cluster level fixed effects to take account of time-invariant community-level heterogeneity.

There are two problems with respect to time period in NIDS: firstly that the interview dates vary between respondents and secondly that time gaps between the surveys are not equally spaced. We address the first problem by allowing the starting date – and thus also the period from which we measured ART access – to vary between respondents. We address the second problem of inconsistent spacing between periods by employing a series of period indicators (or time dummies) rather than a time trend.

The identifying assumption for our model is that areas with early access to ART did not have a different response trajectory cf. areas that received ART at a later period.

The following equation is employed to estimate the effect of ARV access on mortality and self-reported health:

$$\boldsymbol{Y_{jt} = \tau ARV_{jt} + \alpha v_j + \gamma u_t + e_{jt}}$$

where $\boldsymbol{Y_{jt}}$ is mortality rate/self-reported health for cluster j for period t, $\boldsymbol{ARV_{jt}}$ is the fraction of year that cluster j had access to ARVs, $\boldsymbol{v_j}$ are the cluster dummies (cluster fixed effects), $\boldsymbol{u_t}$ is the time fixed effect, $\boldsymbol{e_{jt}}$ is the error term.

We used the District Health Information System (NDOH, 2018), a facility-level administrative data set to capture the rollout of ART services to an increasing number of facilities. The data provide the number of new and existing ART enrolments at each public health facility for each month since January 2004. For the years before 2011 these data were captured retrospectively based on physical records after National Department of Health initiated a standardised ART programme monitoring strategy in December 2010. Because of concerns about the quality of administrative data on new enrolments in the early phases of ART provision, we used a binary specification of ART availability,

[2] A CD4 count is used to measure the health of the immune system. CD4s are white blood cells that are important for fighting off infections. For HIV patients, CD4 counts are used to track disease progression and to manage the treatment of patients.

implementing a maximum likelihood algorithm to identify the introduction of ART at a facility. We used the aggregate quarterly data to monthly facility-level ART enrolment data in the DHIS to estimate the quarter when ART became readily available at a specific facility.We aggregated the individual outcomes to obtain rates of annual mortality and bi-annual reports of poor health by community cluster.

We do not have information on HIV status in our data and therefore we have not been able to restrict our analysis to only those individuals who are HIV+. Instead, we measure the intention-to-treat effect of access to ART for the full population – thus including both HIV+ and HIV- individuals. As the proportion, $p$, of HIV positive individuals within the subgroup increases, we would expect $\tau_{ITT}$ to also increase. We would expect ART access to have a higher mortality and morbidity impact on people living with HIV, $\tau_1$, cf. the group of individuals who do not have HIV, $\tau_0$. This is also why we expect a higher impact amongst the groups where HIV prevalence is higher, such as the 15–49 year-olds.

Using GIS data, each household in NIDS was matched to all facilities within a 10 km radius. A household was categorised as having ART available to them when at least one of the facilities within this radius had initiated ART provision. This definition of availability recognises the important role of distance to the facility for ART uptake (Cooke et al., 2010). The ART availability variable reflects the share of the period where ART was available to the household.

To validate the mortality estimates derived from NIDS, we compared them to estimates from three much larger national surveys: the 2007 Community Survey (n = 1 047 652), a 10% sample of the 2011 Census (n = 4 418 594), and the 2016 Community Survey (n = 3 328 867) (Statistics South Africa, 2007, 2012 & 2016). All three of these surveys were stratified according to province and district council and, within each district council, by local authority and enumeration area type.

### 2.2. Statistical analysis

We use a difference-in-difference model to estimate the intention-to-treat effect of ART availability on the annual probability of non-injury mortality and self-assessed health. Fixed effects for community clusters and time periods are included in our model to eliminate the common time trends (shared across clusters) and time-invariant differences between clusters so that the analysis was concentrated on evaluating the relative difference in the changes in mortality and self-assessed ill-health between clusters with and without ART availability over time. We include time fixed effects to capture nationwide trends in the expansion of ART eligibility and improvements in ART efficacy. The identifying assumption is that the time trends in outcomes for areas with and without ART availability would be parallel in the absence of ART rollout. Cluster weights are proportional to the community cluster's sample share.

