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Supplementary appendix

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Methods appendix to Measuring universal health coverage based on an index of effective coverage of health services in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019

This appendix provides further methodological detail on measuring UHC effective coverage. The appendix is organized into broad sections following the structure of the main paper.

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Preamble

This appendix provides methodological detail for estimating effective coverage to inform universal health coverage (UHC) service coverage monitoring. This study complies with the Guidelines for Accurate and Transparent Health Estimates Reporting (GATHER) recommendations.[1] It includes detailed information on our analytical steps in an effort to maximise transparency in estimation processes.

Some of the methods outlined in this appendix have been described further in other GBD publications.[2–5] Portions of Part 4 in this appendix have been directly reproduced from a pre-print manuscript by Peng and colleagues[6] in order to preserve the accuracy of model documentation.

The accompanying results appendix provides supplementary figures and tables.

GATHER statement

This study complies with the Guidelines for Accurate and Transparent Health Estimates Reporting (GATHER) recommendations.[1] We have documented the steps involved in our analytical procedures and detailed the data sources used in compliance with GATHER. For additional GATHER reporting, please refer to the GATHER table at the end of this appendix.

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Part 1. UHC effective coverage measurement development process

Section 1. Overview

Broadly, achieving "universal health coverage (UHC) means that all people receive the quality services they need without...financial hardship."[1] Making progress toward and ultimately attaining UHC for all rose to global policy prominence with the adoption of the UN Sustainable Development Goals (SDGs) in 2015,[2] wherein an explicit target – SDG 3.8 – called for achieving UHC by 2030. Two SDG indicators comprise this UHC target, one of which aims to represent service coverage (SDG 3.8.1)[3] and one of which reflects financial risk protection (SDG 3.8.2).[4]

In the next sections, we summarise the background and events leading to the development of the UHC effective coverage index (UHC ECI) (Section 2). We also summarise consultative steps on the UHC effective coverage measurement framework and indicator selection (Sections 3 and 4).

Section 2. Background on UHC measurement considerations in the SDG era

Since the initial release of the global SDG indicator framework in 2016,[5] the measurement of each UHC component has been subject to considerable debate.[6–10] For instance, the original SDG 3.8.2 indicator, "number of people covered by health insurance or a public health system per 1,000 population," was met with such negative feedback and critique that hundreds of organisations and individuals effectively campaigned for its replacement by the Inter-agency Expert Group on SDG Indicators (IAEG-SDGs) and UN Statistical Commission in March 2017.[11] The revised 3.8.2 indicator, "proportion of population with large household expenditures on health as a share of total household expenditure or income,"[4] is viewed as a more direct measure of financial risk protection within UHC.

Measuring UHC service coverage, especially for global monitoring purposes within the SDG framework, has faced two main challenges: (1) defining what should constitute health services needed by populations; and (2) optimally quantifying receipt of these services and corresponding quality. At the global level, the definition of UHC has varied over time, as well as by group and/or resolution focused on its pursuit (examples shown in Table 1.1).[1,2,12–19] Definitional differences are most striking for the service coverage component of UHC – whether the emphasis is on access to services versus their actual use or receipt; types of services expressly referenced (eg, inclusion of palliation, incorporation of public health programmes); and how service effectiveness or quality is incorporated.

Global UHC measurement needs were further elevated by the announcement of WHO's draft Thirteenth General Programme of Work (GPW13) and its "triple billion targets" in November 2017.[20] Designed to guide WHO priorities for 2019–2023 and accelerate progress during the SDG era, the GPW13 explicitly included UHC under ones of its billion targets. This target was eventually formalised as "1 billion more people benefiting from UHC" by 2023, with 2018 serving as the baseline for the five-year evaluation period.[17] In late 2017, the WHO Director General established the GPW13 Expert Reference Group (ERG) in order to develop measurement approaches for the triple billion targets, including the one focused on UHC. During its consultative process in 2017–2018, the GPW13 ERG and its Metrics Taskforce recommended developing a UHC service coverage measure that could capture the construct of effective coverage,[21] or the fraction of potential health gain associated with receiving a service or intervention that is actually delivered by a population.[22–24] It was also recommended to establish a measurement framework reflective of health service areas that address the needs of major population groups across the life course, and then aim to fill the resulting matrix with corresponding indicators.

Table 1.1: Examples of global definitions of UHC

Year	Source	UHC definition
2005	World Health Assembly Resolution 58.33[13]	"Access to key promotive, preventive, curative, and rehabilitative interventions for all at an affordable cost, thereby achieving equity in access."
2010	WHO. *The World Health Report 2010: Health systems financing: the path to universal coverage.*[14]	"Financing systems need to be specifically designed to: - provide all people with access to needed health services (including prevention, promotion, treatment and rehabilitation) of sufficient quality to be effective; - ensure that the use of these services does not expose the user to financial hardship."
2014	WHO/World Bank. *Monitoring progress towards universal health coverage at country and global levels: framework, measures, and targets.*[15]	"All people who need health services (promotion, prevention, treatment, rehabilitation and palliation) receive them, without undue financial hardship." "UHC has two interrelated components: the full spectrum of good-quality essential health services according to need, and protection from financial hardship, including possible impoverishment, due to out-of-pocket payments for health services."
2015	UN Sustainable Development Goals (SDGs), Target 3.8[2]	"Achieve UHC, including financial risk protection, access to quality essential health care services and access to safe, effective, quality and affordable essential medicines and vaccines for all."
2015	WHO/World Bank. *Tracking universal health coverage: first global monitoring report.*[1]	"UHC means all people receiving the health services they need, including health initiatives designed to promote better health (such as anti-tobacco policies), prevent illness (such as vaccinations), and to provide treatment, rehabilitation, and palliative care (such as end-of-life care) of sufficient quality to be effective while at the same time ensuring that the use of these services does not expose the user to financial hardship."
2017	WHO/World Bank. *Tracking universal health coverage: 2017 Global Monitoring Report.*[16]	"Universal health coverage means that all people receive the health services they need, including public health services designed to promote better health (such as anti-tobacco information campaigns and taxes), prevent illness (such as vaccinations), and to provide treatment, rehabilitation and palliative care (such as end-of-life care) of sufficient quality to be effective, while at the same time ensuring that the use of these services does not expose the user to financial hardship."
2019	WHO. *Thirteenth General Programme of Work 2019–2023: Promote Health, Keep the World Safe, Serve the Vulnerable.*[17]	"The goal of ensuring that all people and communities have access to and can use the high quality promotive, preventive, curative, rehabilitative and palliative health services that are appropriate to their needs and expectations, while not exposing the user to financial hardship."
2019	WHO. *Primary Health Care on the Road to Universal Health Coverage: 2019 Monitoring Report.*[18]	"Universal health coverage means that all people receive the health services they need, including public health services designed to promote better health (such as anti-tobacco information campaigns and taxes), prevent illness (such as vaccinations), and to provide treatment, rehabilitation and palliative care (such as end-of-life care) of sufficient quality to be effective, while at the same time ensuring that the use of these services does not expose the user to financial hardship."
2019	United Nations General Assembly Resolution 74/2[19] Political Declaration of the High-Level Meeting on Universal Health Coverage. *Universal health coverage: moving together to build a healthier world*[25]	"Universal health coverage implies that all people have access, without discrimination, to nationally determined sets of needed promotive, preventive, curative, rehabilitative, and palliative essential health services, and essential, safe, affordable, effective and quality medicines and vaccines, while ensuring that the use of these services does not expose the users to financial hardship, with a special emphasis on the poor, vulnerable, and marginalized segments of the population."

In March 2018, the UN Statistical Commission endorsed the UHC service coverage index (SCI) as the metric for monitoring SDG indicator 3.8.1.[26] The UHC SCI sought to directly translate the SDG indicator 3.8.1 definition – "Coverage of essential health services (defined as the average coverage of essential services based on tracer interventions that include reproductive, maternal, newborn and child health, infectious diseases, non-communicable diseases and service capacity and access, among the general and the most disadvantaged population)" – by including three to four tracer indicators mapped to each listed category. Some UHC SCI indicators are direct measures of intervention coverage (eg, met need for family planning with modern contraception; antiretroviral therapy [ART] coverage among people living with HIV), while others included rescaled measures of risk factor exposure (eg, prevalence of non-tobacco use; prevalence of non-elevated blood pressure) and health system inputs (eg, hospital beds per capita; health worker density).[3] Limitations of the UHC SCI have been acknowledged by WHO, the indicator's custodial agency,[16,18,27] namely in terms of not expressly accounting for the effectiveness of services received and approximating coverage of non-communicable disease (NCD) interventions with prevalence-based measures. Other critiques involve the UHC SCI's over-emphasis on infectious diseases and reproductive, maternal, neonatal, and child health (RMNCH) interventions;[8,28] its omission of indicators representative of high-priority health needs across the life course;[29] and inadequate representation of health priorities across the development spectrum,[30] among others.

Approximately one year later, in May 2019, the World Health Assembly (WHA) Resolution A72/5 emphasised the importance of moving toward measuring effective coverage for UHC service coverage,[31] a sentiment echoed by the IAEG-SDGs. Such work would be used to inform monitoring of progress toward GPW13 milestones, namely the UHC billion target, conditional on methodological completion, peer-review, and country pilots. Per the GPW13's emphasis on the continuum of care in UHC,[17] the updated UHC effective coverage metric would "include tracer indicators by type of care (promotion, prevention, treatment, rehabilitation, and palliation) and by age group (life course)."[31] The overall index would then be calculated by combining tracers weighted by the potential health gain achievable by the interventions or services represented by each tracer.

As described more in Section 3, the development and consultation process on the UHC effective coverage framework primarily spanned 2017 to 2019. This work was guided by the GPW13's UHC billion target and the prevailing recognition that current measures of UHC service coverage to date were not expressly capturing interventions across the life course and incorporating effective coverage of services received.

Section 3. UHC effective coverage framework development and consultation

As established by the WHO Director-General in late 2017, the ERG on the Draft GPW13 Impact Framework 2019–2023[32] sought to advise on the development and refinement of methods to measure the "triple billion" targets, as well as indicators and targets for the broader WHO Impact Framework. Measuring UHC billion target, which called for "1 billion more people benefiting from UHC," served as the foundation for developing the UHC effective coverage framework and the corresponding UHC effective coverage index (ECI). The high-level timeline for this process is summarised in Table 1.2, as informed by ERG documentation, presentations, and the WHO Secretariat.[24,32]

Table 1.2: High-level timeline for UHC effective coverage methods development and consultation

Year	Months	Methods and/or consultation step
2017	August	WHO Technical programmes propose targets and triple billion methods
	September	WHO Executive Board session on triple billion measurement, WHO Impact Framework targets, and SDG alignment
	October-December	WHO Director-General constitutes GPW13 Expert Reference Group (ERG); ERG initiates deliberations
	November	Draft GPW13 released
2018	January-May	Series of WHO Secretariat and ERG/Taskforce on Metrics meetings on triple billion methods
	February	ERG meeting and Taskforce on Metrics establishment
	May	GPW13 approved at World Health Assembly; initial triple billion methods and ERG/Taskforce on Metrics published[21]
	June	WHO Secretariat, WHO regions, and ERG Taskforce meeting in Seattle, WA, on triple billions methods
	August-October	WHO Secretariat and ERG Taskforce meeting in Geneva on triple billion methods; continued methods refinement and consultation via Regional Committee meetings, web-based engagement with partners, including recommendations to present effective coverage as improved approach to measuring SDG 3.8.1 to the IAEG-SDGs
	November	IAEG-SDGs presentation on 3.8.1 measurement; African Union Statistical commission engagement
	December	Pan-American Health Organization (PAHO) consultation; Mission briefing
2019	January-May	Continued methods refinement and consultation coordinated via WHO Secretariat
	January	IAEG-SDGs presentation on 3.8.1 measurement;[24] WHO Executive Board meeting briefing; UHC 2030 and SDG3 action plan partners briefing
	May	World Health Assembly Resolution 72/5 on GPW13 and WHO Impact Framework measurement[31]
	October	WHO Secretariat and Member State meeting in Geneva on triple billion methods
	December	UHC effective coverage index methodology submitted for peer-review

Per the ERG and consultation feedback,[21] we used the following recommendations to inform the overall UHC effective coverage measurement framework and methods development:

1) **Include the main services households seek and/or receive that can lead to catastrophic health spending**, thus representing the two key dimensions of measuring UHC (ie, service coverage and financial risk protection).
   i. WHO has expressly included public health programmes and policy like tobacco taxation in its definition of UHC under health promotion for several years (see Table 1.1).[1,16,18] While multisectoral actions to improve health have vital roles alongside or in coordination with UHC initiatives, to understand and measure progress toward achieving overall UHC (ie, all people receiving quality health services they need without financial hardship), the focus should be on interventions and services provided within the immediate health system.

2) **Incorporate constructs of effective coverage**, such that tracer indicators of UHC service coverage ideally reflect access to quality care and health gains associated with effective intervention receipt. At the health system level, effective coverage reflects the fraction of potential health gain received through services or interventions that is actually delivered to a given population.[22,23]

3) **Expand included health service areas to better represent the range of service types** (ie, promotive, preventive, curative, rehabilitative, and palliative services) emphasised by the GPW13 and prior WHO definitions of UHC.
    i. Past and current measures of UHC service coverage,[16,18,27,33] including those proposed by the GBD collaboration for health-related SDG monitoring,[28,34,35] have not sought to structure measurement around these types of services. Rehabilitation and palliative care indicators are not included in any global UHC service coverage measure to date.

4) **Represent priority health needs across settings based on tracer indicators of UHC service coverage**. The specific interventions or packages of services that are ultimately included in UHC will vary by country or Member State due to differences in local epidemiological profiles, health system organisation, financial resources, and political or societal demands.

5) **As appropriate, use outcome-based tracer indicators to better approximate health-care access and quality to key services**. This approach enables comparable measurement while recognising differences in Member State UHC service packages and implementation.
    i. Such outcome-based indicators should be risk-adjusted to account for factors and risks that can affect health outcomes outside of the immediate purview of UHC and health systems. Robust methods on risk-adjustment or standardisation should be used.[36,37]
    ii. Other types of outcome-based measures, like mortality-to-incidence ratios (MIRs), should be considered where there are sufficient, high-quality data on both cause-specific deaths and non-fatal outcomes (eg, cancer registries). In the case of cancers, MIRs have been shown to be good measures of access to quality cancer diagnostic and treatment services.[38–41]

6) **Ground UHC service coverage measurement on a framework mapping needs of major population groups against main service types relevant to UHC.** This matrix will be composed of x cells representing different combinations of population groups and service areas.

7) **Map one or several UHC service coverage indicators per health service area–population group** based on these criteria:
    i. Tracer indicators should be correlated with a broader set of interventions or services that provide health gains in that area;
    ii. Tracer indicators should be measurable (ie, currently available data and methods support their measurement today);
    iii. Tracer indicators should be important in their own right for UHC and thus improving health;
    iv. Tracer indicators should reflect variations in UHC service coverage and not factors that are outside of the immediate scope of health systems and UHC (ie, social and environmental determinants);
    v. Tracer indicators should be drawn from indicators already included in the SDGs or GWP13, and/or the data systems required for SDG or GPW13 monitoring.

8) **Represent a range of health areas where UHC can provide health gains across conditions, including communicable, RMNCH, NCDs, and injuries.** Where possible, seek balance in indicator representation.

9) **Combine individual indicators into an overall measure of UHC service coverage by reflecting the magnitude of health gain potentially achievable through health service or interventions.** Weighting

indicators relative to potential disease burden addressable under maximum performance of interventions or service received would be a recommended approach, per prior effective coverage methodologies.[22,23]

In May 2018, the initial UHC effective coverage framework, as proposed to the ERG and Taskforce on Metrics, was a matrix composed of seven population groups – neonates (< 28 days); infants and children under 5 (29 days–4 years); children and adolescents (5–19 years); adults (20–64 years), separated by sex (male and female); reproductive health, female; older adults (≥65 years) – against health services subdivided by platform (ie, levels of care), function (ie, prevention and treatment), and service areas.[42] A total of 36 indicators were mapped to this matrix, drawing from tracer indicators included the UHC SCI,[27] the GBD 2016 measure for UHC service coverage for health-related SDGs monitoring,[28] and the draft GPW13 monitoring framework at that time. This exercise was viewed as a helpful start, but likely too complex or unwieldy to garner further traction.

From May to December 2018, a streamlined UHC effective coverage framework was developed in consultation with the ERG, WHO Secretariat, and partners (eg, WHO regional office representatives). This matrix consolidated population-age groups to a total of five categories – reproductive and newborn, children under 5 years, children and adolescents (5–19 years), adults (20–64 years), and older adults (≥65 years) – to represent the life course and focused on five main health service areas (promotion, prevention, treatment, rehabilitation, and palliation), with treatment sub-divided into communicable diseases and maternal and child health (MCH) and then NCDs.[24] A total of 30 unique "cells" (ie, combinations of population–age groups and health service types) resulted from this matrix, which became the UHC effective coverage measurement framework used in the present study (Figure 1.1; Figure 1A in the main manuscript).

Figure 1.1: UHC effective coverage framework as a matrix of population age groups and health service types

Population age-group	Health service type					
	Promotion	Prevention	Treatment		Rehabilitation	Palliation
			Communicable diseases and MNCH	NCDs		
Reproductive and newborn						
Children under 5 years						
Children and adolescents (5-19						
Adults (20-64 years)						
Older adults (≥ 65 years)						

Consolidating each portion of the measurement matrix was recognised as a potential drawback, a decision that could mask important differences within particular population age groups (eg, older children and adolescents; adults aged 20–40 versus 40–64 years) and subtypes of important health services. However, providing a more streamlined initial framework was viewed as necessary for facilitating further progress on UHC effective coverage measurement. Future iterations of this work could further assess data availability and methods for quantifying further sub-divisions, especially within population age groups.

Section 4. UHC effective coverage indicator selection

In line with ERG recommendations and feedback from consultation processes, we sought to identify tracer indicators that met inclusion criteria (Section 2) and could be mapped to the UHC effective coverage measurement framework. First, we examined currently available multi-country UHC service coverage measures from WHO, the World Bank, and the GBD collaboration, as well as individual indicators included in the global SDG indicator framework and GPW13. We also considered indicators that had been previously omitted from these sources to date but were considered important for capturing priority health services across the life course (eg, receipt of hearing aids or rehabilitative hearing services for hearing impaired; dental care). We then consider if, and then how, these indicators could be directly measured through the effective coverage construct or could be well-approximated through outcome-based measures like mortality-to-incidence ratios (MIRs) or risk-adjusted mortality rates. Last, we sought to identify a parsimonious set of indicators that could (1) appropriately represent the range of health services and population–age groups within the UHC effective coverage framework; and (2) be measured via data systems required for monitoring SDG or GPW13 progress. For instance, as shown in Table 1.3, some interventions and services may have been over-represented in GBD UHC service coverage measure (eg, DTP3 coverage and risk-standardised death rates from diphtheria, tetanus, and pertussis were all included in this index).

