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Estimating the effect of measles vaccination on child growth using 191 DHS from 65 low- and middle-income countries

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A B S T R A C T

Background: Childhood vaccinations reduce morbidity and mortality and are highly cost-effective. They may also protect children from malnutrition and lead to improved child growth. Stunting, wasting and underweight are targets used to monitor progress towards the achievement of the sustainable development goals (SDGs).
Methods: We use data from Demographic and Health Surveys (DHS) covering the period from 1990 to 2017 to estimate the effect of measles vaccination at 12 months of age on stunting, wasting, and underweight. For causal estimation, we use household- and mother-fixed effects, which allows us to compare outcomes across siblings while controlling for all observed and unobserved confounders that are shared by the siblings, such as household social characteristics and home location. In addition, we control for a wide range of sibling-varying confounders, including sex, age, birth order and mother's age at birth, as well as vaccination with diphtheria-tetanus-polio (DPT), as a broad indicator of general likelihood to receive vaccinations.
Results: Our samples include 347,808 individuals in 132 surveys from 59 countries (for stunting), 430,963 individuals in 190 surveys from 65 countries (for wasting), and 353,520 individuals in 130 surveys from 59 countries (for underweight). Measles vaccination is associated with significantly reduced odds of stunting (odds ratio 0.90 [95% CI 0.86–0.94], $p < 0.001$) and underweight (odds ratio 0.90 [95% CI 0.86–0.95], $p < 0.001$). The association with wasting is weaker and not statistically significant (odds ratio 0.95 [95% CI 0.89–1.02], $p = 0.143$). Our results remain robust across several alternative specifications of our regression models.
Conclusions: Measles vaccination substantially reduces stunting and underweight among children in low- and middle-income countries. Increasing measles coverage from the current low to near-universal levels would provide a large boost to child growth and the attainment of the SDGs.
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1. Introduction

Vaccine-preventable diseases remain a major cause of morbidity and mortality [1]. Immunization coverage is below recommended levels in many parts of the world and varies highly within countries [1]. The World Health Organization (WHO) estimates that 19.9 million infants worldwide miss out on basic vaccines [2]. Meanwhile, evidence abounds that childhood immunization is not only effective against the specific diseases targeted by the vaccine [3–8] but that it also reduces all-cause mortality, even beyond the reduction in disease-specific mortality [9–14]. Child immunization is one of the most cost-effective health interventions, especially when considering a broader set of economic benefits in the evaluation [15–17].

Several studies investigate the relationship between childhood immunization and malnutrition [18–20]. With 155 million children stunted in 2016 [21], malnutrition still poses a global challenge [22]. It is often used as indicator for overall child health, which is especially crucial as it has been found to influence adult health and living circumstances [23–25]. Malnutrition, with specific targets for stunting and wasting, is the main focus of SDG 2, highlighting its relevance on the global development agenda.

Anekwe and Kumar analyse the effect of an immunization programme in India (UIP) on child anthropometric outcomes and on vaccination coverage [26]. Using the district-by-cohort variation in the exposure to the programme, they find that UIP led to

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decreased child stunting. Semba et al. demonstrate for Indonesia that children who missed routine immunizations are more likely to be malnourished and anaemic [27]. These studies investigate specific immunization programmes or focus on a particular location. The few cross-country studies at population level, such as Frongillo et al. [28] and Milman et al. [29] show that a higher immunization rate is one of the most important factors that are positively associated with child growth.

We identified only one study that examines the relation between childhood vaccination and malnutrition at individual level for a broader set of countries. Berendsen et al. use Demographic and Health Surveys (DHS) from 33 Sub-Saharan African countries to study the effect of BCG, DTP and measles vaccination on stunting and haemoglobin concentration [30]. They investigate the role of timing of vaccination and find a time-dependent relation where vaccination early in life lowered the odds of stunting while vaccination given later in infancy did not. However, in their regression analysis they use fixed effects on the regional level, not accounting for a large part of unobserved heterogeneity, particularly at the household level, which may cause biased and inconsistent estimates [31].