We expect to see much of the impact of ART availability on mortality and morbidity within the same time period because on average ART tends to act fast, with efficacy benchmarked as 78% viral suppression at 24 weeks (Barth et al., 2010). Because disease progression from seroconversion[3] (usually occurring a few weeks after infection) to death is estimated to be 11.7 years in the absence of ART, the decline in mortality is expected to work primarily via treatment over this period, and not via new infections.

We focus our analysis on the highest HIV prevalence subpopulation of black African males and females aged 25–49 for two reasons: because our estimates are expected to be most precise for the high prevalence subpopulations, and because we expect most of the impact of ART to be concentrated in such high prevalence groups. Black Africans aged 25–49 carried a disproportionate 71.4% (95% CI 69.0–73.7) of the HIV burden, compared to their population share of 27.3% (95% CI 27.3–27.3), based on the 2011 Census. The 2012 South African HIV prevalence survey estimated that HIV prevalence was 30.9% (95% CI 28.7–33.2) for black Africans aged 25–49; 5% (95% CI 4.4–5.6) for black Africans aged 24 and below; and 11.0% (95% CI 9.5–12.7) for black Africans aged 50 and above (Shisana et al., 2012). HIV rates were much lower for other races: the survey found HIV prevalence to be 0.8% for whites, 6.4% for coloureds and 1.1% for Indians and Asians in the 25–49 age group.

Statistical analysis was performed in Stata version 14.2. On 6 March 2019 the Stellenbosch University institutional review committee issued an ethical waiver for this secondary data analysis.

### 2.3. Results: ART expansion and mortality trends over time

Between 2006 and 2016 there was a consistent, steep upward trend in the availability of ART. The share of households living within 10 km of an ART facility rose sharply from 18.8% (95% CI17.3–20.3) to 95.6% (95% CI 95.0–96.2) between 2006 and 2016 (see Fig. 1. (See Supporting material Table A2 in Appendix A comparing coverage for 5 km, 10 km and 20 km radius). In 2006 ART was available at a few hospitals in urban centres, but by 2016 it was available from almost all primary care facilities, which had overtaken hospitals as the main providers of ART (Fig. 2a–c).

Over the same period, there was a sharp decline in the annual non-injury mortality rate for black Africans aged 25–49 from 2.5% (95% CI 2.2–2.9) in 2006 to 0.6% (95% CI 0.5–0.8) in 2016 (Fig. 3a–c, Table A1 in Appendix A). The 50 and older age category had the highest mortality rates, but we do not observe a steep mortality decline over this period for this age category. Black Africans aged 50 and older had annual non-injury mortality rates of 3.2% (95% CI 2.7–3.8) in 2006 and this declined to 2.6% (95% CI 2.2–3.0) in 2016. The youngest age category (15–24) had the lowest mortality rates showing a modest absolute (but large relative) decline from 0.6% (95% CI 0.4–0.8) to 0.1% (95% CI 0.04–0.18) over this period.

In Fig. 3a–c we compare the NIDS observed mortality rates with the more precise annual mortality estimates derived from the three (much larger) surveys, the national Census and the Community Surveys (mini-Census surveys). The NIDS estimates reflect the national mortality patterns quite well: both sets of estimates show a similar picture, with the Census estimates mostly lying within the 95% confidence bands of the NIDS estimates.