Following consultation and feedback from the GPW13 ERG and Metrics Taskforce, WHO Secretariat, and partners (eg, WHO regional official representatives), a total of 39 tracer indicators were proposed for an updated measure of UHC service coverage to the IAEG-SDGs in January 2019 (Table 1.4).[24] Of this total, 31 indicators were considered potentially measurable at that point in time (though some were conditional on gaining access to more microdata), while eight indicators were considered "aspirational" due to their inadequate data availability and/or measurement strategy.

The IAEG-SDGs requested additional refinement as well as formal peer review before taking any further action on considering methodological updates to SDG indicator 3.8.1. This feedback was also reflected in the WHA 72/5 resolution adopted in May 2019, wherein: "The IAEG-SDGs agreed that there was a need to make progress towards measuring 'effective' coverage and recommended that in the interim the Secretariat continue to use the current service coverage index. Once the methodological work related to the updated index has been completed, peer-reviewed and piloted in some countries, the Secretariat will approach the IAEG-SDGs to request approval of the updated methodology."[31]

Coordinated by WHO Secretariat, continued consultation on the UHC effective coverage framework and effective coverage indicators pointed to the need to further consolidate proposed indicators for methodological testing and future country pilots. Focusing on currently measurable indicators for which sufficient data across countries and methods for measurement existed today, all aspirational indicators were excluded. An additional seven indicators were then excluded, as further investigation into data availability and quality for directly measuring intervention coverage or developing proxy indicators showed serious gaps and/or challenges in appropriately estimating performance across countries and over time.

Table 1.3: UHC service coverage indicators included in multi-country indices published by WHO, World Bank, and the GBD collaboration. UHC=universal health coverage. SCI=service coverage index. SC=service coverage. RMNCH=reproductive, maternal, neonatal, and child health. NCDs=non-communicable diseases. ANC=antenatal care. DTP=diphtheria, tetanus, pertussis vaccine. ART=antiretroviral therapy. TB=tuberculosis. ITN=insecticide-treated net. IHR=International Health Regulations. BCG= Bacillus Calmette-Guérin. MCV1=measles-containing vaccine, 1 dose. HAQ=Healthcare Access and Quality.

UHC SCI[16,27]	SC index[43]*	GBD UHC service coverage index[28,35]
Total indicators: 14	**Total indicators:** 8	Total indicators: 41
Categorisation: 4 (RMNCH, infectious diseases, NCDs, service access and capacity)	**Categorisation:** 2 (prevention and treatment)	**Categorisation:** no formal; 9 intervention coverage measures and 32 outcome-based measures from the HAQ Index[36,37]
Indicators RMNCH -Met need for family planning with modern contraception -ANC4 -DTP3 -Care-seeking for suspected pneumonia for under-5 children Infectious diseases -ART coverage -TB case detection and treatment -ITN use for under-5 children (*high malaria transmission countries only*) NCDs -Prevalence of non-tobacco use -Prevalence of non-raised blood pressure -Mean fasting plasma glucose Service capacity access -Hospital beds per capita -Health worker density (physicians, surgeons, psychiatrists) -IHR score	**Indicators** Prevention -ANC4 -Full vaccination (BCG, DTP3, Polio3, MCV1) -Cervical cancer screening -Breast cancer screening Treatment -Skilled birth attendance -Treatment for acute respiratory infection (ARI) -Treatment for diarrhoea -Inpatient admission rates	**Indicators** Intervention coverage: -Met need for family planning with modern contraception -ANC1 -ANC4 -Skilled birth attendance -In-facility delivery rate -DTP3 -Polio3 -MCV1 -ART coverage Outcome-based (risk-standardised death rates or mortality-to-incidence ratios) -Tuberculosis -Diarrhoeal diseases -Lower respiratory infections -Upper respiratory infections -Asthma -Diphtheria -Whooping cough -Tetanus -Measles -Maternal disorders -Neonatal disorders -Colon and rectum cancer -Non-melanoma skin cancer -Breast cancer -Cervical cancer -Uterine cancer -Testicular cancer -Hodgkin lymphoma -Leukaemia -Rheumatic heart disease -Ischaemic heart disease -Cerebrovascular disease -Hypertensive heart disease -Peptic ulcer disease -Appendicitis -Hernia -Gallbladder and biliary diseases -Epilepsy -Diabetes -Chronic kidney disease -Chronic obstructive pulmonary disease -Congenital heart anomalies -Adverse effects of medical treatment
	*A study using these SC indicators was published in 2020.[33]	

Table 1.4: Proposed effective coverage (EC) tracer indicators for UHC service coverage measurement, January 2019. For additional detail, please refer to addendum documents found on the IAEG-SDGs website.[24]

No	EC indicator	Service type(s)	Population age groups	Proposal status
1	**Met need for FP with modern contraception**: fraction of women with need for family planning met by using modern contraceptives	Promotion	Reproductive and newborn	Include
2	**Breastfeeding promotion**: fraction of newborns initiating breastfeeding within 1 hour of birth	Promotion	Reproductive and newborn	Include
3	**Antenatal care:** fraction of women who received at least 4 ANC visits with quality indicators	Prevention	Reproductive and newborn	Aspirational
4	**Immunisation:** proportion of children receiving DTP3, MCV2, PCV3	Prevention	Children under 5	Include
5	**NTD preventive services**: geometric mean of treatment coverage of 5 NTDs	Prevention	Children under 5; children and adolescents (5-19); adults (20-64); older adults ($\geq$ 65 years)	Include
6	**Malaria vector control**: fraction of a population sleeping under an ITN or with effective IRS	Prevention	Children under 5; children and adolescents (5-19); adults (20-64); older adults ($\geq$ 65)	Include
7	**HPV vaccination:** fraction of girls receiving final HPV dose	Prevention	Children and adolescents (5-19)	Include
8	**Elevated BP management**: fraction of individuals with hypertension reaching treatment targets of SBP/DBP <140/90	Prevention	Adults (20-64); older adults ($\geq$ 65)	Include
9	**Elevated blood glucose management**: fraction of individuals with elevated blood sugar reaching the treatment target of FPG < 126 mg/dL	Prevention	Adults (20-64); older adults ($\geq$ 65)	Include
10	**Management of labour and delivery**: proportion of livebirths delivered with a skilled birth attendant present	Treatment, Comm & MCH	Reproductive and newborn	Include
11	**Antenatal, peripartum, and postnatal care for the newborn**: proxied using rescaled early neonatal death rate	Treatment, Comm & MCH	Reproductive and newborn	Include
12	**Antenatal, peripartum, and postnatal care for the mother:** proxied using rescaled maternal mortality ratio	Treatment, Comm & MCH	Reproductive and newborn	Include
13	**Perinatal care:** proxied using ratio of stillbirths to total births (livebirths and stillbirths)	Treatment, Comm & MCH	Reproductive and newborn	Include
14	**Treatment for pneumonia (LRIs):** proxied using rescaled death to incidence ratio for pneumonia (LRIs)	Treatment, Comm & MCH	Children under 5	Include
15	**Treament of severe acute nutrition:** proxied using rescaled death to incidence ratio for severe acute malnutrition.	Treatment, Comm & MCH	Children under 5	Include
16	**Treatment for diarrhoea**: proxied using rescaled death to incidence ratio for diarrhoea	Treatment, Comm & MCH	Children under 5	Include
17	**ART**: fraction of individuals with HIV/AIDS receiving ART	Treatment, Comm & MCH	Children and adolescents (5-19); adults (20-64); older adults ($\geq$ 65)	Include

No	EC indicator	Service type(s)	Population age groups	Proposal status
18	**TB treatment:** proxied by ratio of notified and treated tuberculosis cases (all forms) to estimated incidence	Treatment, Comm & MCH	Adults (20-64); older adults ($\geq$ 65)	Include
19	**Hepatitis C virus treatment:** fraction of persons diagnosed with chronic hepatitis C virus infection receiving treatment	Treatment, Comm & MCH	Adults (20-64); older adults ($\geq$ 65)	Include
20	**Congenital heart disease treatment:** proxied using rescaled death to prevalence ratio for congenital heart disease	Treatment, NCDs	Children under 5	Include
21	**Surgical care for abdominal emergencies**: proxied using rescaled death to incidence ratio for appendicitis, paralytic ileus, and intestinal obstruction	Treatment, NCDs	Children and adolescents (5-19); adults (20-64); older adults ($\geq$ 65)	Include
22	**Refractive error correction:** proxied using rescaled prevalence of moderate distance vision loss, severe distance vision loss, blindness due to uncorrected refractive error	Treatment, NCDs	Children and adolescents (5-19); adults (20-64); older adults ($\geq$ 65)	Include
23	**Treatment of childhood leukaemias:** proxied using rescaled death to incidence ratio for childhood leukaemias	Treatment, NCDs	Children and adolescents (5-19)	Include
24	**Treatment of asthma:** proxied using rescaled death to prevalence ratio for asthma	Treatment, NCDs	Children and adolescents (5-19)	Include
25	**Dental care:** proxied using rescaled prevalence of caries in permanent teeth	Treatment, NCDs	Children and adolescents (5-19); adults (20-64); older adults ($\geq$ 65)	Include
26	**Treatment for breast, cervical, colorectal, and uterine cancers:** proxied using rescaled death to incidence ratio of each cancer	Treatment, NCDs	Adults (20-64); older adults ($\geq$ 65)	Include
27	**Treatment for ischaemic heart disease:** proxied using rescaled death to incidence ratio for ischaemic heart disease	Treatment, NCDs	Adults (20-64); older adults ($\geq$ 65)	Include
28	**Treatment of stroke**: proxied using rescaled death to incidence ratio for stroke	Treatment, NCDs	Adults (20-64); older adults ($\geq$ 65)	Include
29	**Treatment of COPD**: proxied using rescaled death to prevalence ratio for COPD	Treatment, NCDs	Adults (20-64); older adults ($\geq$ 65)	Include
30	**Treatment of end-stage renal disease**: proxied using rescaled ratio of deaths to CKD to prevalence of end-stage renal disease	Treatment, NCDs	Adults (20-64); older adults ($\geq$ 65)	Include
31	**Cataract surgery**: proxied using proportion of individuals with cataracts who have received cataract surgery	Treatment, NCDs	Older adults ($\geq$ 65)	Include
32	**Treatment of endentulism (individuals with zero remaining permanent teeth):** proxied using rescaled prevalence of endentulism	Treatment, NCDs	Older adults ($\geq$ 65)	Aspirational
33	**Treatment of severe mental health conditions**: proxied using rescaled coverage of treatment for severe mental health conditions	Treatment, NCDs	Adults (20-64); older adults ($\geq$ 65)	Aspirational
34	**Treatment for substance abuse:** proxied using fraction of people with substance abuse disorders who receiving some type of treatment	Treatment, NCDs	Adults (20-64); older adults ($\geq$ 65)	Aspirational
35	**Prehospital emergency care services:** proxied using rescaled proportion of adults and children dying of acute injury in hospital among all acute injury deaths	Treatment, NCDs	Children and adolescents (5-19); adults (20-64); older adults ($\geq$ 65)	Aspirational

No	EC indicator	Service type(s)	Population age-groups	Proposal status
36	**Rehabilitation after complex injury:** proxied using proportion of individuals with complex injuries who receive multiple modes of rehabilitation	Rehabilitation	Adults (20-64); older adults ($\geq$ 65)	Aspirational
37	**Treatment for hip osteoarthritis**: proxied using ratio of people with hip replacements with people who need a hip replacement	Rehabilitation	Older adults ($\geq$ 65)	Aspirational
38	**Rehabilitation for hearing loss for infants**: proxied by proportion of deaf or hard-of-hearing infants receiving hearing loss services	Rehabilitation	Children under 5	Aspirational
39	**Palliation for cancer:** proxied using morphine-equivalent strong opioid analgesics (excluding methadone) per death from cancer	Palliation	Adults (20-64); older adults ($\geq$ 65)	Include

These 7 omitted indicators were (1) preventive therapy for select NTDs; (2) HPV vaccination; (3) hepatitis C treatment; (4) cataract surgery; (5) refraction error correction; (6) dental care; and (7) palliation for cancer. Breastfeeding, malnutrition treatment, and stillbirths proxying perinatal care were then omitted due to mixed evidence on effectiveness at the population level, followed by skilled birth attendance because the indicator using maternal mortality to ratio (MMR) to proxy antenatal, peripartum, and postnatal care for the mother was viewed as preferable for representing access to quality care. Congenital heart disease was then excluded due to data quantity and quality issues with consistently capturing prevalence across countries and over time.

From September to December 2019, additional indicator refinements and/or exclusions took place based on testing individual indicator and overall UHC effective coverage index measurement with GBD 2019 results. PCV3 coverage was excluded due to its partial introduction worldwide; for countries that had yet to introduce PCV3, neither of the measurement options explored for its inclusion – applying 0% for the effective coverage indicator value or not counting its associated burden in the health gains calculation – was considered sufficient to merit either risking over- or under-counting the potential health gains deliverable by health systems. MCV2 coverage was replaced with MCV1 for similar reasons: using MCV1 was preferred to implying 0% coverage – and thus no protection against measles – for countries that had not yet introduced MCV2, especially given the high efficaciousness of MCV1. The malaria vector control indicator was simplified to all-age ITN use, as no cohesive estimates of ITN use or indoor residual spraying (IRS) had yet to be generated across all malaria-endemic countries. Correspondingly, we limited the all-age ITN use to 39 medium-to-high malaria transmission countries in sub-Saharan Africa, following similar restrictions used by WHO for the UHC SCI.[3,18] This decision was made to avoid "penalizing" malaria-endemic countries where ITNs are not widely used and other types of interventions (eg, IRS, seasonal chemoprevention), which likely support population-level health gains against malaria, are more prevalent. Insufficient access to microdata on elevated blood pressure management and elevated blood glucose management ultimately hindered the generation of time series estimates across the 204 countries and territories included in the GBD 2019 study. Inclusion of these NCD treatment indicators will be revisited in future iterations of the GBD.

Last, in recognising that some countries may could have variable performance on subsets of cancers or types of surgical care for abdominal emergencies, the previously combined indicator on cancer (ie, breast, cervical, colon/rectum, and uterine cancers) were divided into four site-specific indicators, as was appendicitis and then paralytic ileus and intestinal obstruction.

After receiving feedback via formal peer review and commentary collected through the GBD collaboration, the following effective coverage indicator revisions were made in January to March 2020:
- The exclusion of all-age ITN use, as its currently limited application to a subset of countries made it similar to indicators (eg, PCV3) previously excluded;
- The addition of epilepsy for three population–age groups (children and adolescents [5–19 years], adults [20–64 years], and older adults [≥65 years]), which offers an effective coverage indictor for a neurological condition with good data availability and for which access to quality care should prevent mortality;[36,37,44,45]
- The refinement of the childhood leukaemia treatment indicator, such that the indicator is now limited to acute lymphoid leukaemia for two population–age groups (children under 5 years, children and adolescents [5–19 years]). This update is viewed as a better reflection of amenability to current cancer care for childhood leukaemias.

As also emphasised in the main manuscript, the currently included indicators were based on their mapping to health service types and population–age groups, as well as their fulfillment of inclusion criteria. Currently excluded indicators could certainly fulfill these specifications, particularly as data systems are strengthened and involve more high-priority indicator measurement (eg, palliation services). The indicators included in the present analysis are not meant to be prescriptive; rather, the primary objective was to establish a robust, comparable measurement framework from which UHC effective coverage could be assessed across settings and inform efforts to incorporate effective coverage into UHC monitoring. Continuing to improve UHC effective coverage measurement in the future is a high priority for the GBD collaboration and its partners.

Figure 1.2: Mapping of proposed effective coverage indicators to the UHC effective coverage measurement framework. Indicators coloured in blue are those included in the present framework; indicators in yellow were part of the January 2019 proposal, while indicators in orange were considered aspirational but not currently measurable due to data and/or methodological limitations.

Population age-group	Health service type					
	Promotion	Prevention	Treatment		Rehabilitation	Palliation
			Communicable diseases and MNCH	NCDs		
Reproductive and newborn	Met need for FP with modern contraception Breastfeeding initiated within 1 hour of birth	Antenatal, peripartum, and postnatal care for newborns Antenatal, peripartum, and postnatal care for mothers	Skilled birth attendance Perinatal care Antenatal care measured with quality indicators			
Children under 5 years		DTP3 coverage MCV2 coverage Malaria vector control coverage Preventive therapy against select NTDs	Pneumonia (LRI) treatment Diarrhea treatment Severe acute malnutrition treatment	Congenital heart disease treatment Refractive error correction Prehospital emergency care services	Rehabilitation for hearing loss among infants	
Children and adolescents (5-19 years)		HPV vaccination Malaria vector control Preventive therapy against select NTDs	ART coverage	Leukaemia treatment Asthma treatment Surgical care for abdominal emergencies (appendicitis, paralytic ileus, and intestinal obstruction treatment) Refractive error correction Dental care (proxied by dental caries) Prehospital emergency care services	Rehabilitation after complex injury	
Adults (20-64 years)		Elevated BP management Elevated blood glucose management Malaria vector control Preventive therapy against select NTDs	ART coverage TB treatment Hepatitis C treatment	Diabetes treatment IHD treatment Stroke treatment CKD treatment COPD treatment Cancer treatment (breast, cervical, colorectal, uterine Surgical care for abdominal emergencies (appendicitis, paralytic ileus, and intestinal obstruction treatment) Refractive error correction Dental care (proxied by dental caries) Treatment of severe mental health conditions Treatment for substance abuse Prehospital emergency care services	Rehabilitation after complex injury	Palliation for cancer care
Older adults (≥ 65 years)		Elevated BP management Elevated blood glucose management Malaria vector control Preventive therapy against select NTDs	ART coverage TB treatment Hepatitis C treatment	Diabetes treatment IHD treatment Stroke treatment CKD treatment COPD treatment Cancer treatment (breast, cervical, colorectal, uterine cancers) Surgical care for abdominal emergencies (appendicitis, paralytic ileus, and intestinal obstruction treatment) Refractive error correction Cataract surgery Dental care (proxied by dental caries) Treatment of severe mental health conditions Treatment for substance abuse Prehospital emergency care Edentulism	Rehabilitation after complex injury Treatment for hip osteoarthritis	Palliation for cancer care

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Part 2. UHC effective coverage measurement