Using data from DHS for all countries available, we investigate whether childhood measles vaccination is associated with stunting, wasting and underweight. Our analysis therefore responds to the call for more and larger observational studies on non-specific effects of childhood vaccination [32]. We consider the importance of timing of vaccination [33,34] by focusing on vaccinations at 12 months of age and use household- and mother-fixed effects. We focus on measles as it remains one of the leading causes of death among young children and measles vaccination has been proven effective in reducing measles death worldwide [35]. Combating measles is one of the targets included under SDG 3 on good health and well-being. Nevertheless, coverage remains below the 90% targeted by the World Health Assembly for measles control and the 89% to 94% herd protection threshold [36], especially in Sub-Saharan Africa and Southeast Asia [37], with recurring measles outbreaks [38–40].

2. Methods

2.1. Data sources and procedures

Data are from the DHS, nationally representative cross-sectional surveys containing accurate data on health and population in low- and middle-income countries. Since the programme's establishment in 1984, there have been more than 300 surveys in over 90 countries [41]. Each survey consists of standard model questionnaires. These include a household questionnaire to identify household members and basic characteristics, and one for women at reproductive age (15–49 years) to collect information on reproductive behaviour as well as health of women and children [42].

DHS use a multi-stage, stratified sampling design. Countries are divided into sub-regions or domains and the population of each region is stratified by urban and rural areas. Within this stratum the samples are selected independently using a two stage selection process. In the first stage enumeration areas, the primary sampling units (PSU), are selected using a probability proportional to enumeration area size. In those selected areas, all existing households are mapped and listed. On the second stage households within each enumeration area are randomly selected for an interview by equal-probability systematic sampling. All eligible women within these households are identified [43].

For this analysis, we use the children's recode files, constructed by women questionnaires, from the Standard DHS. They include detailed information on child health, child mortality and anthropometric indicators about children born to the women five years prior to the interview. Information on child immunization status is available only for children alive at the time of interview. These data files also contain information on characteristics of the mother and the household.

We use children's recode files from all DHS over the years 1990 to 2017 which contain full information on at least one of the outcome variables, measles vaccination as the main explanatory variable, and DPT vaccination. Surveys of DHS phase 1, the earliest surveys conducted before 1990, were omitted as the main explanatory and outcome variables were often missing. For constructing the base sample, we only include cases of children who are alive at the time of the survey, are older than 12 months of age, and have at least one sibling meeting the same criteria. From this base sample, we construct one sample for each outcome by dropping cases with a missing or biologically implausible outcome variable, missing or inconsistent vaccination variables, and missing covariates (see Fig. 1 for details). The final stunting sample includes 132 surveys in 59 countries, consisting of 347,808 cases. The final samples for wasting and underweight include 190 and 130 surveys in 65 and 59 countries, consisting of 430,963 and 353,520 cases, respectively. The number of observations stated in the estimation results is smaller, since only children who have a vaccination discordant sibling (another child in the same household or another child of the same mother) contribute to the effect estimation.

The main explanatory variable is the binary measles vaccination variable. We follow the recommendation of the WHO, stating that measles vaccine should be given within the first 12 months, or even earlier, in countries with a high disease prevalence [44]. In this study, a child is considered vaccinated if it has received the measles vaccination before the age of 12 months, complying with the WHO recommendation. Consequently, children under the age of 12 months must be excluded from the analysis. For coding the variable, we use information on the vaccination status of the child based on the health card or the mother's report if there is no health card, and the vaccination date.

2.2. Outcomes and covariates

Child anthropometry is a common and internationally recognised approach for determining malnutrition. We use anthropometric data from DHS to calculate whether a child was stunted, underweight or wasted as defined by WHO standards and classifications [45]. Stunting describes whether children are too short for their age. A z-score is calculated as the child's height minus the median height for that child's age and sex in the WHO reference population, divided by the standard deviation of this group in the reference population [46]. Underweight children are too light for their age and wasting describes children who are too light for their height. For these two outcomes, z-scores are calculated similarly as for stunting. Z-scores of less than -2 define cases of stunting, underweight, and wasting; z-scores of less than -3 define severe cases. Observations with biologically implausible values are excluded from the analysis. Those values are z-scores of less than -5 and more than +5 for wasting, -6 and +6 for stunting, and -6 and +6 for underweight.

We use age, sex, twin birth, birth order of the child, mother's age at birth, and mother's education as covariates for the analysis. Further characteristics of the mother, namely undernutrition, relationship status, and whether she is currently breastfeeding or pregnant, are also included. As one household can house more than one mother, these variables may vary between children within the same household and may have an effect on the health status of the child.