We estimate the effect of ART availability on annual non-injury

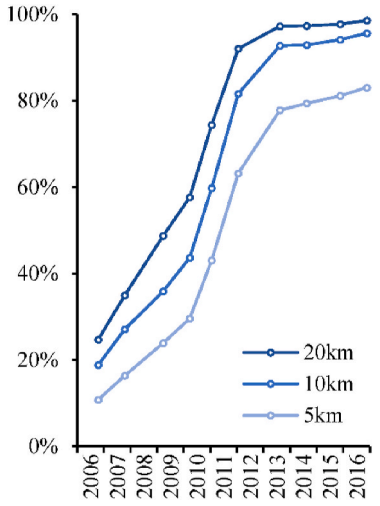
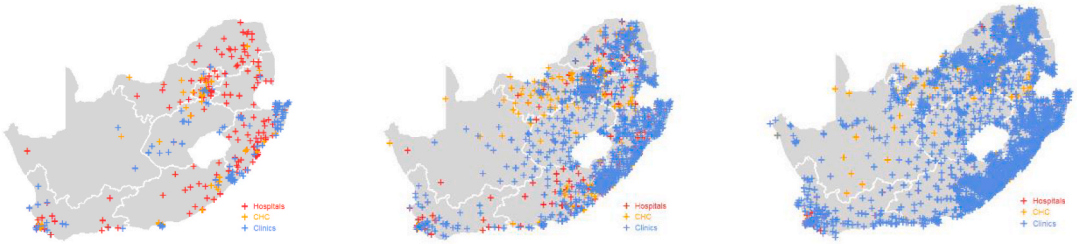
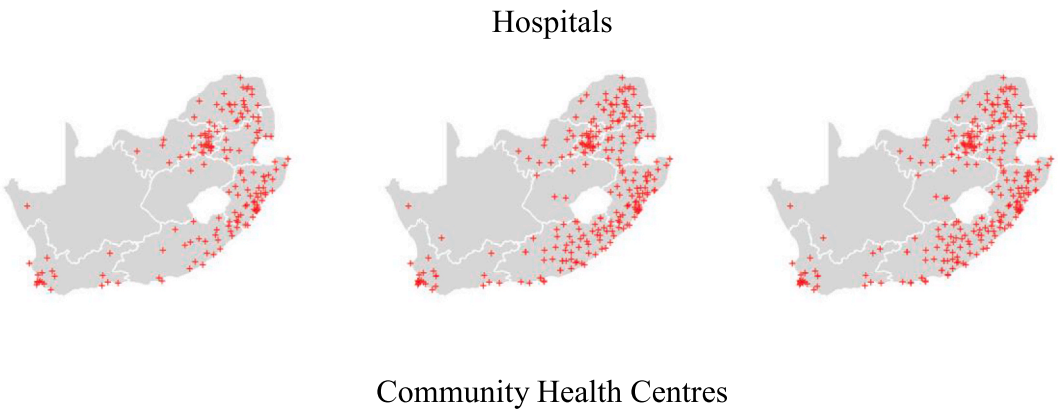


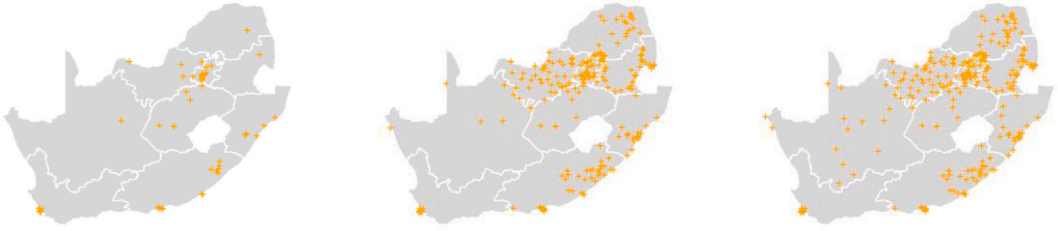

**Fig. 1.** ART coverage from 2006 to 2016, by distance from facility.
Note: Data for graph is shown Appendix Table A2

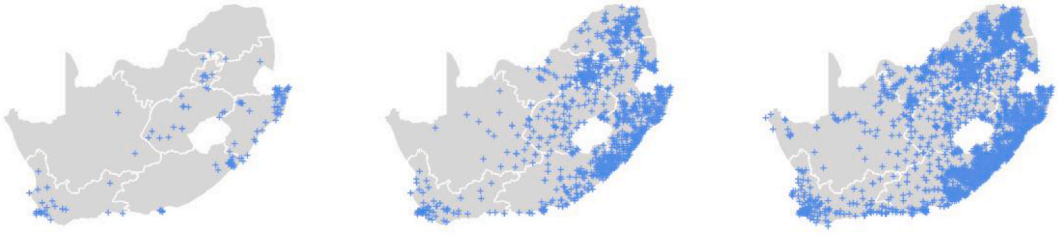
[3] Seroconversion marks the stage of HIV infection when enough antibodies are produced by the body to identify the presence of the virus via testing. This typically occurs between 3 and 12 weeks after contracting the virus. Seroconversion is usually associated with the onset of flu-like symptoms, although in some cases people report no symptoms.