Section 1. Overview

As also illustrated below, three main steps comprise measuring the UHC effective coverage index, which are detailed more in the following sections: 1) estimating effective coverage (EC) indicators; 2) calculating health gain weights; and 3) constructing the overall UHC effective coverage index.
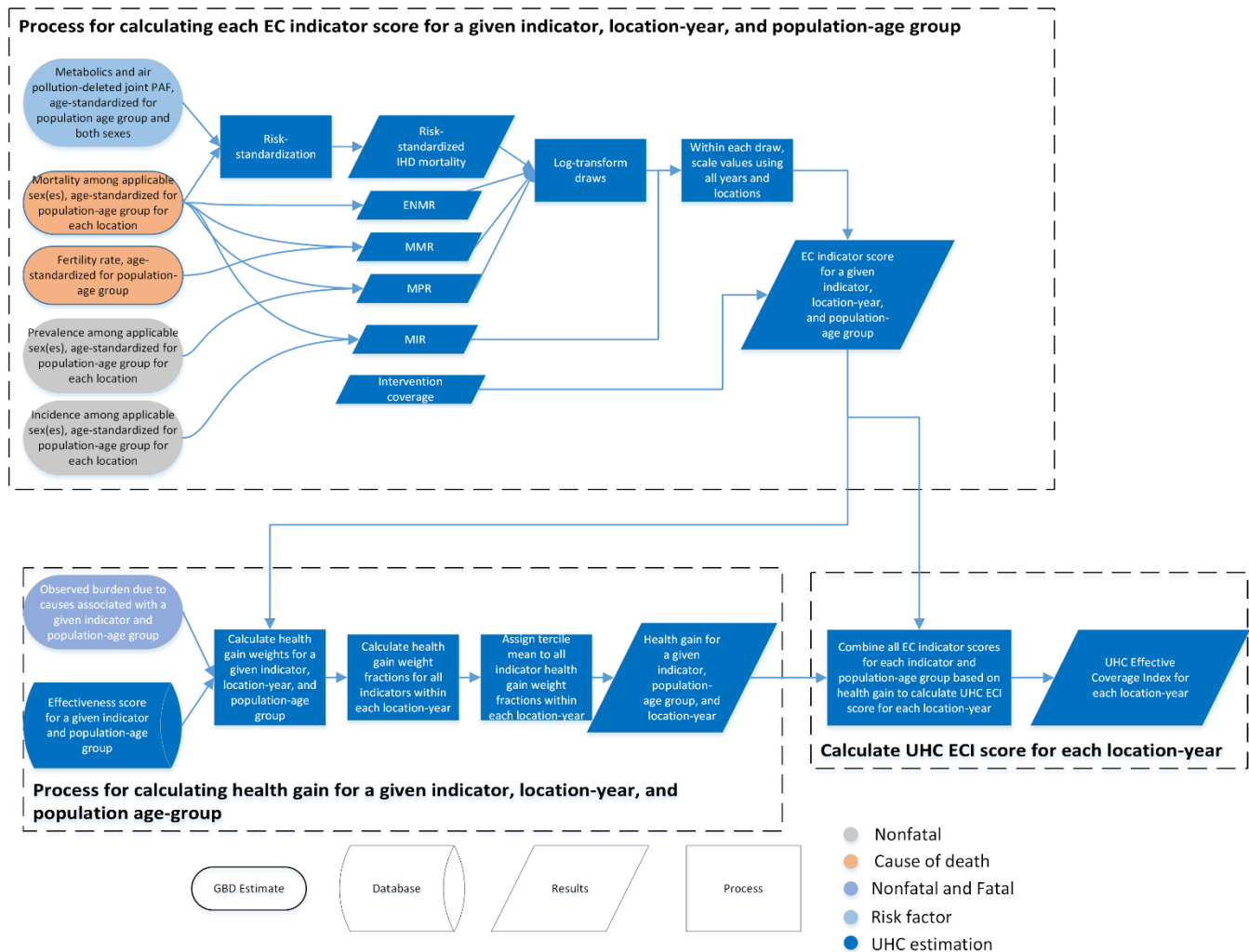
These analytical steps were informed by the UHC effective coverage measurement framework, which is described in the main manuscript and further in Part 1 of this methods appendix. This framework was informed by the WHO General Programme of Work 13 (GPW13) Task Force on Metrics and Expert Reference Group's recommendations,[1] as well as prior UHC monitoring efforts by WHO and the World Bank.[2,3]

Unless indicated otherwise, all inputs used for estimating UHC effective coverage index come from the broader Global Burden of Diseases, Injuries, and Risk Factors Study 2019 (GBD 2019); subsequently, greater detail on data inclusion, modelling processes and selection, and sensitivity analyses pertaining to each indicator, corresponding disease burden, and populations can be found in the GBD 2019 capstone publications.[4–6]

Analyses were conducted and figures were generated with R version 3.6.2 or Python 3.7.0.

Section 2. Estimating effective coverage indicators

EC indicators fall into two broad categories: 1) direct estimates of intervention coverage (also known as crude coverage); and 2) outcome-based indicators that approximate health-care access and quality. Three different types of outcome-based indicators were used, as they each could better approximate health-care access and quality for a given set of interventions or services due to data or measurement considerations. These outcome-based indicators were ratio metrics (ie, mortality-to-incidence ratios [MIRs] or mortality-to-prevalence ratios [MPRs]), mortality measures transformed to a scale of 0-100 (ie, neonatal mortality and maternal mortality ratio [MMR]), and risk-standardised death rates (RSDRs).

EC indicator values, all of which ultimately were on a scale of 0 to 100 to represent coverage, were estimated separately for each population–age group relevant to the indicator. For instance, for the indicator on ischaemic heart disease (IHD) treatment, EC indicator values (for coverage scores and health gain weights) were computed separately for the population–age groups of adults 20–64 years and ≥65 years. Whenever single EC indicator values were required (eg, figure 1 in the main manuscript), they were based on combining individual population-age group indicator scores. Figure 1B in the main manuscript further details population–age groups associated with each EC indicator, as well as what comprises each indicator.

Direct estimates of intervention coverage indicators

Four indicators were direct measures of intervention coverage (or crude coverage): antiretroviral therapy (ART) coverage among people living with HIV; diphtheria-tetanus-pertussis vaccine, three doses (DTP3) coverage; measles-containing vaccine, 1 dose (MCV1); and met need for family planning satisfied with modern contraception.

Intervention coverage estimates were drawn from GBD 2019, many of which are computed as part of broader models for GBD (eg, ART coverage as part of HIV modelling with Spectrum EPP;[7] vaccine coverage for vaccine-preventable disease modelling;[5] met need for family planning for fertility estimation[4]) and/or monitoring the health-related Sustainable Development Goals (SDGs) (eg, SDG indicator 3.7.1 on met need for family planning with modern contraception[8]), and thus have corresponding uncertainty intervals (UIs) computed across 1000 draws associated with each location-year estimate.

In terms of alignment with population–age groups within the measurement framework, vaccine coverage indicators (DTP3 and MCV1) were based on coverage among children aged 12–23 months but were applied to represent coverage among children under 5 years of age. Met need for family planning with modern methods was estimated for women 15–49 years of age without age-standardisation.

Outcome-based indicators

Mortality-to-incidence and mortality-to-prevalence ratios

MIRs were used for ten causes, while MPRs were used for six causes (as listed in figure 1B in the main manuscript). MPRs were preferred over MIRs for these six causes given the long duration of cases relative to potential mortality. For these 16 causes, MIRs and MPRs were viewed as good indicators approximating access to quality services targeting these conditions, particularly in the absence of robust coverage data across settings and over time.

To construct MIRs or MPRs for each cause and corresponding population–age group in the measurement framework, deaths and cases (incident or prevalent) were age-standardised by location-year and population–age group (eg, 5–19 years, 20–64, ≥65). Since our inputs are estimates from GBD 2019, 1000 draws of MIRs and MPRs were generated. Age-standardised mortality rates were then divided by the non-fatal equivalent to produce MIRs or MPRs. MPRs were logged using the natural log prior to scaling, though MIRs were not. Logging was not appropriate for some MIR indicators (eg, diarrhoea) since we found that logging MIRs led to arbitrarily decreased high coverage values in high-income places where we would expect coverage to consistently be very high. Last, these values were transformed to the 0–100 scale by rescaling locations i for years j 1990 to 2019, taking the 2.5th percentile (ie, lowest levels of MIRs or MPRs) observed of indicator I across location-years as the "best" (100) and the 97.5th percentile (ie, highest levels of MIRs or MPRs) as the "worst" (0):

$$S_{i,j} = \frac{I_{i,j} - I_{2.5th}}{I_{97.5th} - I_{2.5th}}$$

This scaling approach has been widely used for other GBD-based index measures.[8–11] It is preferred over taking the absolute minimum or maximum values to set the rescaling bounds to minimise sensitivity to outliers or particular fluctuations over time. Only GBD Level 3 locations (countries and territories, no subnational locations) were included in the scaling process.

Mortality measures

Early neonatal mortality and MMR were used to approximate care for newborns and mothers, respectively. We used the same scaling approach as described for MIRs and MPRs; prior to scaling, values were transformed on the natural log scale at the draw level. Uncertainty estimates in the form of 1000 draws were used for both early neonatal mortality and MMR.

Risk-standardised deaths

We used risk-standardised deaths for IHD. Only acute incidence of IHD was estimated for GBD 2019, whereas mortality included all IHD sub-causes.[5] The use of MPRs would also not be ideal given that IHD deaths can be due to chronic or acute IHD.

For the present analysis, we drew from the risk-standardisation process used in previous GBD studies, namely those used for estimating the Healthcare Access and Quality (HAQ) Index.[9,10] Uncertainty, in the form of 1000 draws, was propagated through for each quantity in the risk-standardisation process. First, we risk-deleted deaths jointly attributable to risk factors, not including deaths attributable to high systolic blood pressure, high LDL cholesterol, high fasting plasma glucose, and air pollution. Like for the HAQ Index,[9,10] we did not standardise deaths attributable to high systolic blood pressure, high LDL cholesterol, and high fasting plasma glucose, as those risk factors are considered to be directly amenable to high-quality personal health care. According to GBD 2019, around 25% of deaths due to IHD in low-income countries were due to air pollution (almost two-thirds related to household air pollution).[6] The impact of air pollution on IHD death rate estimates in low-income countries led to very low risk-standardised death rates in low-income countries relative to high-income countries when air pollution deaths were deleted from the total IHD death rate. Based on the lack of face validity, we decided to not standardise for air pollution in addition to high systolic blood pressure, high LDL cholesterol, and high fasting plasma glucose. We will further evaluate the effect of risk factors on IHD mortality and the use of risk-standardisation in future iterations of the UHC effective coverage index. We used the joint exposure, referred to as the joint population attributable fraction (PAF), for all risk factors minus the PAF for those four risks to arrive at a new PAF (NPAF). We then scaled the NPAF so that 0.9 (out of 1) is the maximum mean of the draws for a given age group, sex, location, and year. Deaths attributable (ND) to the NPAF were calculated by

multiplying cause-specific deaths (D) by NPAFs for each location l, year y, GBD age group a within population-age group p (eg, 20–24, 25–29, etc., for the population–age group 20–64 years), sex s, and indicator i:

$$ND_{l,y,a,s,i,p} = D_{l,y,a,s,i,p} * NPAF_{l,y,a,s,i,p}$$

We combined sex-specific estimates to arrive at both-sex counts of ND:

$$ND_{l,y,a,i,p} = ND_{l,y,a,males,i,p} + ND_{l,y,a,females,i,p}$$

We then age-standardised ND based on the GBD age groups within each included population–age group for a given indicator, and converted these estimates into proportions by dividing the both-sex, age-standardised ND by the both-sex, age-standardised number of total cause-specific deaths.

$$NPAF_{l,y,i,p} = \frac{ND_{l,y,i,p}}{D_{l,y,i,p}}$$

We then multiplied one minus the NPAF by all deaths to get the both-sex, age-standardised number of risk-deleted deaths (RDD):

$$RDD_{l,y,i,p} = D_{l,y,i,p} * (1 - NPAF_{l,y,i,p})$$

We then estimated risk-standardised deaths (RSD) by adding back deaths due to the global level of NPAF (as computed by one minus the global NPAF, or GPAF) averaged across all years using the following formula:

$$RSD_{l,y,i,p} = \frac{RDD_{l,y,i,p}}{(1 - GPAF_{i,p})}$$

We divided risk-standardised deaths by corresponding populations to convert these values into rates. After taking the natural log of these values, we then transformed these indicators to the 0–100 scale based on the rescaling approach described above.

Section 3. Calculating health gain weights

In following the effective coverage conceptual framework at the health system level,[12] we sought to quantify the fraction of potential health gains delivered to populations relative to the health gains that could have been delivered given intervention or service effectiveness and health needs of a given setting. To do this across multiple health service areas, we needed a principled way of representing potential health gains and then weighting each indicator of health service area relative to potential health gains provided. In the present study, we developed health gain weights based on a given location's observed effective coverage indicator values and associated disease burden (as measured by disability-adjusted life-years [DALYs]), relative to what burden could have been addressed and effectiveness associated with EC indicators. These weights were applied at the indicator-population-age group level to ultimately compute the overall UHC effective coverage index for each location-year.

Burden associated with EC indicators

As provided in figure 1 in the main manuscript, each EC indicator was linked to DALYs considered addressable by the interventions or services represented by the indicator. Of note, total DALYs due to maternal disorders were equally split (50%/50%) between met need for family planning with modern methods and the maternal care

indicator based on MMR; this was done to avoid double-counting of burden due to maternal disorders. To estimate burden associated with early neonatal mortality, we multiplied the number of early neonatal deaths by life expectancy at birth, per the theoretical minimum risk life table from GBD 2019.[4] We used 1000 draws of DALYs for each cause.

Effective coverage indicator effectiveness

EC indicator effectiveness categories were informed by previously published literature (ie, Cochrane, Tufts Cost-Effectiveness Analysis [CEA] Registry, and DCP3[13–15]). Five categories were ultimately assigned, ranging from 1 (most effective) to 5 (least effective), with incremental values assumed for each category (ie, 90% effectiveness for category 1, 70% for category 2, 50% for category 3, 30% for category 4, and 10% for category 5). Assignments were made at the population–age group level for each EC indicator, as provided in Figure 1B in the main manuscript.

For some EC indicators, a large number of potential interventions or services have been identified for targeting a given condition, and reported effectiveness of these interventions or services is equally variable. Distilling such heterogeneous information into a summary measure of effectiveness was very challenging for some EC indicators, a recognised limitation of the present analysis.

Health gain weights computation

First, we calculated two hypothetical burden scenarios ("zero coverage" and "full coverage") for a given indicator (i), population–age group (p), and location-year (l, y).

The "zero coverage" burden scenario was based on observed estimates of DALYs divided by one minus the effective coverage indicator value, which represented intervention coverage, multiplied by intervention effectiveness value assigned to the indicator; the zero coverage burden scenario represented expected disease burden in the total absence of interventions or health services.

$$Zero\ Coverage_{i,p,l,y} = \frac{Observed\ burden_{i,p,l,y}}{1 - intervention\ coverage_{i,p,l,y} * intervention\ effectiveness_{i,p}}$$

Second, the "full coverage" burden scenario was calculated by multiplying the burden estimated under "zero coverage" by one minus intervention effectiveness; the full coverage burden scenario represented expected disease burden if maximum levels of service coverage were achieved:

$$Full\ Coverage_{i,p,l,y} = Zero\ Coverage_{i,p,l,y} * (1 - 1 * intervention\ effectiveness_{i,p})$$

Subtracting levels of "full coverage" burden from burden under the "zero coverage" scenario resulted in the health gain weight – the population health gains potentially deliverable by health systems:

$$Health\ gain\ weight_{i,p,l,y} = Zero\ Coverage_{i,p,l,y} - Full\ Coverage_{i,p,l,y}$$

Below are examples of how the health gain weights are calculated for two hypothetical locations and two EC indicators.

EC indicator on ART coverage and HIV burden

	Country 1	Country 2
2019 estimates and effectiveness		
EC coverage for 20-64 year olds	0.93	0.47
Estimated burden (DALYs)	5,837,148	593,241
Effectiveness: Category 1 (90%)	0.90	0.90
Zero coverage scenario		
Estimated burden (DALYs)	5,837,148	593,241
EC coverage*effectiveness	0.84	0.42
1-(EC coverage*effectiveness)	0.16	0.58
Hypothetical burden (at 0%)	**35,810,724**	**1,028,147**
*HB (at 0%) = DALYs / (1-(EC coverage * effectiveness))*		
Full coveage scenario		
Hypothetical burden (at 0%)	35,810,724	1,028,147
1-(1*effectiveness)	0.10	0.10
Hypothetical burden (at full %)	**3,581,072**	**102,815**
HB (at full %) = HB (at 0%)(1-(1*effectiveness))*		
Potential health gain		
Hypothetical burden (at 0%)	35,810,724	1,028,147
Hypothetical burden (at full %)	3,581,072	102,815
Potential health gain	**32,229,652**	**925,333**
PHG = HB (at 0%) - HB (at full %)		

EC indicator on stroke treatment and stroke burden

	Country 3	Country 4
2019 estimates and effectiveness		
EC coverage for ≥ 65 year olds	0.33	0.85
Estimated burden (DALYs)	296,892	15,744
Effectiveness: Category 2 (70%)	0.70	0.70
Zero coverage scenario		
Estimated burden (DALYs)	296,892	15,744
EC coverage*effectiveness	0.23	0.60
1-(EC coverage*effectiveness)	0.77	0.41
Hypothetical burden (at 0%)	**386,075**	**38,874**
*HB (at 0%) = DALYs / (1-(EC coverage * effectiveness))*		
Full coveage scenario		
Hypothetical burden (at 0%)	386,075	38,874
1-(1*effectiveness)	0.30	0.30
Hypothetical burden (at full %)	**115,823**	**11,662**
HB (at full %) = HB (at 0%)(1-(1*effectiveness))*		
Potential health gain		
Hypothetical burden (at 0%)	386,075	38,874
Hypothetical burden (at full %)	115,823	11,662
Potential health gain	**270,253**	**27,212**
PHG = HB (at 0%) - HB (at full %)		

Health gain weights were transformed into fractions by dividing weights for each population–age group and EC indicator combination by the sum of all weights for a given location-year:

$$Health\ gain\ weight\ fraction_{i,p,l,y} = \frac{Health\ gain\ weight_{i,p,l,y}}{\sum(Health\ gain\ weight_{i,p,l,y})}$$

To ensure that the overall UHC effective coverage index was not dominated by one or a small subset of coverage scores, we grouped all health gain weight fractions for a given location-year into terciles, based on means of all draws. Then, within each tercile, location-year, and over each draw, we take mean health gain weight fraction of all of the EC indicator and population-age group combinations. That mean health gain weight fraction value is then used as the health gain weight fraction value for that draw for all indicators within that tercile.

Section 4. Constructing the UHC effective coverage index

The UHC effective coverage index was constructed based on weighting each EC indicator by its corresponding health gain weight fractions at the population–age group level. This aggregation approach approximates the fraction of total health gains delivered at the population level by location-year. We also considered the effects of constructing the UHC effective coverage index without accounting for health gain weights; to do this, we took the arithmetic mean of each EC indicator, by population–age group, by location-year.