In model 2 we investigate the effect of adding full diphtheria-pertussis-tetanus (DPT) immunization as covariate. Much of the

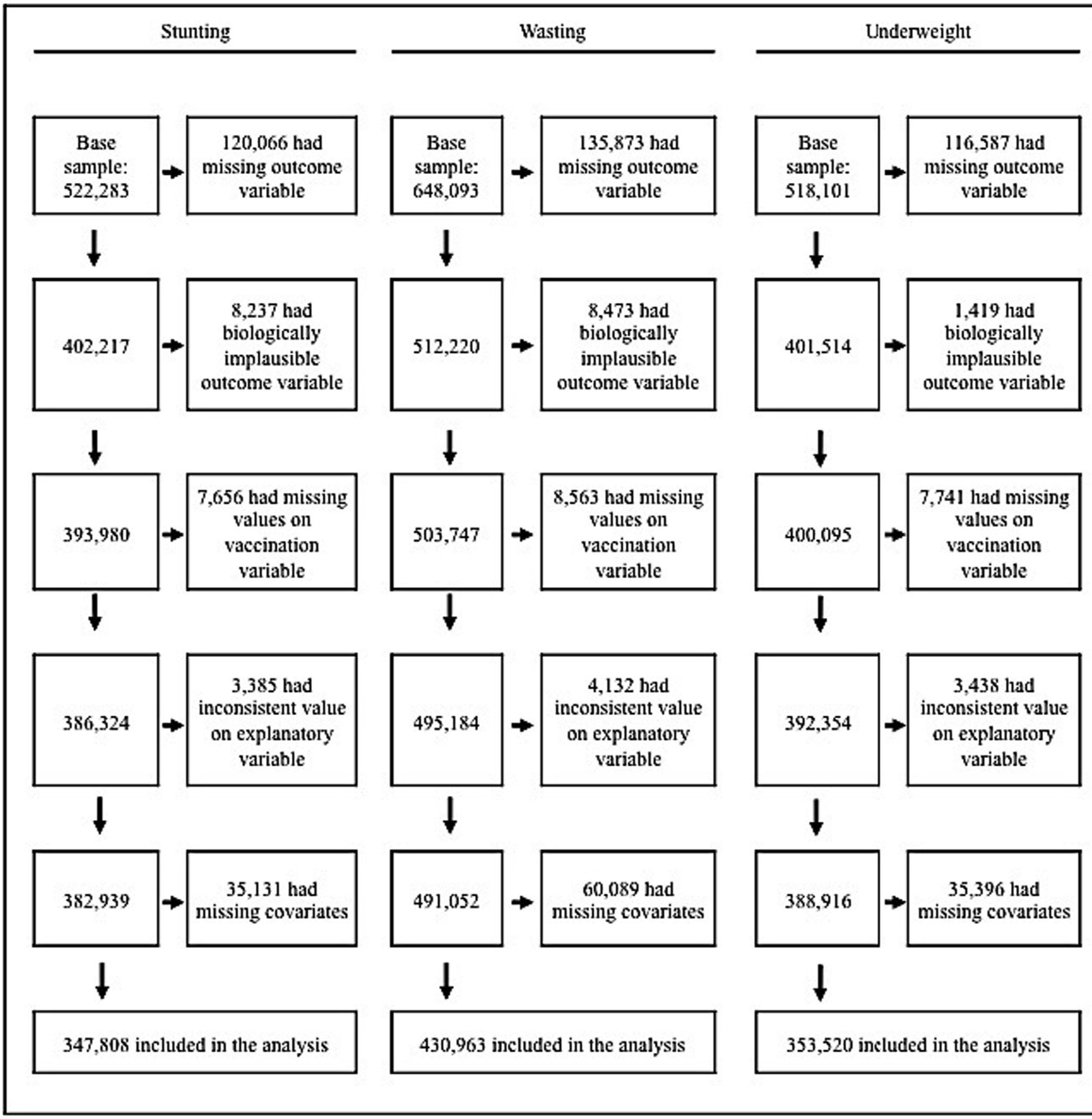

Fig. 1. Sample selection.

unobserved heterogeneity is removed from the analysis by using household- and mother-fixed effects. However, there could be variation over time within a household that affects whether one sibling receives the vaccine whereas another one does not. At the time of vaccination, there could be a lack of required resources that hinders the mother to vaccinate the child or the health system could fail to provide the vaccine. Adding the DPT variable acts as a control for this variation over time. A child is considered fully vaccinated against DPT, if it received three doses of DPT vaccination according to the WHO recommendations during the first year of life.