**a: ART access by 2006** **b: ART access by 2011** **c: ART access by 2016**



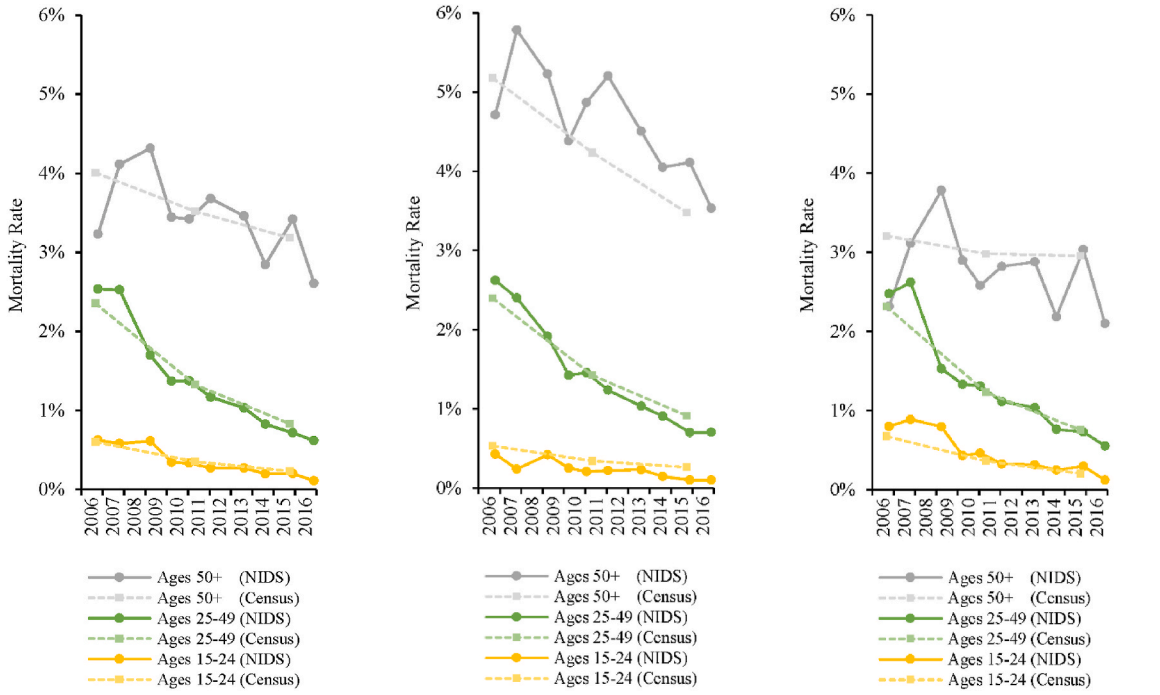




**a: ART access by 2006** **b: ART access by 2011** **c: ART access by 2016**

**Fig. 2.** a ART access by 2006; b ART access by 2011; c ART access by 2016.

mortality and self-assessed health for black Africans of both sexes and three age groups: 15–24; 25–49; and 50+, while controlling for fixed community cluster effects and time effects. Full regression results (with time trends) are shown in Tables A3 and A4 in Appendix A).

Table 1 shows a summary of the estimated relative effects of ART availability on mortality (Table 1a) and self-reported health (Table 1b) based on the regression in Tables A3 and A4 in Appendix A respectively. We can see that the relative effects are largest for the age group with the highest HIV prevalence. For black Africans aged 25–49, ART availability significantly reduced the likelihood of dying by 0.45 percentage points (95% CI -0.80 to −0.11) and the likelihood of reporting poor health by 1.8 percentage points (95% CI -3.00 to −0.66). While the beneficial




**a: Mortality Rate for black Africans, 2006 – 2016, NIDS vs. population census surveys**

**b: Mortality Rate for black African women, 2006 – 2016, NIDS vs. population census surveys**

**c: Mortality Rate for black African men, 2006 – 2016, NIDS vs. population census surveys**

**Fig. 3.** a Mortality Rate for black Africans, 2006 – 2016, NIDS vs. population census surveys; b Mortality Rate for black African women, 2006 – 2016, NIDS vs. population census surveys; c Mortality Rate for black African men, 2006 – 2016, NIDS vs. population census surveys.