As shown in figure 2 in the main manuscript, index values were highly correlated (r=0.95) across locations. However, the effects varied by location and over GBD super-regions, with many countries in sub-Saharan Africa as well as some high-income countries showing higher index values under the weighted index versus unweighted index. In contrast, many locations in central Europe, eastern Europe, and central Asia, as well as Oceania, had higher index values under the unweighted approach versus health gains weighting scheme.

Section 5. Sensitivity analyses

Scaling percentiles

We implemented a scaling procedure for our outcome-based measures in order transform ratio metrics, mortality measures, and risk-standardised death rates into coverage measures on a 0 to 100 scale. Part of the scaling process involved trimming the outcome-based measures so that the scale was set using 2.5th percentile as the minimum and the 97.5th percentile as the maximum, in order to control for outliers. We tested varying the scaling cutoffs, using the 1st percentile as the minimum and the 99th percentile as the maximum. Varying the cutoffs to use the wider 1st percentile and 99th percentile caused some EC indicator-specific and overall index scores to vary, but the correlation between the overall index scores remained quite high (r=0.999) across all years.

Varying effectiveness scores

Each EC indicator was ascribed an effectiveness score from 1 to 5. We tested the sensitivity of our index results to changes in the effectiveness scores. We subtracted 1 from each effectiveness score, thereby making each indicator 20 percentage points more effective (eg, shifting a category 2 [70%] EC indicator to category 1 [90%]; the exception being indicators that already had a score of 1, which remained the same), which resulted in overall index scores that were highly correlated (r=0.996) with our results. We also added 1 to each effectiveness score, thereby making each indicator 20 percentage points less effective (eg, shifting a category 3 [50%] EC indicator to category 2 [30%]; the exception being indicators that already had a score of 5, which remained the same), which also resulted in overall index scores that were highly correlated (r=0.996) with our current results.

Using a different number of bands for the health gain weight fractions

The weighting process involved breaking up the health gain weight fractions into terciles and assigning the mean tercile weight to each indicator within a tercile. We tested using quartiles instead of terciles and found that the correlation between overall index scores in all location-years was quite high (r=0.992). We also tested using two groups, splitting at the median for each location-year, and again found that the correlation between overall index scores was quite high (r=0.986).

Section 6. Uncertainty analysis

GBD aims to propagate sources of uncertainty throughout its estimation process, resulting in uncertainty intervals (UIs) that accompany each point estimate. For each GBD estimate, UIs are computed based on 1000 draws from the posterior distribution, and 95% UIs are based on the 2.5th and 97.5th percentile of draws for each quantity of interest.

For this analysis, we take the 1000 draws produced for the underlying values for each EC indicator and corresponding disease burden estimates from the GBD 2019 study.[4–6] Uncertainty was not formally propagated for effectiveness categories in health gain weights estimation as we used single values per category, or for GBD 2019 population estimates as the mean population estimate was used for each location, year, sex, and age group.

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3. Validation
Section 1. Overview
Since no gold standard of UHC service coverage exists presently, we compared UHC effective coverage index performance against previous multi-country UHC service coverage indices on three validity tests: content validity, known-groups validity, and convergent validity. Details are provided in the following sections and are accompanied by figures and tables with each validity test's results.

These approaches and inputs were selected *a priori* in October 2018 based on inputs and guidance from the WHO GPW13 Expert Reference Group (ERG). Since then, the only updates or changes incorporated into these validity tests were on the basis of newly published estimates or studies: WHO published new UHC SCI estimates for 2017 in September 2019;[1] a study on overall UHC was first published in December 2019[2] and corresponding SC index estimates were made available in January 2020;[3] and Global Burden of Disease (GBD) 2019 estimates were finalised over the course of late December 2019 to early 2020.[4–6] Beyond the GBD 2019-based UHC effective coverage index, GBD 2019 estimates also were used for healthy life expectancy (HALE) and the Socio-demographic Index (SDI) as inputs for the convergent validity.

We compared performance for four multi-country index measures of UHC service coverage: (1) the GBD 2019-based UHC effective coverage index; (2) the GBD 2017-based UHC service coverage index,[7] which has been used previously for monitoring the health-related SDGs; (3) the WHO UHC SCI,[1] which is the current measure for SDG indicator 3.8.1;[8] and (4) the World Bank's SC index.[3] We did not include earlier estimates of the GBD-based UHC service coverage index[9] or the WHO UHC SCI;[10,11] because more recent analyses draw from the most up-to-date data sources and otherwise use the same measurement approach, earlier iterations of these indices are considered superseded by their more recent publications. For known-groups and convergent validity, we also included the unweighted average for the GBD 2019 UHC effective coverage index since the resulting index values differed from the health-gains weighted UHC effective coverage index.

Section 2. Content validity
This test of validity was based on the UHC effective coverage framework, as developed by the GPW13 ERG and WHO Secretariat (see Part 1 under the methods appendix for more detail on this process). This framework involves a matrix of health service types and population–age groups, resulting in 30 unique "cells" that are meant to represent the range of potential health services needed across the life course. For each index, we mapped their individual indicators to each cell and calculated what percentage of those 30 cells were represented by currently included indicators. As shown in Table 3.1, the GBD 2019 UHC effective coverage index had 40% coverage, followed by the GBD 2017-based UHC service coverage index (33%), the UHC SCI (20%), and SC index (17%).

No index included indicators representing rehabilitation or palliation, a limitation for all measurement in trying to optimally capture UHC service coverage needs across populations. In addition, nearly all indices lacked indicators for promotion or prevention beyond a subset of population–age groups (namely reproductive and newborn, and children under 5); the main exception was the SC index, which included two cancer screening indicators. However, the SC index lacked NCD treatment indicators or proxies across population–age groups.

Figure 3.1: UHC effective coverage framework as a matrix of population–age groups and health service types

Population age-group	Health service type					
	Promotion	Prevention	Treatment		Rehabilitation	Palliation
			Communicable diseases and MNCH	NCDs		
Reproductive and newborn						
Children under 5 years						
Children and adolescents (5-19						
Adults (20-64 years)						
Older adults (≥ 65 years)						

Section 3. Known-groups validity

For known-groups validity, we compared how well each index could discriminate between country-pairs for which previous studies show "country A" as having higher performance or faster progress on UHC service coverage than "country B", a country of similar geographical location and/or sociodemographic status with historically lower performance. 16 country-pairs and thus a total of 32 countries were identified for this test (Table 3.2); selections were made in October 2018 via inputs of the GPW13 ERG and thus were based on a combination of expert input and documentation by journal articles and reports.[12–22]

For each index, we calculated the percentage of total country-pairs (16) for which the mean for "country A" was higher than that of "country B." We also reported the ratio of "country A" to "country B" to approximate the distance between each country's performance (ie, values closer to 1 indicate greater similarity between the countries' means). For indices with reported uncertainty associated with their mean values, we also determined whether the performance of "country A" still exceeded that of "country B" when accounting for uncertainty (ie, each country's uncertainty bounds do not overlap). The WHO UHC SCI and World Bank SC index do not report uncertainty associated with their index estimates.

As shown in Table 3.2, using mean values, GBD-based indices (both methods for UHC effective coverage index and then the GBD 2017-based UHC service coverage index) each had 94% (15/16) of country-pairs with "country A" exceeding the average index performance of "country B." The UHC SCI for 2017 had 75% (12/16) and the SC index had 56% (9/16); of note, the latter did not have service coverage measures for five countries (Bolivia, Cuba, Belarus, Singapore, and Brunei). When uncertainty was accounted for, the GBD-based indices had lower percentages of country-pairs (56% to 69%). Five country pairs had overlapping uncertainty for GBD-based indices (ie, Brazil-Paraguay; Ethiopia-DRC; Rwanda-Burundi; Thailand-Sri Lanka; Turkey-Iran). In terms of "country A" to "country B" ratios, the GBD 2019 effective coverage index with health weight gains ranged from 0.99 (Turkey-Iran) to 1.41 (Singapore-Brunei). A somewhat similar range was found for the UHC SCI, spanning from 0.92 (Chile-Ecuador) to 1.37 (Rwanda-Burundi). In contrast, the World Bank SC index had a much wider range, from 0.48 (Turkey-Iran) to 3.05 (Ghana-Côte d'Ivoire). This may be related to country-level SC index

values being reported on the basis of most recent year of data available; subsequently, results for each country-pair could be from very different years and may not be wholly comparable.

To some degree this exercise was inherently subjective. No gold-standard measure of UHC service coverage exists, and thus comprehensive, consistently quantified time series of country-level UHC service coverage are not available outside of the indices being compared in the current study. It is very possible that a different set or number of country-pairs may been selected if this analysis occurred at a different point in time; on the basis of different types of consultation with different groups; and/or captured articles or reports published local languages. We do not view these results on their own as definitively conclusive of superior (or inferior) index performance; rather, they are meant to contribute toward a better understanding of how different UHC service coverage indices may correspond with prior perceptions of different countries' UHC performance.

Section 4. Convergent validity

For convergent validity, we estimated how much variation in healthy life expectancy (HALE) – a measure of overall population health – could be explained by each index after accounting for values of the Socio-demographic Index (SDI),[4,23] an indicator of overall development based on income per capita, educational attainment among populations aged 15 and older, and fertility rates among women under 25.

We viewed controlling for SDI's effect on HALE before assessing the relationship between HALE and UHC service coverage measures as necessary due to the high co-linearity of SDI with these metrics (eg, r=0.84 for SDI and HALE in 2019; r=0.87 for SDI and the health gains weighted UHC effective coverage index in 2019); Figures 3.1–3.5 depict the relationships between each index, SDI, and HALE. In an effort to avoid exaggerating the relationship between HALE and measures of UHC service coverage, we focused on the extent to which each index explained variation on HALE above and beyond what was associated with SDI.

To do this, we regressed country-level values of SDI in 2019, as estimated for GBD 2019, on corresponding estimates of HALE (also from GBD 2019). Second, we took the residuals from the first model – ie, variations in HALE not explained by SDI – and then regressed country-level index values against those residuals to determine how much of HALE could be explained by UHC service coverage performance. This two-step regression was conducted for each index separately, dropping corresponding values of SDI and HALE for indices that had fewer than the 204 countries and territories included in GBD 2019 (ie, 195 for GBD 2017, 183 for UHC SCI, 111 for the SC index). As also reported in Table 1 in the main manuscript, R^2 values – or how much UHC service coverage measures explained variation in HALE after accounting for SDI – spanned from 0.073 for the GBD 2019 UHC effective coverage index with health gains weighting to 0.010 for the World Bank SC index.

Index (year reported)	Source	Convergent validity (variation of HALE explained, accounting for SDI)		
		Beta coefficient	Standard error	R^2
UHC effective coverage index, health gains weighted (2019)	GBD 2019	5.00	1.72	0.073
UHC effective coverage index, unweighted average (2019)	GBD 2019	4.19	1.49	0.068
UHC service coverage index for SDGs (2017)	GBD 2017	4.30	1.76	0.053
UHC SCI for SDG indicator 3.8.1 (2017)	WHO 2019	4.21	1.88	0.044
Service coverage index (most recent year)	World Bank 2020	1.24	1.18	0.010

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Table 3.1 Mapping multi-country UHC health service coverage indicators against the UHC effective coverage measurement framework matrix of health service types and population-age groups. Indicators that do not directly map to specific service types and/or population-age groups are listed in the farthest right column. The percentage of matrix cells covered are calculated based on whether at least 1 indicator occupies a given cell of health services for a population-age group. Indicators are not included for population-age groups in which at least some portion of the population-age group is excluded (eg, ceiling of 74 years will not map to ≥ 65). UHC=universal health coverage. GBD=Global Burden of Disease. MNCH=maternal, neonatal, and child health. NCDs=Non-communicable diseases. FP=family planning. ENMR= early neonatal mortality rate. MMR=maternal mortality ratio. MIR=mortality-to-incidence ratio. MPR=mortality-to-prevalence ratio. RSDR=risk-standardised death rate. DTP=diptheria-tetanus-pertussis vaccine. MCV=measles-containing vaccine. ITN=insecticide-treated net. ART=antiretroviral therapy. TB=tuberculosis. ANC=antenatal care. SBA=skilled birth attendance. LRI=lower respiratory infection. URI=upper respiratory infection. IHD=ischaemic heart disease. RHD=rheumatic heart disease. HHD=hypertensive heart disease. CKD=chronic kidney disease. COPD=chronic obstructive pulmonary disease. BP=blood pressure. FPG=fasting-plasma glucose. IHR=International Health Regulations. ORS=oral rehydration solution. BCG=Bacille Calmette-Guerin vaccine.

Population-age group	Health service type						Not mappable to specific health service types
	Promotion	Prevention	Treatment		Rehabilitation	Palliation	
			Communicable diseases and MNCH	NCDs			
UHC effective coverage index (GBD 2019)	**40% (12 of 30 matrix cells)**						
Reproductive and newborn	Met need for FP with modern contraception	Antenatal, peripartum, and postnatal care for newborns based on ENMR Antenatal, peripartum, and postnatal care for mothers based on MMR					
Children under 5 years		DTP3 coverage MCV1 coverage	LRI treatment based on MIR Diarrhea treatment based on MIR	Leukaemia treatment based on MIR			
Children and adolescents (5-19 years)			ART coverage	Leukaemia treatment based on MIR Asthma treatment based on MPR Epilepsy treatment based on MPR Appendicitis treatment based on MIR Paralytic ileus and intestinal obstruction treatment based on MIR			
Adults (20-64 years)			ART coverage TB treatment based on MIR	Diabetes treatment based on MPR IHD treatment based on RSDR Stroke treatment based on MIR CKD treatment based on MPR COPD treatment based on MPR Cervical cancer treatment based on MIR Breast cancer treatment based on MIR Uterine cancer treatment based on MIR Colon/rectum cancer treatment based on MIR Epilepsy treatment based on MPR Appendicitis treatment based on MIR Paralytic ileus and intestinal obstruction treatment based on MIR			
Older adults (≥ 65 years)			ART coverage TB treatment based on MIR	Diabetes treatment based on MPR IHD treatment based on RSDR Stroke treatment based on MIR CKD treatment based on MPR COPD treatment based on MPR Cervical cancer treatment based on MIR Breast cancer treatment based on MIR Uterine cancer treatment based on MIR Colon/rectum cancer treatment based on MIR Epilepsy treatment based on MPR Appendicitis treatment based on MIR Paralytic ileus and intestinal obstruction treatment based on MIR			
UHC service coverage index (GBD 2017)	**33% (10 of 30 matrix cells)**						
Reproductive and newborn	Met need for FP with modern contraception	ANC1 coverage ANC4 coverage Neonatal care based on RSDR Maternal care based on RSDR	SBA coverage In-facility delivery rate Neonatal care based on RSDR Maternal care based on RSDR				Avoidance of adverse effects of medical treatment based on RSDR
Children under 5 years		DTP3 coverage MCV1 coverage Polio3 coverage Diphtheria prevention based on RSDR Pertussis prevention based on RSDR Tetanus prevention based on RSDR Measles prevention based on RSDR	Diarrhea treatment based on RSDR LRI treatment based on RSDR URI treatment based on RSDR	Treatment of congenital heart anomalies based on RSDR			
Children and adolescents (5-19			ART coverage LRI treatment based on RSDR URI treatment based on RSDR	Treatment of leukaemia based on MIR Treatment of asthma based on RSDR			

| Population-age group | Health service type | | | | | | |
| | Promotion | Prevention | Treatment | | Rehabilitation | Palliation | Not mappable to specific health service types |
			Communicable diseases and MNCH	NCDs			
Adults (20-64 years)			ART coverage LRI treatment based on RSDR URI treatment based on RSDR	Treatment of colon/rectum cancer based on MIR Treatment of breast cancer based MIR Treatment of cervical cancer based on MIR Treatment of uterine cancer based on MIR Treatment of non-melanoma skin cancer based on MIR Treatment of testicular cancer based on MIR Treatment of Hodgkin's lymphoma based on MIR Treatment of RHD based on RSDR Treatment of IHD based on RSDR Treatment of stroke based on RSDR Treatment of HHD based on RSDR Treatment of diabetes based on RSDR Treatment of CKD based on RSDR Treatment of epilepsy based on RSDR Surgical care for peptic ulcer disease based on RSDR Surgical care for appendicitis based on RSDR Surgical care for paralytic ileus and intestinal obstruction based on RSDR Surgical care for gallbladder and biliary diseases based on RSDR			
Older adults (≥ 65 years)							
UHC SCI, SDG 3.8.1 indicator (WHO)	**20% (6 of 30 matrix cells)**						
Reproductive and newborn	Met need for FP with modern contraception	ANC4 coverage					Basic sanitation; prevalence of non-smoking; hospital beds per 1,000; health worker density (physicians, surgeons, psychiatrists); IHR score
Children under 5 years		DTP3 coverage ITN use by children under 5 (for high malaria burden countries)	Care-seeking for ARI				
Children and adolescents (5-19 years)							
Adults (20-64 years)			ART coverage TB case detection and treatment	Prevalence of non-elevated BP Mean FPG			
Older adults (≥ 65 years)							
SC index (World Bank 2020)	**17% (5 of 30 matrix cells)**						
Reproductive and newborn		ANC4 coverage	SBA coverage				Inpatient admission rates
Children under 5 years		Full vaccination (DTP3, MCV1, BCG, Polio3)	Care-seeking for ARI ORS treatment for diarrhea				
Children and adolescents (5-19 years)							
Adults (20-64 years)		Breast cancer screening rates Cervical cancer screening rates					
Older adults (≥ 65 years)							

Table 3.2. Known-group validity results based on 16 country-pair comparisons on UHC service coverage measures. Based on previous literature and expert inputs, Country A was expected to have higher performance on UHC service coverage than Country B. Mean index values are reported for the following: UHC effective coverage index in 2019, both with health gains weights and the unweighted average (GBD 2019); UHC service coverage index for the health-related SDGs in 2017 (GBD 2017); and UHC SCI, the SDG 3.8.1 measure, in 2017 (WHO 2019); and service coverage (SC) index for most recent years (World Bank 2020). GBD-based indices have estimates of uncertainty, which we include and also assess Country A versus Country B performance on the basis of uncertainty (i.e., no overlap in uncertainty bounds). The WHO and World Bank indices to not do report estimates of uncertainty accompanying their mean index values. UHC=universal health coverage. GBD=Global Burden of Disease. SDGs=Sustainable Development Goals. SCI=Service coverage index.

Known-group validity country pairs		Index values		Validity indicators		
Country A	Country B	Country A	Country B	A > B (mean)	A > B (with uncertainty)	A / B (mean)
UHC effective coverage index for 2019, with health gains weights (GBD 2019)				**94% (15/16)**	**63% (10/16)**	
Brazil	Paraguay	64.8 (63.0 to 66.7)	63.4 (58.0 to 68.3)	Yes	No	1.02
Chile	Ecuador	74.6 (69.7 to 77.8)	64.5 (60.4 to 68.4)	Yes	Yes	1.16
Colombia	Plurinational State of Bolivia	74.5 (69.3 to 79.0)	52.5 (47.2 to 58.1)	Yes	Yes	1.42
Costa Rica	El Salvador	79.1 (74.2 to 83.1)	61.7 (56.3 to 66.6)	Yes	Yes	1.28
Cuba	Dominican Republic	72.5 (69.0 to 76.4)	52.7 (46.6 to 58.0)	Yes	Yes	1.38
Czechia	Belarus	82.1 (77.6 to 85.9)	70.5 (66.7 to 73.8)	Yes	Yes	1.16
Ethiopia	Democratic Republic of the Congo	46.5 (42.3 to 51.1)	45.1 (39.5 to 51.1)	Yes	No	1.03
France	United States	91.0 (86.6 to 93.6)	82.2 (80.4 to 83.6)	Yes	Yes	1.11
Ghana	Cote d'Ivoire	49.2 (45.5 to 53.1)	42.7 (37.8 to 49.3)	Yes	No	1.15
Japan	Portugal	96.4 (95.0 to 97.4)	83.8 (80.3 to 85.8)	Yes	Yes	1.15
Malaysia	Indonesia	66.6 (62.3 to 70.7)	48.6 (42.2 to 54.9)	Yes	Yes	1.37
Rwanda	Burundi	59.3 (54.5 to 64.4)	50.0 (43.5 to 55.8)	Yes	No	1.19
Singapore	Brunei	92.6 (90.1 to 93.9)	65.6 (62.6 to 67.9)	Yes	Yes	1.41
Spain	Peru	90.3 (87.1 to 91.6)	76.0 (70.4 to 79.9)	Yes	Yes	1.19
Thailand	Sri Lanka	71.6 (66.3 to 76.6)	65.6 (59.7 to 71.2)	Yes	No	1.09
Turkey	Islamic Republic of Iran	69.2 (64.6 to 73.9)	69.6 (67.4 to 71.4)	No	No	0.99
UHC effective coverage index for 2019, unweighted average (GBD 2019)				**94% (15/16)**	**56% (9/16)**	
Brazil	Paraguay	64.5 (62.6 to 66.4)	62.7 (57.8 to 67.0)	Yes	No	1.03
Chile	Ecuador	76.5 (72.0 to 79.5)	64.9 (60.5 to 68.1)	Yes	Yes	1.18
Colombia	Plurinational State of Bolivia	75.5 (70.6 to 79.3)	52.4 (47.2 to 57.2)	Yes	Yes	1.44
Costa Rica	El Salvador	79.7 (75.4 to 83.0)	66.5 (61.9 to 70.5)	Yes	Yes	1.20
Cuba	Dominican Republic	77.2 (73.6 to 80.4)	55.5 (50.3 to 60.0)	Yes	Yes	1.39
Czechia	Belarus	85.4 (81.6 to 88.0)	79.8 (76.2 to 82.5)	Yes	No	1.07
Ethiopia	Democratic Republic of the Congo	31.2 (26.5 to 37.8)	39.0 (34.4 to 43.2)	No	No	0.80
France	United States	87.9 (84.0 to 90.3)	84.7 (82.9 to 86.1)	Yes	No	1.04
Ghana	Cote d'Ivoire	43.5 (38.9 to 47.7)	40.1 (35.2 to 44.9)	Yes	No	1.08

Known-group validity country pairs		Index values		Validity indicators		
Country A	Country B	Country A	Country B	A > B (mean)	A > B (with uncertainty)	A / B (mean)
Japan	Portugal	93.8 (92.6 to 94.7)	86.4 (83.1 to 88.2)	Yes	Yes	1.09
Malaysia	Indonesia	68.2 (64.1 to 71.5)	44.9 (38.6 to 52.4)	Yes	Yes	1.52
Rwanda	Burundi	45.7 (41.1 to 50.2)	35.3 (29.6 to 41.0)	Yes	Yes	1.29
Singapore	Brunei	92.6 (89.9 to 94.0)	67.2 (63.9 to 69.7)	Yes	Yes	1.38
Spain	Peru	90.8 (87.5 to 92.2)	73.6 (68.5 to 77.2)	Yes	Yes	1.23
Thailand	Sri Lanka	72.4 (67.7 to 75.9)	69.9 (65.5 to 73.8)	Yes	No	1.04
Turkey	Islamic Republic of Iran	70.3 (66.7 to 73.5)	70.2 (68.2 to 72.0)	Yes	No	1.00
UHC service coverage index for the health-related SDGs for 2017 (GBD 2017)				**94% (15/16)**	**69% (11/16)**	
Brazil	Paraguay	70.0 (69.4 to 70.7)	69.6 (66.7 to 72.4)	Yes	No	1.01
Chile	Ecuador	81.1 (79.2 to 83.1)	67.9 (66.0 to 69.7)	Yes	Yes	1.19
Colombia	Plurinational State of Bolivia	74.8 (73.0 to 76.7)	61.0 (57.8 to 65.0)	Yes	Yes	1.23
Costa Rica	El Salvador	76.7 (75.5 to 77.8)	70.1 (67.1 to 73.0)	Yes	Yes	1.09
Cuba	Dominican Republic	78.1 (76.2 to 79.9)	64.3 (61.4 to 66.8)	Yes	Yes	1.21
Czechia	Belarus	88.6 (87.7 to 89.6)	83.6 (82.0 to 84.9)	Yes	Yes	1.06
Ethiopia	Democratic Republic of the Congo	44.2 (41.4 to 47.1)	43.9 (40.5 to 47.1)	Yes	No	1.01
France	United States	93.6 (92.7 to 94.4)	87.8 (87.3 to 88.2)	Yes	Yes	1.07
Ghana	Cote d'Ivoire	57.1 (54.2 to 60.0)	50.3 (47.5 to 53.3)	Yes	Yes	1.14
Japan	Portugal	93.7 (93.2 to 94.1)	90.2 (89.1 to 91.1)	Yes	Yes	1.04
Malaysia	Indonesia	72.9 (71.1 to 74.7)	61.8 (60.6 to 63.1)	Yes	Yes	1.18
Rwanda	Burundi	50.1 (46.5 to 54.1)	45.1 (41.3 to 49.2)	Yes	No	1.11
Singapore	Brunei	92.4 (91.7 to 93.2)	76.5 (74.9 to 78.0)	Yes	Yes	1.21
Spain	Peru	93.6 (92.9 to 94.3)	71.9 (69.5 to 74.4)	Yes	Yes	1.30
Thailand	Sri Lanka	76.4 (74.6 to 78.4)	77.1 (74.4 to 79.8)	No	No	0.99
Turkey	Islamic Republic of Iran	77.8 (76.2 to 79.3)	76.7 (75.3 to 77.9)	Yes	No	1.01
UHC SCI for 2017, SDG 3.8.1 measure (WHO 2019)				**75% (12/16)**	**-**	
Brazil	Paraguay	78.6	68.5	Yes	-	1.15
Chile	Ecuador	70.2	76.5	No	-	0.92
Colombia	Plurinational State of Bolivia	75.9	68.3	Yes	-	1.11
Costa Rica	El Salvador	77.0	75.6	Yes	-	1.02
Cuba	Dominican Republic	82.8	74.3	Yes	-	1.12
Czechia	Belarus	76.0	76.5	No	-	0.99
Ethiopia	Democratic Republic of the Congo	39.4	41.5	No	-	0.95
France	United States	77.7	83.9	No	-	0.93
Ghana	Cote d'Ivoire	47.4	47.3	Yes	-	1.00
Japan	Portugal	83.1	81.5	Yes	-	1.02
Malaysia	Indonesia	73.3	57.3	Yes	-	1.28

Known-group validity country pairs		Index values		Validity indicators		
Country A	Country B	Country A	Country B	A > B (mean)	A > B (with uncertainty)	A / B (mean)
Rwanda	Burundi	56.9	41.6	Yes	-	1.37
Singapore	Brunei	85.8	81.5	Yes	-	1.05
Spain	Peru	82.7	76.9	Yes	-	1.08
Thailand	Sri Lanka	79.8	66.0	Yes	-	1.21
Turkey	Islamic Republic of Iran	74.4	71.7	Yes	-	1.04
SC index for most recent year (World Bank 2020)				**56% (9/16)**	**-**	
Brazil	Paraguay	75.4	52.5	Yes	-	1.44
Chile	Ecuador	83.3	54.8	Yes	-	1.52
Colombia	Plurinational State of Bolivia	65.3	-	No	-	-
Costa Rica	El Salvador	63.1	48.1	Yes	-	1.31
Cuba	Dominican Republic	-	73.6	No	-	-
Czechia	Belarus	92.0	-	No	-	-
Ethiopia	Democratic Republic of the Congo	16.2	33.1	No	-	0.49
France	United States	93.1	89.5	Yes	-	1.04
Ghana	Cote d'Ivoire	46.1	15.1	Yes	-	3.05
Japan	Portugal	70.2	91.9	No	-	0.76
Malaysia	Indonesia	67.7	27.4	Yes	-	2.47
Rwanda	Burundi	38.2	29.8	Yes	-	1.28
Singapore	Brunei	-	-	No	-	-
Spain	Peru	86.2	52.5	Yes	-	1.64
Thailand	Sri Lanka	57.8	52.9	Yes	-	1.09
Turkey	Islamic Republic of Iran	31.9	66.6	No	-	0.48

Figure 3.1. Comparing the the UHC effective coverage index in 2019 with health gains weighting to HALE (A) and SDI (B). Locations are colour-coded by GBD super-region and abbreviated by ISO3 code. UHC=universal health coverage. GBD=Global Burden of Disease. SDI=Socio-demographic index. HALE=healthy life expectancy.
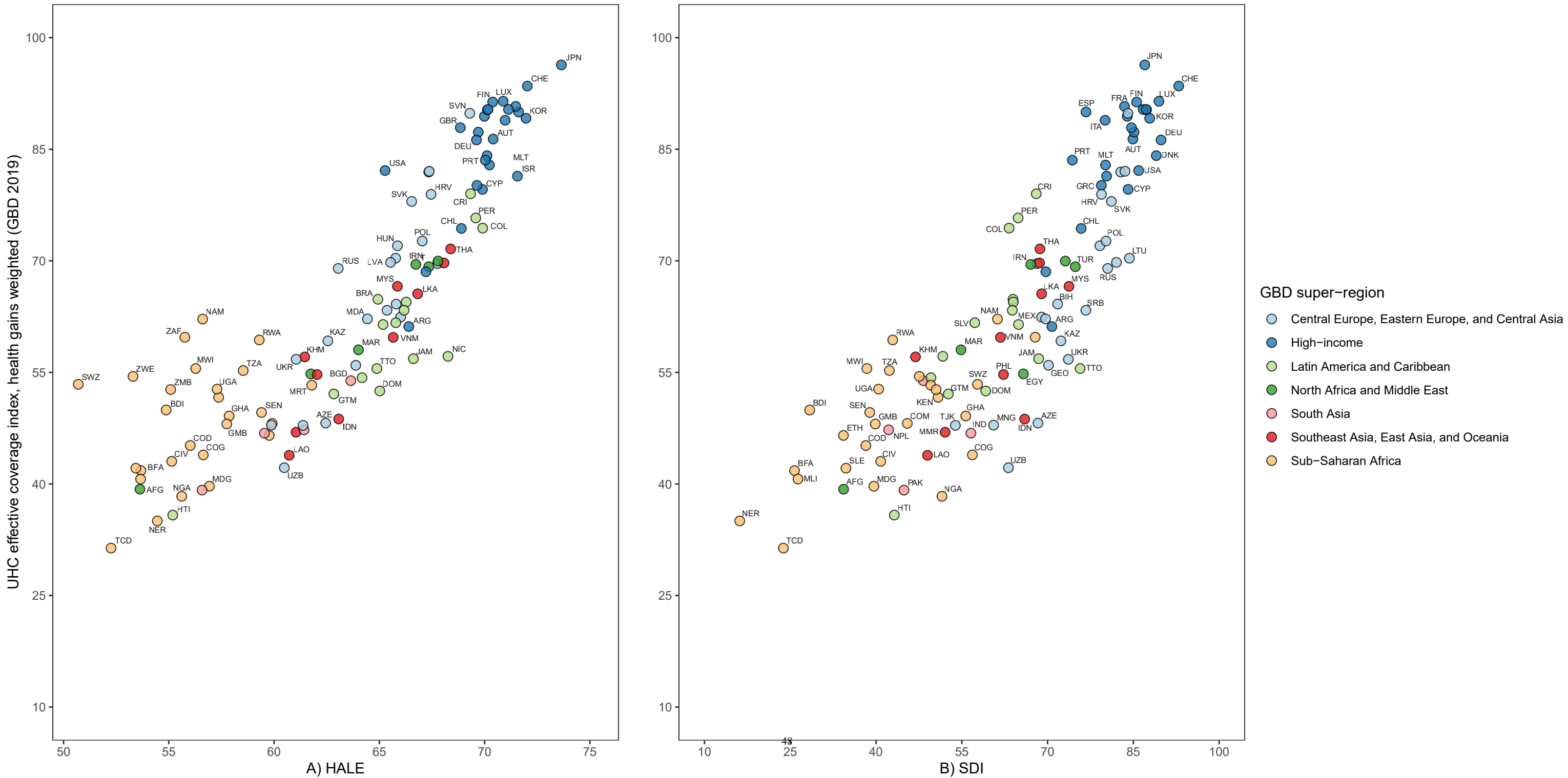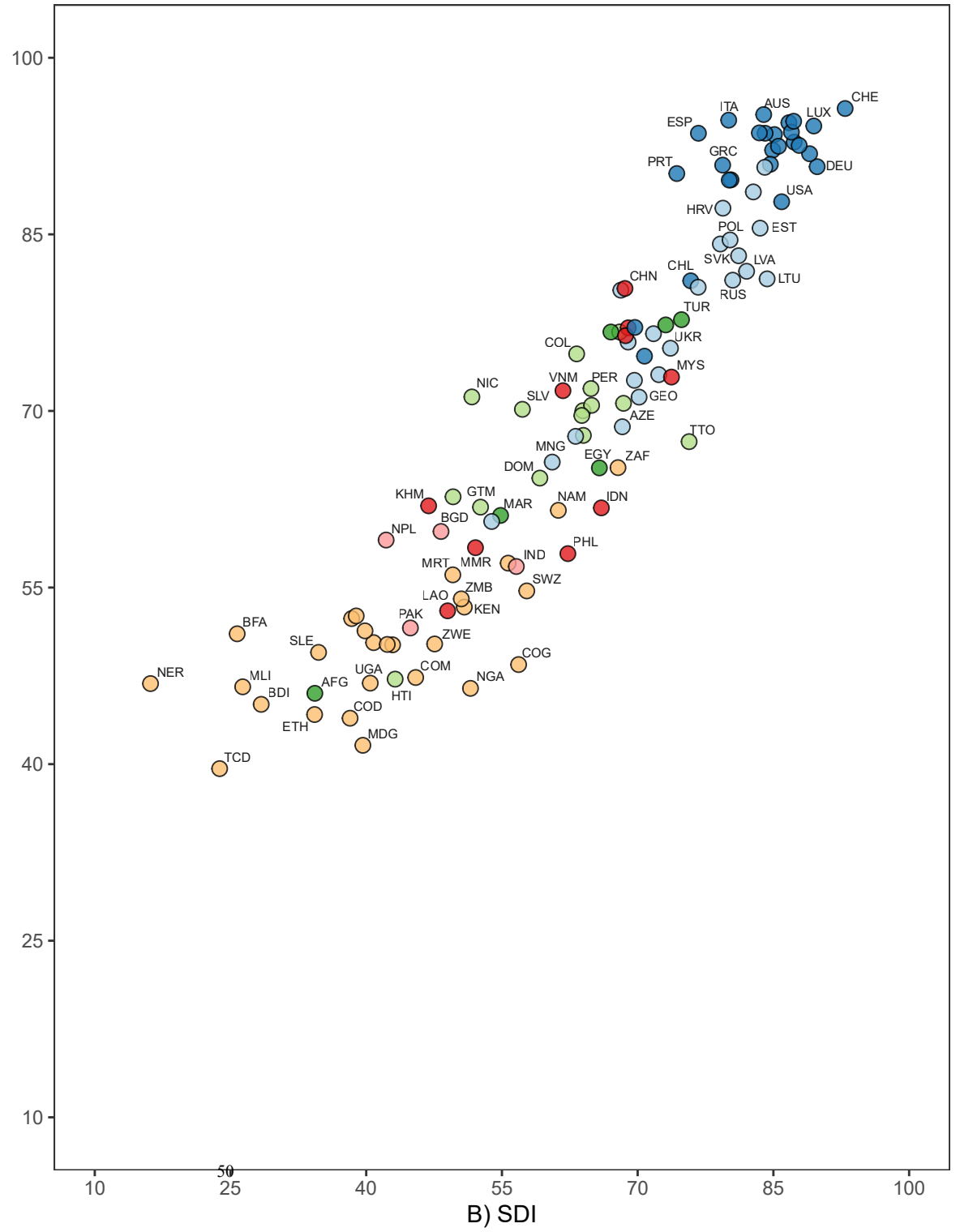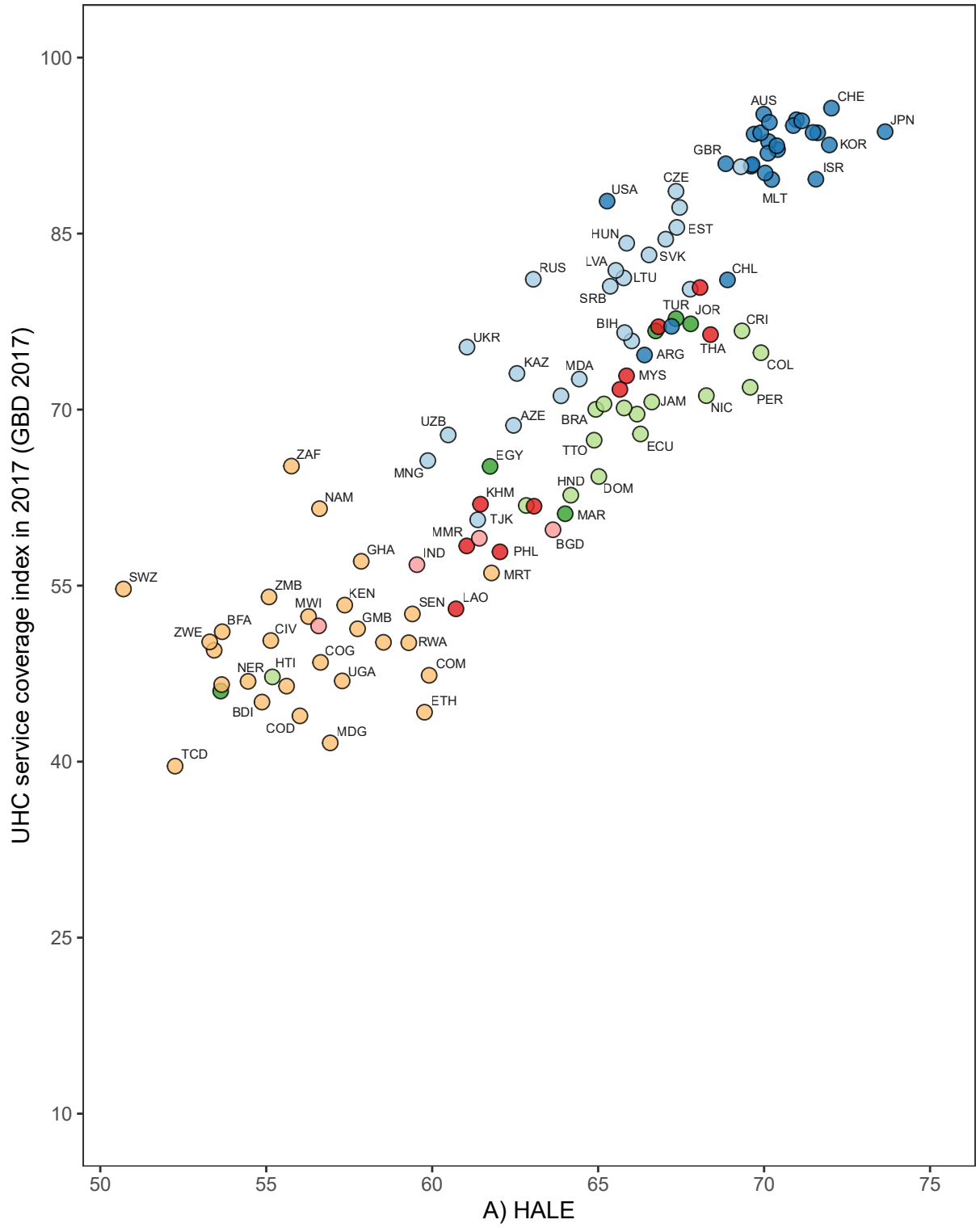
Figure 3.2. Comparing the the UHC effective coverage index in 2019 (unweighted average) to HALE (A) and SDI (B). Locations are colour-coded by GBD super-region and abbreviated by ISO3 code. UHC=universal health coverage. GBD=Global Burden of Disease. SDI=Socio-demographic index. HALE=healthy life expectancy.
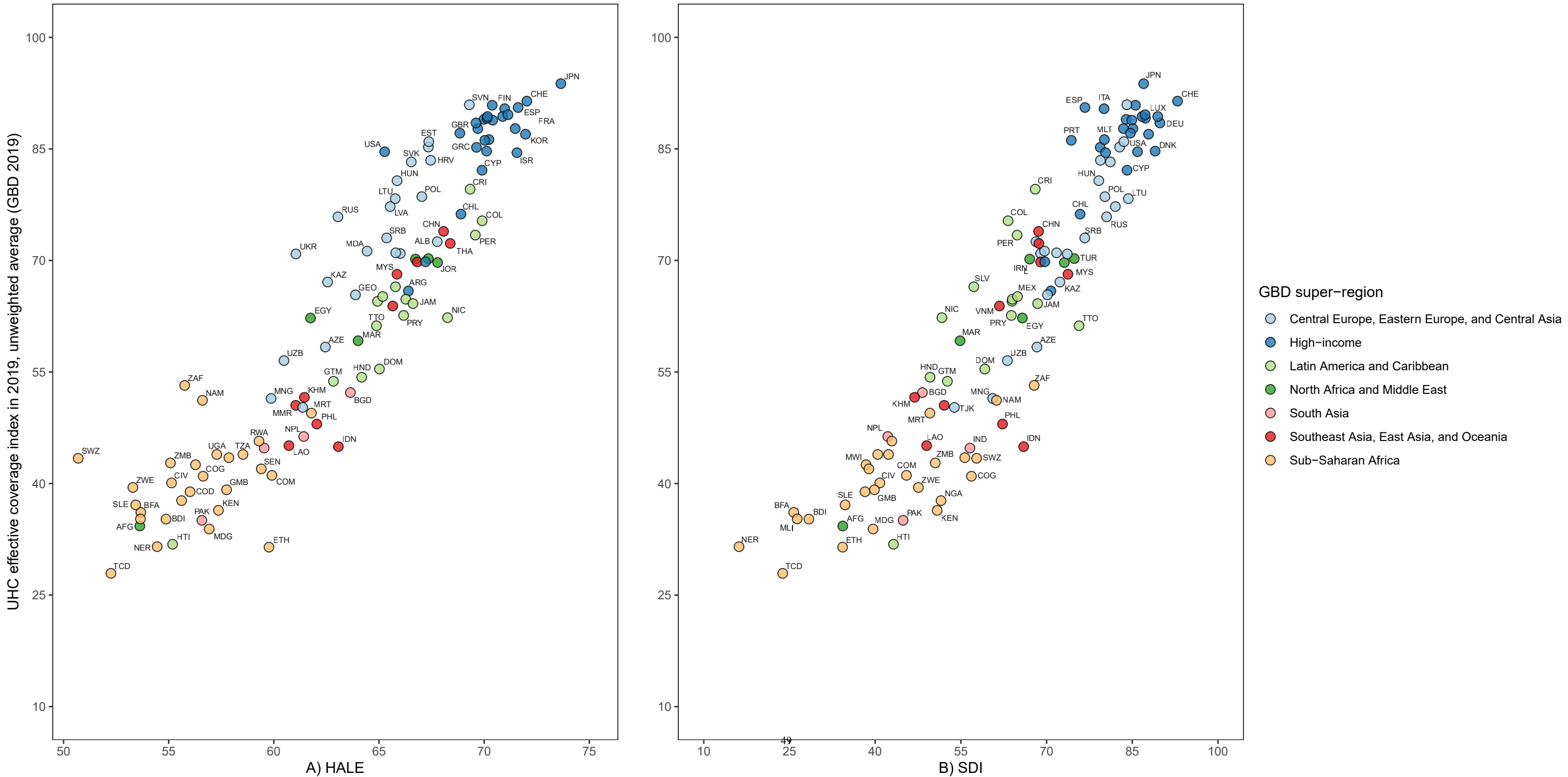
Figure 3.3. Comparing the GBD 2017 UHC service coverage index in 2017 to HALE (A) and SDI (B). Locations are colour-coded by GBD super-region and abbreviated by ISO3 code. UHC=universal health coverage. GBD=Global Burden of Disease. SDI=Socio-demographic index. HALE=healthy life expectancy