**Table 1a**
Impact of ART access on non-injury mortality of black Africans, 2006–2016 [Percentage point change].

| 1 | Effect | SE | 95% CI | p-value |
|---|---|---|---|---|
| **Aged 15–24** | | | | |
| All | −0.34 | 0.10 | (-0.54; −0.14) | 0.001 |
| Males | −0.26 | 0.11 | (-0.48; −0.05) | 0.018 |
| Females | −0.46 | 0.17 | (-0.79; −0.14) | 0.006 |
| **Aged 25–49** | | | | |
| All | −0.45 | 0.18 | (-0.80; −0.11) | 0.010 |
| Males | −0.52 | 0.28 | (-1.06; 0.03) | 0.063 |
| Females | −0.48 | 0.23 | (-0.92; −0.04) | 0.032 |
| **Aged 50+** | | | | |
| All | −0.07 | 0.35 | (-0.75; 0.61) | 0.841 |
| Males | −0.42 | 0.64 | (-1.69; 0.84) | 0.511 |
| Females | −0.05 | 0.39 | (-0.80; 0.71) | 0.903 |

Note: Coefficients, standard errors and confidence intervals were multiplied by 100 to allow for a percentage change interpretation. Full regression results in Table A3

**Table 1b**
Impact of ART access on self-reported poor health of black Africans, 2006–2016 [Percentage point change].

| 2 | Effect | SE | 95% CI | p-value |
|---|---|---|---|---|
| **Aged 15–24** | | | | |
| All | −0.21 | 0.30 | (-0.80; 0.37) | 0.479 |
| Males | −0.82 | 0.39 | (-1.58; −0.06) | 0.034 |
| Females | 0.32 | 0.49 | (-0.64; 1.28) | 0.514 |
| **Aged 25–49** | | | | |
| All | −1.83 | 0.60 | (-3.00; −0.66) | 0.002 |
| Males | −2.57 | 0.86 | (-4.25; −0.88) | 0.003 |
| Females | −1.45 | 0.73 | (-2.88; −0.02) | 0.047 |
| **Aged 50+** | | | | |
| All | −0.58 | 1.32 | (-3.16; 2.00) | 0.658 |
| Males | −0.62 | 1.76 | (-4.07; 2.83) | 0.725 |
| Females | 0.15 | 1.58 | (-2.95; 3.26) | 0.922 |

Note: Coefficients, standard errors and confidence intervals were multiplied by 100 to allow for a percentage change interpretation. Full regression results in Table A4

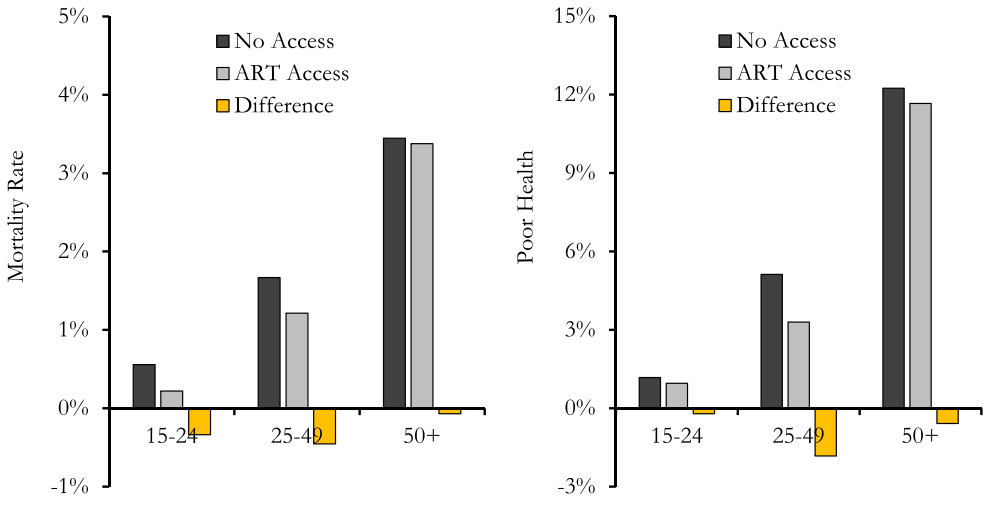
effects are slightly larger for males, they do not differ significantly from those for females.

For the younger adult group (15–24) the estimated mortality impact of ART availability is smaller. ART availability causes an estimated 0.3 percentage point drop in mortality (95% CI -0.5 to −0.1). It results in a 0.3 percentage point decline in male mortality, which is significant but smaller than the 0.5 percentage point decline in female mortality (95% CI -0.8 to −0.1). It has a significant impact on the self-reported health of males in this age group (−0.8 percentage points; 95% CI -1.6 to −0.1), but no significant impact on the self-reported health of females or the combination of males and females.

For black Africans older than 50, we do not detect a significant impact on either mortality or morbidity.

We estimate upper bound estimates of the mortality and morbidity impact of ART, excluding the time period indicators. We find that excluding those indicators increases the estimated effect by a factor of 3–4 for black Africans aged 25–49 (see Appendix A: Tables A3-6).

The main findings by age are summarised in Fig. 4a–b, which allow a visual comparison of the absolute and relative magnitudes of the mortality and morbidity effects. They confirm that while both mortality and morbidity rates are much higher for the oldest age group (50+), the largest absolute reduction is for black Africans aged 25–49, i.e. the group which stands to benefit most from ART because it has the highest HIV prevalence. This demographic group experienced an annual reduction in mortality of 27% and in self-reported health of 36%.




a: Mortality rate for black Africans, 2006 – 2016

b: Poor health for black Africans, 2006 – 2016

**Fig. 4.** Notes: These bars allow a visual comparison of the absolute and relative magnitudes of the mortality and morbidity effects (shown in Tables A4 and A6). The first bar shows the average mortality and morbidity rates without any ART access (across all the relevant waves), the second bar shows the average estimated mortality and morbidity in years when ARTs are available. The last bar shows the estimated effect of ART access mortality and morbidity (ART Access in A4 and A6) as the difference between the two other bars. The figure confirms that while both mortality and morbidity rates are much higher for the oldest age group (50+), the largest absolute reduction is for black Africans aged 25–49, i.e. the group which stands to benefit most from ART because it has the highest HIV prevalence.

### *2.4. Discussion*

We estimated the impact of the access to free ART at a nearby facility on mortality and morbidity between 2006 and 2016, using longitudinal individual-level data. Our most conservative estimates show that ART availability has decreased annual mortality by 0.5 percentage points and the likelihood of reporting poor health by 1.8 percentage points for the high HIV risk group: black Africans aged 25–49. As expected, the impact is lower and less likely to be significant for the younger and older age categories with lower HIV prevalence. This quasi-experimental study adds to the existing evidence by providing the first causal national estimate of the survival and health impact of a decade of free access to ART in South Africa. We use a unique data set linking facility-level data on ART availability to community means for mortality and self-assessed health from a national longitudinal survey.

We find no significant difference between the male and female mortality impact of ART availability. Higher mortality for males living with HIV has been attributed to their lower testing rates, later ART initiation and poorer ART adherence (Cornell et al., 2017). However, our analysis is based on population-level impact, which shows such effects are off-set by the lower HIV prevalence for males (Johnson et al., 2013).

Because we include both community cluster and time fixed effects in our model, we believe our estimates can be interpreted as lower bound estimates. Our inclusion of time dummies to control for secular time trends may even be overly conservative as it is difficult to find competing explanations for a large gradual drop in overall non-injury mortality that occurred over this period (Reniers et al., 2017; Pillay--Van Wyk, 2016) especially for black Africans aged 25–49. The large gap between these two versions of our model (with and without time period indicators) may also be explained by a willingness of individuals to travel more than 10 km from their home to access ART.