Figure 3.4. Comparing the WHO UHC SCI in 2017 to HALE (A) and SDI (B). Locations are colour-coded by GBD super-region and abbreviated by ISO3 code. UHC=universal health coverage. SCI=service coveage index. GBD=Global Burden of Disease. SDI=Socio-demographic index. HALE=healthy life expectancy.

Figure 3.5 Comparing the World Bank SC index (most recent year) to HALE (A) and SDI (B). Locations are colour-coded by GBD super-region and abbreviated by ISO3 code. UHC=universal health coverage. SCI=service coveage. GBD=Global Burden of Disease. SDI=Socio-demographic index. HALE=healthy life expectancy.
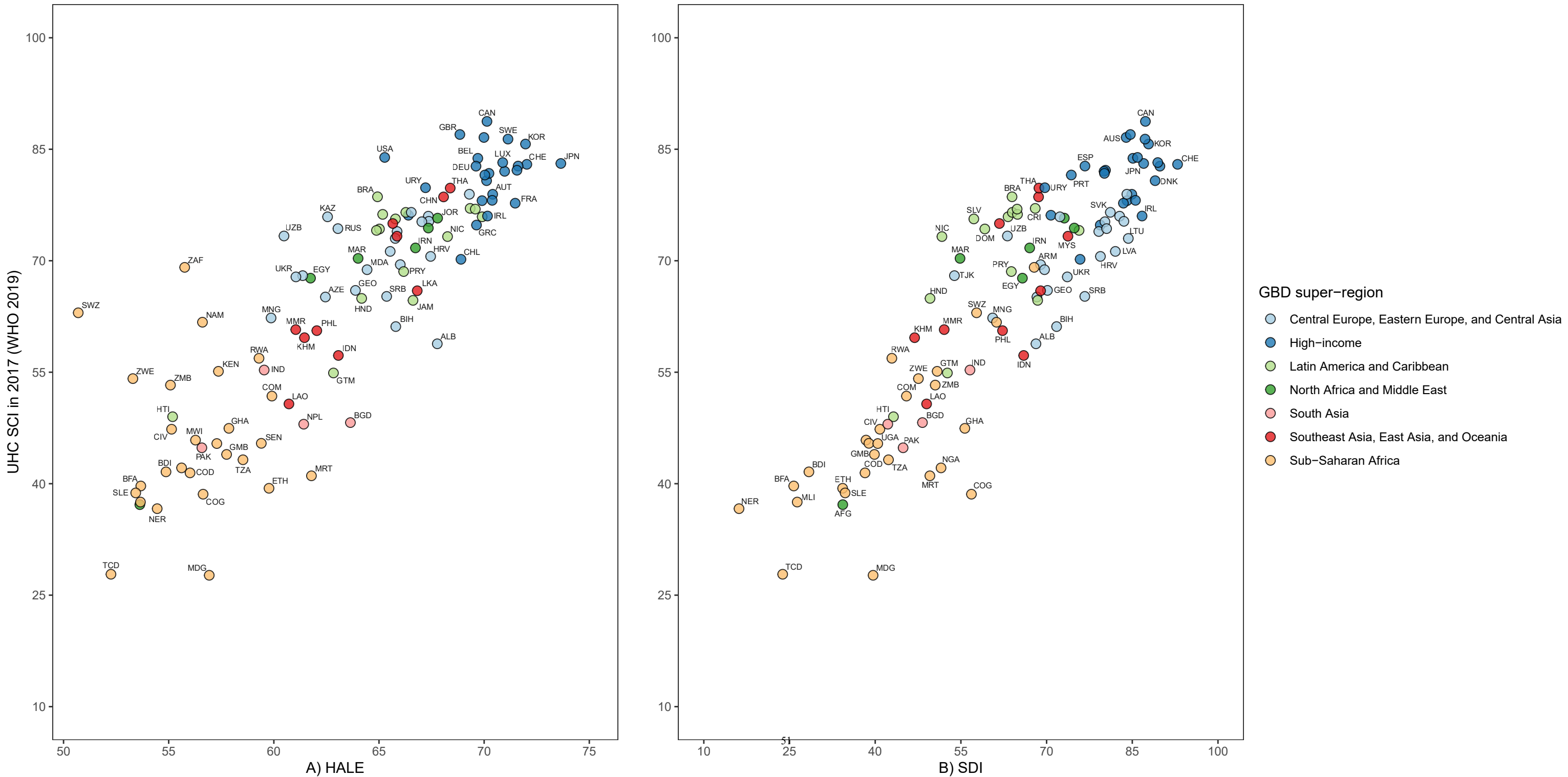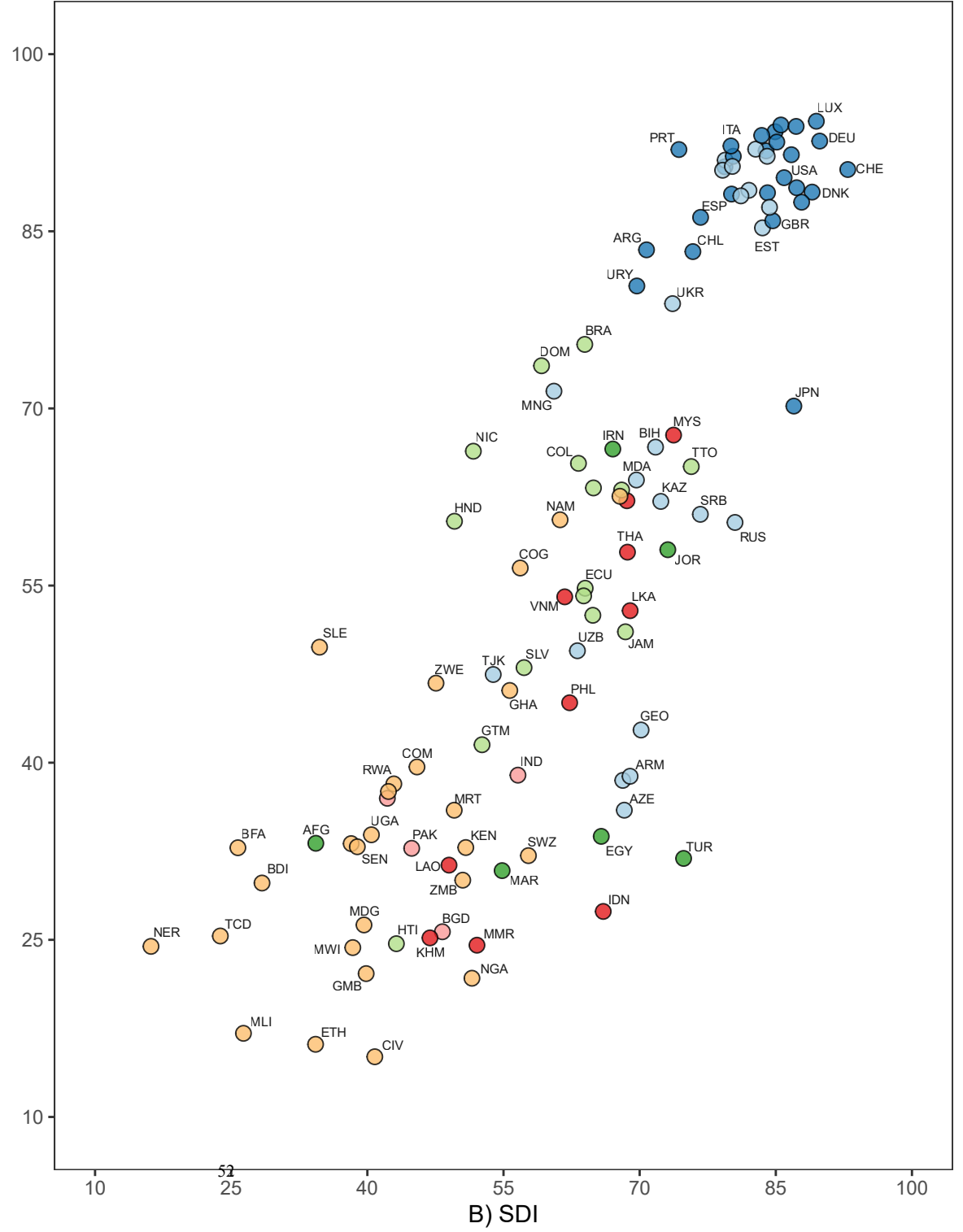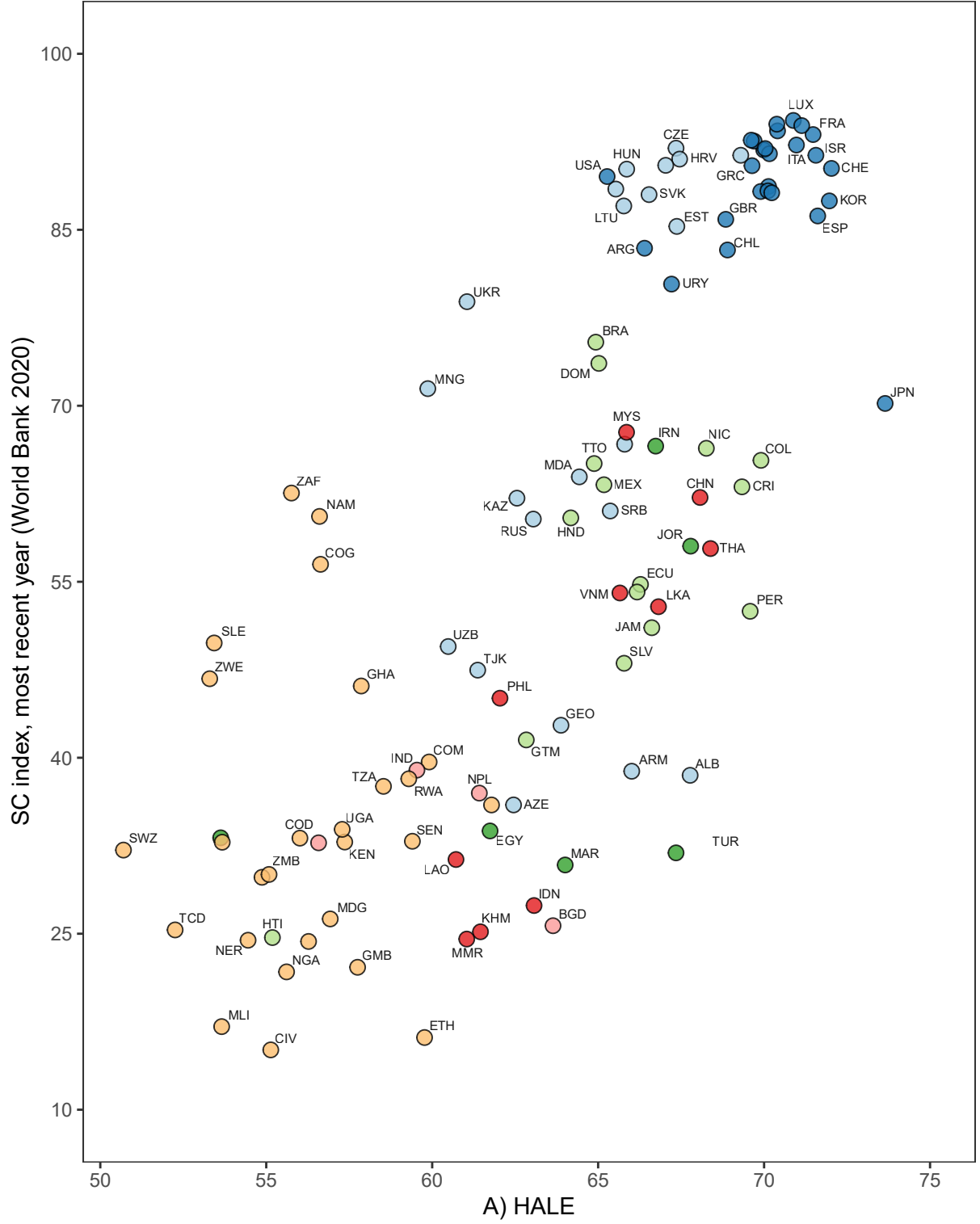
Part 4. Frontier Analysis.

Section 1. Overview

In our frontier analysis, we measured the impact of three types of health expenditure (pooled health spending, domestic pooled health spending, and total health expenditure) on the UHC Effective Coverage Index. In this analysis, pooled health spending is equal to total health expenditure minus out of pocket expenditure and domestic pooled health spending is equal to pooled health spending minus development assistance for health. Based on a priori knowledge, we expected that frontiers would monotonically increase and would exhibit diminishing returns. More explicitly, specifying a monotonically increasing function means that an increase in health expenditure will not decrease the maximum potential UHC effective coverage achievement. Additionally, the presumption of diminishing returns specifies that the contribution of an additional dollar of health expenditure per capita is more significant where spending levels are lower in the frontier. We incorporated both as constraints in the model specification of the frontiers. SFM analyses were run using third degree polynomial splines with six knots and the following constraints: linear tail, monotonically increasing curve, and concave curve. These constraints ensured that where data were sparse (for example, at very high levels of health expenditure), stochastic variation did not drive the flexible frontier toward two unrealistic trends. Firstly, these constraints avoid the incorrect insinuation that at certain level of health expenditure, additional health spending would be detrimental to UHC effective coverage attainment. Secondly, the constraints prevent extrapolation beyond observed levels of UHC effective coverage attainment to ensure scores cannot exceed 100. Given our use of modelled inputs, we did not trim any observations from the frontiers that were constructed. Each of the production frontiers provides an estimate of the theoretical maximum UHC effective coverage attainment under the assumption countries or territories are translating health spending into UHC at an optimal level of efficiency. By comparing observed UHC effective coverage performance to the frontier, our analysis identifies the productive inefficiencies in UHC effective coverage given a location's existing level of health spending. For example, a country with a relatively small pooled health spending may have a UHC effective coverage performance close to the theoretical maximum; therefore, the country has a high efficiency score. Conversely, a country with a relatively larger pooled health spending and higher UHC effective coverage score could have a lower efficiency score if they are not as close to the theoretical maximum. While the frontier is produced relative to different types of health expenditure, the productive inefficiency estimates implicitly entail location-specific capacities related to health system components and contexts beyond levels of health expenditure, as governance framework, human resources for health workforce distribution, transportation infrastructure, and social and gender norms. For more technical details, please see following technical supplement.

Section 2. Stochastic frontier meta-analysis technical supplement

Stochastic frontier analysis (SFA) [1] is a stochastic analysis of the frontier production function, which expresses the maximum amount of output obtainable from a linear combination of variables of interest. The SFA model we start with is given by

$$y_i = \langle \boldsymbol{x}_i, \boldsymbol{\beta} \rangle - v_i, \tag{1}$$

where y_i are observations, $\langle \boldsymbol{x}_i, \boldsymbol{\beta} \rangle$ is the linear model (linear combination of variables in $\boldsymbol{x}_i$ with weights $\boldsymbol{\beta}$), while v_i is the deviation from the *maximum output*, and so is modeled as a *non-negative* random effect. In the context of Universal Health Coverage (UHC), the observations y_i are measures of UHC, and the model $\langle \boldsymbol{x}_i, \boldsymbol{\beta} \rangle$ is a spline that relates health spending to UHC. The spline model is explained in detail in Section 2.3.

We develop a meta-analytic extension of SFA, which we call Stochastic Frontier Meta-analysis (SFM). Every observation y_i is subject to random error (computed from aggregated data). We consider the modified model

$$\boldsymbol{y} = \boldsymbol{X}\boldsymbol{\beta}^* - \boldsymbol{v} + \boldsymbol{\epsilon}, \tag{2}$$

with each entry v_i of $\boldsymbol{v}$ a half-normal non-negative random effect with unknown variance η, while each entry ϵ_i of $\boldsymbol{\epsilon}$ is Gaussian $\mathcal{N}(0, \sigma_i^2)$, and represents the reported study-specific error sources with known variances σ_i^2. In order to carry out the UHC analysis we introduce three innovations.

- We formulate the explicit likelihood problem for the SFM model, assuming a half-normal model for the non-negative random effects v_i.

- Outliers are a big problem for SFA [1]. We apply the trimmed robust approach [2] in order to automatically identify and remove outliers from each dataset.

- We allow priors and constraints for the SFM model. In particular this lets us incorporate shape constraints on the spline, similar to what was proposed by [8].

The resulting approach lets us model inherently nonlinear relationships through the linear model (2) using splines, remove outliers, and incorporate reported errors across geographic regions. Each of the pieces listed above is now described in detail.

1. SFM: modeling non-negative random effects.

In this section we derive all likelihood formulations for the Stochastic Frontier Meta-analysis (SFM) approach. We use the half-normal model for the random effects v_i:

$$f(v_i|\eta) = \begin{cases} \frac{\sqrt{2}}{\sqrt{\pi\eta}} \exp\left(-\frac{v_i^2}{2\eta}\right) & v_i \geq 0 \\ 0 & v_i < 0. \end{cases}$$

The goal is to estimate β^* and η^* from observations. The mixed effects framework provides a natural statistical model which can be used for this inference. The joint distribution of fixed and random effects is then given by

$$p(\boldsymbol{\beta}, \eta, \boldsymbol{v}|\boldsymbol{y}) = p(\boldsymbol{\beta}, \eta, |\boldsymbol{v}, \boldsymbol{y})p(\boldsymbol{v}|\boldsymbol{y})$$

$$\propto \prod_{i=1}^m \frac{1}{\sqrt{\sigma_i^2\eta}} \exp\left(-\frac{(y_i - \langle \boldsymbol{x}_i, \boldsymbol{\beta}\rangle + v_i)^2}{2\sigma_i^2}\right) \exp\left(-\frac{v_i^2}{2\eta}\right) \mathbb{1}_{\mathbb{R}_+}(v_i) \tag{3}$$

Integrating out the random effects, and taking the negative log of the resulting distribution, we arrive at equivalent maximum likelihood formulation that does not depend on the random effects $\boldsymbol{v}$, but only depends on β and η. Define $\widetilde{\Phi}$ to be the complementary error function

$$\widetilde{\Phi}(z) = 1 - \frac{2}{\sqrt{\pi}} \int_0^z \exp(-t^2)dt.$$

Then we have the following closed form likelihood.

$$\mathcal{M}(\boldsymbol{\beta}, \eta|\boldsymbol{y}) = -\ln\left(\int_{\mathbb{R}_+^m} p(\boldsymbol{\beta}, \eta, \boldsymbol{v}|\boldsymbol{y})\, d\boldsymbol{v}\right)$$

$$= \sum_{i=1}^m \frac{(y_i - \langle \boldsymbol{x}_i, \boldsymbol{\beta}\rangle)^2}{2(\eta + \sigma_i^2)} + \frac{1}{2}\ln\left(\eta + \sigma_i^2\right) - \ln\left(\widetilde{\Phi}\left(\frac{\sqrt{\eta}(y_i - \langle \boldsymbol{x}_i, \boldsymbol{\beta}\rangle)}{\sqrt{2(\eta + \sigma_i^2)(\sigma_i^2)}}\right)\right) \tag{4}$$

The SFM approach optimizes these likelihoods to estimate $(\boldsymbol{\beta}, \eta)$.

2. Priors, Constraints, and Splines.

In this section we describe how to set up Bayesian priors, constraints for parameters of interest, and spline models for nonlinear relationships in the SFM setup.

2.1. Priors

The likelihood $\mathcal{M}$ can be updated using prior information. Imposing priors is equivalent to adding penalties to the likelihood function. For the SFM analysis, the only priors we use are those related to the final section of the frontier.

Given a Gaussian prior on $\beta \sim N(\overline{\beta})$, we find the *a posteriori* estimate by solving the problem

$$\min_{\beta, \eta} \mathcal{M}(\beta, \eta) + \frac{1}{2}(\beta - \overline{\beta})^T \Sigma_\beta^{-1}(\beta - \overline{\beta}). \tag{5}$$

2.2. Constraints

We allow box constraints and general linear inequality constraints on (β, η). Taking (5) as a running example, we can impose constraints of the form

$$\begin{aligned}
\min_{\beta, \eta} \quad & \mathcal{M}(\beta, \eta) + \frac{1}{2}(\beta - \overline{\beta})^T \Sigma_\beta^{-1}(\beta - \overline{\beta}) + \frac{1}{2}(\eta - \overline{\eta})^T \Sigma_\eta^{-1}(\eta - \overline{\eta}) \\
\text{such that} \quad & l_f \leq \begin{bmatrix} \beta \\ \eta \end{bmatrix} \leq u_f, \quad C \begin{bmatrix} \beta \\ \eta \end{bmatrix} \leq c,
\end{aligned} \tag{6}$$

where (l_f, u_f) are lower and upper bounds on the variables, while C is any matrix. This functionality can be used to impose shape constraints on spline models, including increasing/decreasing, convex/concave, and combinations of these designs.

2.3. Splines

In this section we discuss spline models for dose-response relationships. For general background on splines and spline regression see [5] and [6].

B-splines and bases. A spline basis is a set of piecewise polynomial functions with designated degree and domain. If we denote polynomial order by p, and the number of knots by k, we need $p + k$ basis elements s_j^p, which can be generated recursively as illustrated in Figure 1.

Given such a basis, we can represent any dose-response relationship as the linear combination of the spline basis elements, with coefficients $\beta \in \mathbb{R}^{p+k}$:

$$f(t) = \sum_{j=1}^{p+k} \beta_j^p s_j^p(t). \tag{7}$$

An explicit representation of (7) is obtained by building a design matrix $\mathbf{X}$. Given a set of t values at which we have data, the jth column of $\mathbf{X}$ is given by the expression

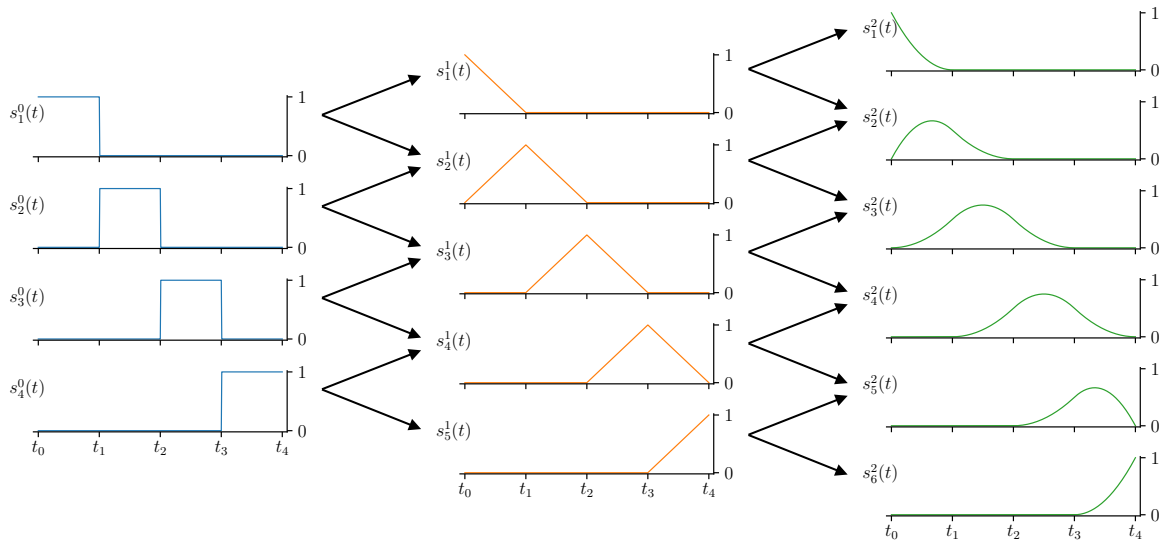$$\mathbf{X}_{\cdot, j} = \begin{bmatrix} s_j^p(t_0) \\ \vdots \\ s_j^p(t_k) \end{bmatrix}.$$

Figure 1. Recursive generation of bspline basis elements (orders 0, 1, 2).
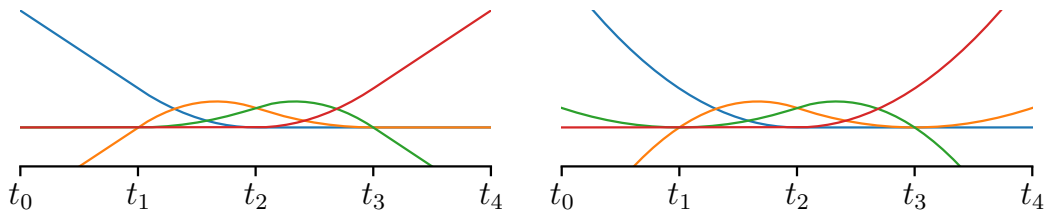
Figure 2. Spline extrapolation. Left: linear extrapolation. Right: nonlinear extrapolation.

The model for direct observations data coming from the spline (7) can now be written compactly as

$$\boldsymbol{y} = \mathbf{X}\boldsymbol{\beta} + \boldsymbol{v} + \boldsymbol{\epsilon}_i,$$

and has the same form as (1).

Enforcing linear tails.   For the frontier analysis, we need to ensure that the last segment of the spline does not go above a theoretical limit, typically set at 1. To do this, we allow an option to make the last segment linear. The prior capabilities can then be used to set a prior for the slope of this segment to be 0 (i.e. flat). The estimated spline is then a best fit to the data, subject to this specification.

In general, using linear head and/or tail pieces to extrapolate outside the original domain or interpolate in the data sparse region is far more stable that using higher order polynomials, see Figure 2. The figure shows symmetric linear tail modifications, but for the analyses in the paper we only impose a right linear tail shape constraint.

Shape constraints.   We can use constraints to enforce monotonicity, convexity, and concavity. Monotonicity across the domain of interest follows from monotonicity of the spline coefficients. This relationship is derived for particular basis constructions by [5], and has been used in the literature to enforce shape constraints [8]. Current approaches work around the natural inequality constraints by using additional 'exponentiated' variables. Instead we impose these constraints directly as described below.

Focusing just on
, the relationship

$_1 \leq$
$_2$ can be written as

$_1 -$
$_2 \leq 0$. Stacking these inequality

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constraints for each pair (α_i, α_{i+1}) we can write all constraints simultaneously as

$$
\underbrace{\begin{bmatrix} 1 & -1 & 0 & \dots & 0 \\ 0 & 1 & -1 & \dots & 0 \\ \ddots & \ddots & \ddots & \ddots & \vdots \\ 0 & \dots & \dots & 1 & -1 \end{bmatrix}}_{C} \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \vdots \\ \alpha_n \end{bmatrix} \leq \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} .
$$

These constraints are directly imposed through the IPOPT interface, along with any lower- and upper-limit constraints on α.

Convexity and Concavity. For any $\mathcal{C}^2$ (twice continuously differentiable) function $f : \mathbb{R} \to \mathbb{R}$, convexity and concavity are captured by the signs of the second derivative. Specifically, f is convex if $f''(t) \geq 0$ is everywhere, an concave if $f''(t) \leq 0$ everywhere. We impose linear inequality constraints on the expressions for $f''(t)$ over each interval. We can therefore easily pick any of the eight shape combinations given in [8, Table 1], as well as imposing any other constraints on α (including bounds).

3. Robust Extension via Trimming

Trimming estimators is a general methodology for robust estimation [10, 2]. For convenience, define

$$
\boldsymbol{\theta} = \begin{bmatrix} \boldsymbol{\beta} \\ \eta \end{bmatrix} .
$$

Given any likelihood problem of form

$$
\min_{\boldsymbol{\theta}} \sum_{i=1}^{m} f_i(\boldsymbol{\theta}) + R(\boldsymbol{\theta}),
$$

with f_i is the contribution from the ith datapoint, while $R(\boldsymbol{\theta})$ collects all terms that do not depend on the data, including priors in Section 2.1 and constraints in Section 2.2 [1].

Then the trimmed estimator is formulated as

$$
\min_{\boldsymbol{\theta}, \boldsymbol{w}} \sum_{i=1}^{m} w_i f_i(\boldsymbol{\theta}) + R(\boldsymbol{\theta}), \quad 0 \leq w_i \leq 1, \quad \mathbf{1}^T \boldsymbol{w} = h \tag{8}
$$

where $h \leq m$ is the estimate of inlier datapoints. The set

$$
\Delta_h := \left\{ \boldsymbol{w} : 0 \leq w_i \leq 1, \mathbf{1}^T \boldsymbol{w} = h \right\}
$$

is known as the *capped simplex*, since it is the intersection of the simplex with the unit box [2]. The estimator (8) is compactly written as

$$
\min_{\boldsymbol{\theta}, \boldsymbol{w} \in \Delta_h} \sum_{i=1}^{m} w_i f_i(\boldsymbol{\theta}) + R(\boldsymbol{\theta}). \tag{9}
$$

4. Optimization

The SFM model is fit using an algorithm based on variable projection [4, 7, 3], which allows us to leverage a third-party solver, IPOPT [9] to optimize over $\boldsymbol{\theta}$, significantly reducing complexity. Consider

---

[1] In particular, since R includes constraints, it is infinite-valued off of the feasible region.

the joint likelihood (9) and define the value function $v(\boldsymbol{w})$ and values $(\boldsymbol{\theta}(\boldsymbol{w}), \boldsymbol{\gamma}(\boldsymbol{w}))$ by

$$
v(\boldsymbol{w}) = \min_{\boldsymbol{\theta}} \sum_{i=1}^{m} w_i f_i(\boldsymbol{\theta}) + R(\boldsymbol{\theta})
$$

$$
\boldsymbol{\theta}(\boldsymbol{w}) = \arg\min_{\boldsymbol{\theta}} \sum_{i=1}^{m} w_i f_i(\boldsymbol{\theta}) + R(\boldsymbol{\theta}).
$$

(10)

We use IPOPT to solve this problem for each $\boldsymbol{w}$, reducing the problem to

$$
\min_{\boldsymbol{w} \in \Delta_h} v(\boldsymbol{w}).
$$

where $v(\boldsymbol{w})$ is differentiable with derivative given by

$$
\nabla v(\boldsymbol{w}) = \begin{bmatrix} f_1(\boldsymbol{\theta}) \\ \vdots \\ f_m(\boldsymbol{\theta}) \end{bmatrix}
$$

(11)

The top level algorithm is simply a projected gradient method

$$
\boldsymbol{w}^+ = \mathsf{proj}_{\Delta_h}(\boldsymbol{w} - \alpha \nabla v(\boldsymbol{w}))
$$

for an appropriately chosen stepsize. Each evaluation of ∇v requires a full minimization step over the constrained weighted likelihood with respect to $\boldsymbol{\theta}$ using IPOPT, see (11) and (10). The capped simplex Δ_h is a closed convex set with a simple projection [2]; a simple proximal gradient with line search converges in this case.