Differences in methods and definitions mean that our effect estimates are not directly comparable to previous studies showing population-level evidence that ART availability has decreased mortality, expanded life expectancy and improved health. However, our work adds value to the available evidence from surveillance sites (Bor et al., 2013; Herbst et al., 2009; Herbst et al., 2011; Reniers et al., 2017) and modelling estimates (Johnson et al., 2017; Cornell et al., 2017; Johnson et al., 2013). because it is based on health outcomes observed in the NIDS national longitudinal survey which was linked to administrative data on ART rollout. The Supplementary data describes our judicious use of the administrative data to gauge when ART became available in a community. While our estimates have their own limitations, they are important points of reference for triangulation because they do not rely on modelling assumptions about ART take-up or adherence and do not suffer from the external validity problems associated with estimates derived from specific geographic surveillance sites or cohorts, where there could also be concerns that the close observation of healthcare and patient ART adherence could be distorting the real-world picture.

Our South Africa evidence also adds to that generated for other African countries (not including South Africa) using Demographic and Health Survey data comparing all-cause mortality in the PEPFAR (US President's Emergency Plan for AIDS Relief) focus countries with non-focus countries (Bendavid et al., 2012). Using a similar difference-in-difference comparison, they estimated that the PEPFAR scaled up delivery of expanded antiretroviral therapy (ART) and support to other large-scale prevention efforts between 2003 and 2008 had reduced the annual adult mortality (19–59) by an average 16% (0.84 odds ratio). Our estimated relative reduction of the annual non-injury mortality by about 27% (i.e. a drop from 1.67 to 1.22 as shown in Fig 4a) is larger but refers to a later period (between 2006 and 2016) and is for black African adults 25–49 only.

## 3. Limitations

Our study has three limitations. One is that we do not observe either the prevalence of HIV or the uptake of ART by HIV infected individuals in the NIDS clusters. As a result, we can relate the improvements in survival and self-reported health to the availability of ART at a nearby clinic. That means that our estimate measures the impact of ART availability, given the HIV prevalence, diagnosis and treatment with ART in South Africa between 2006 and 2016. We therefore cannot show to what extent these intermediate factors have contributed to the outcomes. A second limitation is that we mainly capture the first round and direct effects of ART because we use indicators such as mortality and poor health that are associated with the last and most advanced stages of HIV and AIDS that would typically occur up to 10 years after infection if left untreated (Morgan et al., 2002). We are therefore unlikely to observe the second round and indirect effects of ART availability, which would work via the prevention of future infections. The third limitation is that our observation period of 2006–2016 excludes the first two years of ART rollout, in which substantial initial mortality decreases may have been obtained because many of those initiating ART in this very early phase of the rollout were in advanced stages of HIV (Egger and Boulle, 2008). Conversely, however, this may be viewed as a strength of our

study because it means that our estimates are more representative of the ongoing incremental gains attributable to ART.

## 4. Conclusions

We have exploited the natural experiment of the staggered rollout of ART therapy across time and place in SA in order to conduct a DID analysis which, unlike earlier demonstrations of ART effectiveness, provides us with a nationwide estimate of its causal impact on health survival of black African. Our study provides an estimate of the real-life effectiveness of ART, demonstrating that the rollout of free ART since 2004 has curbed the devastating impact of HIV on communities in South Africa and has yielded large population health benefits, which are disproptionately concentrated in the population groups most affected by HIV.

It adds to the body of literature on the impact of ART from surveillance sites and modelling studies. Studies from surveillance sites tend to offer rich data and enable detailed and sophisticated analysis, but suffer from external validity concerns because they only reflect the results from one particular site. Modelling studies require assumptions and would often be reliant on aggregated data, which can also be a limitation. Using estimates from a national household longitudinal study, our study shows that ART has had a rapid and dramatic real-life impact on both the health and the life expectancy of South African people.

## Authors' contributions

CB was responsible for the statistical analysis. All authors contributed to the literature review, the interpretation of the results and the writing of the report.

## Declaration of competing interest

All authors of this study declare they have no competing interests.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.socscimed.2022.114832.

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