5. Estimating Random Effects (Inefficiencies).

Once fixed effects $\boldsymbol{\theta}$ have been estimated, we want to obtain estimates of inefficiency from the joint likelihood (3). We optimize

$$
\min_{v_i \geq 0} \frac{(y_i - \langle \boldsymbol{x}_i, \boldsymbol{\beta} \rangle + v_i)^2}{2\sigma_i^2} + \frac{v_i^2}{2\eta}
$$

(12)

We get the closed form solution

$$
\hat{v}_i = \max\left(0, \frac{\frac{1}{\sigma_i^2}(\boldsymbol{x}_i^T \boldsymbol{\beta} - y_i)}{\frac{1}{\sigma_i^2} + \frac{1}{\eta}}\right) = \max\left(0, \frac{\eta(\boldsymbol{x}_i^T \boldsymbol{\beta} - y_i)}{\sigma_i^2 + \eta}\right).
$$

(13)

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Part 5. Projections for UHC effective coverage

Section 1. Overview
UHC has emerged as both a global and national health priority, with achieving UHC viewed as a critical path to improved health outcomes and greater equity in health across all populations. This section focuses on the method used for forecasting the UHC effective coverage index from 2020 through 2030 using our health financing variables, particularly the sum of government health expenditure (GHE), lead-distributed development assistance for health (DAH), out-of-pocket (OOP) and prepaid private spending (PPP) per capita, hereby referred as "total health spending per capita."

Section 2. Forecasting steps
We forecasted the UHC effective coverage index from 2020 through 2030 in the following steps:

1. Forecasts of the total health spending were developed by adding the forecasts of GHE, lead-distributed DAH, OOP, and PPP per capita, modelled previously using ensembles.[1]

2. A meta-stochastic frontier model was fit for 1000 draws, using UHC index as the dependent variable and total health spending per capita estimates as the independent variable, and including all countries and years that health spending data were available.

3. Country- and year-specific inefficiencies were then extracted from the model, and separately forecasted to 2030 in log-transformed space for each country using a non-increasing exponentially weighted ordinary linear regression (using a linear time trend as a covariate), where recent time periods were weighted higher than the further past.

4. Using the draws of reference, better, and worse scenarios of total health spending per capita along with reference scenario forecasts of the efficiency term from (iii), we created reference, better, and worse projections of the UHC effective coverage index from 2020 through 2030.

Section 3. Meta-stochastic frontier analysis
We used a meta-stochastic frontier model[2] to forecast the level of UHC effective coverage index achievable by all countries between 2020 through 2030. This approach used for forecasting, as summarized below, draws from the methods detailed in Part 4 of the methods appendix.

In brief, this model allows for specification of the variance of the datapoints when fitting the frontier, priors and constraints on all parameters, polynomial splines, and outlier trimming. Our SFA model, with a production function specification, was such:

$$
\begin{aligned}
UHC_{i,t} &= \beta\big(X_{i,t}\big) - v_{i,t} + \epsilon_{i,t} \\
v_{i,t} &\sim N^+(0, \sigma_v^2) \\
\epsilon_{i,t} &\sim N(0, \sigma_\epsilon^2)
\end{aligned}
$$

where our observed outcome was the UHC effective cvoreage index, with our single covariate X being the country-year specific total health spending per capita, $\epsilon_{i,t}$ is the noise component and $v_{i,t}$ is the estimated technical efficiency that a country would need to achive the optimal, frontier goal. The prior distribution of technical efficiency is a half-normal distribution, describing an unbounded distribution between zero and very high efficiency.

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Part 6. Online tools and glossary of terms

Online tools

GBD 2019 data sources and additional results are presented in a series of tools and dynamic visualisations, which will be updated and available at the time of publication at http://ghdx.healthdata.org/gbd-2019.

Analytic source code for estimates will be updated and available at time of publication at http://ghdx.healthdata.org/gbd-2019 under GBD 2019 code for the paper "Measuring universal health coverage based on an index of effective coverage of health services in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019."

List of abbreviations

ART	antiretroviral therapy
ANC1	antenatal care, at least 1 visit
ANC4	antenatal care, at least 4 visits
BCG	Bacillus Calmette–Guérin vaccine
BP	blood pressure
CKD	chronic kidney disease
Comm & MCH	communicable diseases and maternal, child, health
COPD	chronic obstructive pulmonary disease
DAH	development assistance for health
DALY	disability-adjusted life-year
DCP3	Disease Control Priorities, third edition
DBP	diastolic blood pressure
DTP	diphtheria-tetanus-pertussis
DTP3	diphtheria-tetanus-pertussis vaccine, 3 doses
EC	effective coverage
ERG	Expert Reference Group
FP	family planning
FPG	fasting plasma glucose
GATHER	Guidelines for Accurate and Transparent Health Estimates Reporting
GBD	Global Burden of Diseases, Injuries, and Risk Factors Study
GPW13	General Programme of Work 13
GHDx	Global Health Data Exchange
GHE	government health expenditure
HALE	healthy life expectancy
HAQ Index	Healthcare Access and Quality Index
HIV/AIDS	human immunodeficiency virus/acquired immunodeficiency syndrome
HPV	human papillomavirus
IHD	ischaemic heart disease
IHR	International Health Regulations
IRS	indoor residual spraying
IAEG-SDGs	Inter-agency Expert Group on SDG Indicators
ITN	insecticide-treated net

LRI	lower respiratory infection
MAP	Malaria Atlas Project
MCV	measles-containing vaccine
MCV1	measles-containing-vaccine, 1 dose
MCV2	measles-containing-vaccine, 2 doses
MDG	Millennium Development Goal
MIRs	mortality-to-incidence ratios
MMR	maternal mortality ratio
MNCH	maternal, neonatal, and child health
MPRs	mortality-to-prevalence ratios
NCDs	non-communicable diseases
ND	deaths attributable to the new population attributable fraction
NMD	non-metabolic deaths
NM PAF	non-metabolic joint population attributable fraction
NPAF	new population attributable fraction
NTD	neglected tropical disease
OOP	out-of-pocket
PAF	population attributable fraction
PAHO	Pan-American Health Organization
PCV	pneumococcal conjugate vaccine
PCV3	pneumococcal conjugate vaccine, 3 doses
Polio3	polio vaccine, 3 doses
RMNCH	reproductive, maternal, neonatal, and child health
PPP	prepaid private spending
RSD	risk-standardised deaths
RSDR	risk-standardised death rate
SBP	systolic blood pressure
SC	service coverage
SCI	service coverage index
SDG	Sustainable Development Goal
SDI	Socio-demographic Index
SFA	stochastic frontier analysis
SFM	stochastic frontier meta-analysis
STEPS	WHO STEPwise approach to surveillance
TB	tuberculosis
UHC	universal health coverage
UHC ECI	universal health coverage effective coverage index
UHC SCI	universal health coverage service coverage index
UI	uncertainty interval
UN	United Nations
WHO	World Health Organization

List of ISO3 codes and location names

AFG   Afghanistan
AGO   Angola
ALB   Albania
AND   Andorra
ARE   United Arab Emirates
ARG   Argentina
ARM   Armenia
ASM   American Samoa
ATG   Antigua and Barbuda
AUS   Australia
AUT   Austria
AZE   Azerbaijan
BDI   Burundi
BEL   Belgium
BEN   Benin
BFA   Burkina Faso
BGD   Bangladesh
BGR   Bulgaria
BHR   Bahrain
BHS   Bahamas
BIH   Bosnia and Herzegovina
BLR   Belarus
BLZ   Belize
BMU   Bermuda
BOL   Bolivia (Plurinational State of)
BRA   Brazil
BRB   Barbados
BRN   Brunei Darussalam
BTN   Bhutan
BWA   Botswana
CAF   Central African Republic
CAN   Canada
CHE   Switzerland
CHL   Chile
CHN   China
CIV   Côte d'Ivoire
CMR   Cameroon
COD   Democratic Republic of the Congo
COG   Congo
COK   Cook Islands
COL   Colombia
COM   Comoros
CPV   Cabo Verde
CRI   Costa Rica
CUB   Cuba
CYP   Cyprus

CZE	Czechia
DEU	Germany
DJI	Djibouti
DMA	Dominica
DNK	Denmark
DOM	Dominican Republic
DZA	Algeria
ECU	Ecuador
EGY	Egypt
ERI	Eritrea
ESP	Spain
EST	Estonia
ETH	Ethiopia
FIN	Finland
FJI	Fiji
FRA	France
FSM	Micronesia (Federated States of)
GAB	Gabon
GBR	United Kingdom
GEO	Georgia
GHA	Ghana
GIN	Guinea
GMB	Gambia
GNB	Guinea-Bissau
GNQ	Equatorial Guinea
GRC	Greece
GRD	Grenada
GRL	Greenland
GTM	Guatemala
GUM	Guam
GUY	Guyana
HND	Honduras
HRV	Croatia
HTI	Haiti
HUN	Hungary
IDN	Indonesia
IND	India
IRL	Ireland
IRN	Iran
IRQ	Iraq
ISL	Iceland
ISR	Israel
ITA	Italy
JAM	Jamaica
JOR	Jordan
JPN	Japan
KAZ	Kazakhstan

KEN	Kenya
KGZ	Kyrgyzstan
KHM	Cambodia
KIR	Kiribati
KNA	Saint Kitts and Nevis
KOR	South Korea
KWT	Kuwait
LAO	Laos
LBN	Lebanon
LBR	Liberia
LBY	Libya
LCA	Saint Lucia
LKA	Sri Lanka
LSO	Lesotho
LTU	Lithuania
LUX	Luxembourg
LVA	Latvia
MAR	Morocco
MCO	Monaco
MDA	Republic of Moldova
MDG	Madagascar
MDV	Maldives
MEX	Mexico
MHL	Marshall Islands
MKD	North Macedonia
MLI	Mali
MLT	Malta
MMR	Myanmar
MNE	Montenegro
MNG	Mongolia
MNP	Northern Mariana Islands
MOZ	Mozambique
MRT	Mauritania
MUS	Mauritius
MWI	Malawi
MYS	Malaysia
NAM	Namibia
NER	Niger
NGA	Nigeria
NIC	Nicaragua
NIU	Niue
NLD	Netherlands
NOR	Norway
NPL	Nepal
NRU	Nauru
NZL	New Zealand
OMN	Oman

PAK	Pakistan
PAN	Panama
PER	Peru
PHL	Philippines
PLW	Palau
PNG	Papua New Guinea
POL	Poland
PRI	Puerto Rico
PRK	North Korea
PRT	Portugal
PRY	Paraguay
PSE	Palestine
QAT	Qatar
ROU	Romania
RUS	Russia
RWA	Rwanda
SAU	Saudi Arabia
SDN	Sudan
SEN	Senegal
SGP	Singapore
SLB	Solomon Islands
SLE	Sierra Leone
SLV	El Salvador
SMR	San Marino
SOM	Somalia
SRB	Serbia
SSD	South Sudan
STP	São Tomé and Príncipe
SUR	Suriname
SVK	Slovakia
SVN	Slovenia
SWE	Sweden
SWZ	Eswatini
SYC	Seychelles
SYR	Syria
TCD	Chad
TGO	Togo
THA	Thailand
TJK	Tajikistan
TKL	Tokelau
TKM	Turkmenistan
TLS	Timor-Leste
TON	Tonga
TTO	Trinidad and Tobago
TUN	Tunisia
TUR	Turkey
TUV	Tuvalu

TWN	Taiwan (province of China)
TZA	Tanzania
UGA	Uganda
UKR	Ukraine
URY	Uruguay
USA	United States of America
UZB	Uzbekistan
VCT	Saint Vincent and the Grenadines
VEN	Venezuela
VIR	Virgin Islands
VNM	Vietnam
VUT	Vanuatu
WSM	Samoa
YEM	Yemen
ZAF	South Africa
ZMB	Zambia
ZWE	Zimbabwe

Part 7. GATHER checklist

GATHER checklist of information that should be included in reports of global health estimates, with description of compliance and location of information.[1]

#	GATHER checklist item	Description of compliance	Reference
Objectives and funding			
1	Define the indicators, populations, and time periods for which estimates were made.	Description of indicators, definitions, relevant time periods, and populations in the paper and appendix.	Provided in the main text and methods appendix.
2	List the funding sources for the work.	Funding sources listed in the paper.	Provided in the main text summary and methods
Data inputs			
For all data inputs from multiple sources that are synthesized as part of the study:			
3	Describe how the data were identified and how the data were accessed.	This analysis uses estimates produced through the broader GBD 2019 study; data-seeking methodologies are described in GBD 2019 publications.[2–4] References to the non-GBD data sources used to estimate intervention effectiveness are provided in the main text. Overarching data inputs used for estimating met need for family planning, ART coverage, and vaccination coverage are found in the GBD 2017 SDG analysis.[5] Updated data inputs and modeling parameters for GBD 2019 will be covered in corresponding papers; further, such information is available upon request.	Methods described in GBD 2019. Topic-specific write-ups for each cause are provided in capstone papers.[2–4] Data sources and the process used to ascribe effectiveness to indicators are provided in the main text and section 3 of the methods appendix.
4	Specify the inclusion and exclusion criteria. Identify all ad-hoc exclusions.	This analysis uses estimates produced through the broader GBD 2019 study; data-seeking methodologies are described in GBD 2019 publications.[2–4] The indicator selection process is described in both the main text and methods appendix.	Primary data for underlying GBD models are decribed in topic-specific write-ups for each cause in the GBD 2019 capstone papers.[2–4] The process used to select and exclude indicators

			is described in the main text and, in more detail, in part 1 of the methods appendix.
5	Provide information on all included data sources and their main characteristics. For each data source used, report reference information or contact name/institution, population represented, data collection method, year(s) of data collection, sex and age range, diagnostic criteria or measurement method, and sample size, as relevant.	An interactive, online data source tool for GBD 2019 that provides metadata for data sources by location and over time.	Online data tools can be accessed here: http://ghdx.healthdata.org/gbd-2019
6	Identify and describe any categories of input data that have potentially important biases (eg, based on characteristics listed in item 5).	This analysis uses estimates produced through the broader GBD 2019 study; data-seeking methodologies are described in GBD 2019 publications.[2–4]	Methodology described in GBD 2019. Topic-specific write-ups, which may include discussions of bias and bias-correction, for each cause are provided in capstone papers.[2–4]
For data inputs that contribute to the analysis but were not synthesized as part of the study:			
7	Describe and give sources for any other data inputs.	This analysis uses estimates produced through the broader GBD 2019 study; data-seeking methodologies are described in GBD 2019 publications.[2–4]	Primary data for underlying GBD models are decribed in topic-specific write-ups for each cause in the GBD 2019 capstone papers.[2–4]
For all data inputs:			
8	Provide all data inputs in a file format from which data can be efficiently extracted (eg, a spreadsheet as opposed to a PDF), including all relevant meta-data listed in item 5. For any data inputs that cannot be shared due to ethical or legal reasons, such as third-party ownership, provide a contact name or the name of the institution that retains the right to the data.	Downloads of input data are available through online tools, including data visualisation tools and data query tools.	Online data tools can be accessed here: http://ghdx.healthdata.org/gbd-2019
Data analysis			

9	Provide a conceptual overview of the data analysis method. A diagram may be helpful.	Overview of analysis provided in the manuscript and appendix	Described in the methods section of the main text and part 2 of the methods appendix.
10	Provide a detailed description of all steps of the analysis, including mathematical formulae. This description should cover, as relevant, data cleaning, data pre-processing, data adjustments and weighting of data sources, and mathematical or statistical model(s).	UHC methodology is provided in the methodological write-ups. Methodology for underlying GBD models are described in the GBD 2019 capstone publications.[2–4] Overarching modeling approaches used for estimating met need for family planning, ART coverage, and vaccination coverage are found in the GBD 2017 SDG analysis.[5] Updated data inputs and modeling parameters for GBD 2019 will be covered in corresponding papers; further, such information is available upon request	UHC methodology described in the methods section of the main text and part 2 of the methods appendix. GBD methodology described in topic specific write-ups.[2–4]
11	Describe how candidate models were evaluated and how the final model(s) were selected.	UHC methodology is provided in the methodological write-ups. Methodology for underlying GBD models are described in the GBD 2019 capstone publications.[2–4]	UHC methodology described in the methods section of the main text and part 2, 4, and 5 of the methods appendix. GBD methodology described in topic-specific write-ups.[2–4]
12	Provide the results of an evaluation of model performance, if done, as well as the results of any relevant sensitivity analysis.	We evaluated the UHC effective coverage index using three separate validation criteria and provided results for multiple sensitivity analyses in the main text and appendix.	Validation criteria results are provided in main text table 2 and part 3 of the methods appendix. The results of sensitivity analyses are mentioned briefly in the main text and covered in detail in part 2, section 5 of the methods appendix.
13	Describe methods for calculating uncertainty of the estimates. State which sources of uncertainty were, and were not, accounted for in the uncertainty analysis.	Inputs for this analysis draw from uncertainty estimates produced in GBD 2019 study.[2–4]	Detail on where uncertainty was and was not propagated is included in section 6, part 2 and parts 4 and 5

			of the methods appendix.
14	State how analytic or statistical source code used to generate estimates can be accessed.	Access statement provided.	Links to code can be found here: http://ghdx.healthdata.org/gbd-2019.
Results and discussion			
15	Provide published estimates in a file format from which data can be efficiently extracted.	GBD 2019 results are available through online data visualisation tools, the GHDx, and the online data query tool.	Online data tools are findable at this link: http://ghdx.healthdata.org/gbd-2019
16	Report a quantitative measure of the uncertainty of the estimates (eg, uncertainty intervals).	Uncertainty intervals are provided with results.	Provided in the main text results and supplementary results.
17	Interpret results in light of existing evidence. If updating a previous set of estimates, describe the reasons for changes in estimates.	Discussion provided in narrative of the main paper.	Provided in the summary, research in context, and throughout the main text.
18	Discuss limitations of the estimates. Include a discussion of any modelling assumptions or data limitations that affect interpretation of the estimates.	Discussion of limitations provided in narrative of the main paper.	Provided in limitations section of the main text and in the methods appendix.

References

1 Stevens GA, Alkema L, Black RE, *et al.* Guidelines for Accurate and Transparent Health Estimates Reporting: the GATHER statement. *The Lancet* 2016; **388**: e19–23.

2 GBD 2019 Demographics Collaborators. Global age-sex-specific fertility, mortality, healthy life expectancy (HALE), and population estimates in 204 countries and territories, 1950–2019: a comprehensive demographic analysis for the Global Burden of Disease Study 2019. *The Lancet* In press.

3 GBD 2019 Diseases and Injuries Collaborators. Global burden of 369 diseases and injuries in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. *The Lancet* In press.

4 GBD 2019 Risk Factors Collaborators. Global burden of 87 risk factors in 204 countries and territories, 1990–2019; a systematic analysis for the Global Burden of Disease Study 2019. *The Lancet* In press.

5 Lozano R, Fullman N, Abate D, *et al.* Measuring progress from 1990 to 2017 and projecting attainment to 2030 of the health-related Sustainable Development Goals for 195 countries and territories: a systematic analysis for the Global Burden of Disease Study 2017. *The Lancet* 2018; **392**: 2091–138.

6 Zheng P, Aravkin AY, Barber R, Sorensen RJD, Murray CJL. Trimmed Constrained Mixed Effects Models: Formulations and Algorithms. 2019; published online Sept 24. https://arxiv.org/abs/1909.10700v1