In model 3 we include an interaction term between gender and measles vaccination, as the effect of vaccination could differ between boys and girls. The interaction term is equal to one if the child is female and vaccinated against measles, and zero in all other cases.

2.3. Statistical analysis

We specify conditional logistic regression models for stunting, underweight, and wasting as outcome variables. For each outcome, we adjust the model for household- or mother-fixed effects. The fixed-effects model accounts for observed and unobserved characteristics of the household or mother, which may bias the estimates otherwise. These characteristics may include attitudes toward risk, conscientiousness, and the mother's aspirations for children. In the model with mother-fixed effects, we therefore compare the health outcome of siblings who share the same mother and household but whose vaccination status differs. The household-fixed-effects regression has the form:

$$Y_{ih} = \beta_0 + \beta_1 V_{ih} + \beta_2 X_{ih}^{child} + \beta_3 X_{ih}^{mother} + \delta_h + \varepsilon_{ih}$$

Y_{ih} is the health outcome of child i in household h. V_{ih} is child i's measles vaccination status and β_1 is the main parameter of interest: the association between childhood measles vaccination and child health. X_{ih}^{child} is a vector containing child-specific control variables including DPT vaccination status and the gender interaction term. X_{ih}^{mother} is a vector containing mother-specific control variables. δ_h is the household-fixed effect and ε_{ih} is the error term. In mother-fixed-effects regressions, the vector of mother-specific control variables is dropped and δ_h is the mother-fixed effect with h referring to the mother instead of the household for all variables included in the regression. The high number of fixed effects combined with few observations per group (i.e. children of one woman) may lead to bias in estimating β_1 [47]. However, using conditional instead of unconditional logistic regression greatly reduces this bias [48].

We performed the regression analysis for the child health outcomes stunting, wasting, underweight, and the three respective severe forms of malnutrition. For each outcome, we repeated the analysis with household-fixed effects and mother-fixed effects, without the DPT covariate, with the DPT covariate, and with both DPT covariate and gender interaction term. Analyses were conducted using Stata version 14.

3. Results

Fig. 2 displays rates of stunting, wasting, underweight, and measles vaccination coverage per country based on the final analysis samples. In the following, we refer to the sample created for the analysis of stunting as the outcome as stunting sample, and similarly we refer to the sample used for the wasting and underweight analyses as wasting and underweight samples, respectively. Table 1 presents descriptive statistics for the stunting, wasting, and underweight samples, with only those cases that are included in the household-fixed-effects regressions. 50% of the stunting sample are stunted, 47% of the wasting sample are wasted, and 49% of the underweight sample are underweight. These rates show that the sub-sample used in the regressions is not representative of the full sample, where the prevalence of stunting, wasting and underweight are 40%, 10% and 24% respectively. The main difference stems from the fact that the regressions only consider cases where vaccination status varies between children within one household. On average, less than one quarter of children have received measles vaccination at age 12 months. The low coverage of the measles vaccination may reflect that some countries recommend measles vaccines to be given at age 12 months or above, instead of below 12 months, as applied in this analysis [42]. This relaxed recommendation may result in a large part of vaccinated children who are not vaccinated against measles at the age of 12 months. In fact, measles vaccination coverage at age 12 months is even lower than 10% in some countries. Slightly more children, about one third, have received three doses of DPT vaccination. The majority of the mothers are between 20 and 29 years old and have no education.

Tables 2, 3, and 4 present odds ratios (OR) of being stunted, wasted, and underweight respectively, from the household-fixed-effects regressions. Our results show that childhood measles vaccination significantly reduces a child's probability of being stunted. According to model 1, children vaccinated against measles within 12 months after birth have 0.90 times the odds of the being stunted, compared to other children in their household who are not vaccinated against measles. Put differently, measles vaccination decreases the probability of being stunted by 11.5% $[(1/\mathrm{OR} - 1) * 100]$. Results point in the same direction and are statistically significant for the odds of being underweight (OR 0.904 in model 1). The coefficient in model 1 suggests that measles vaccination decreases the probability of being underweight by 10.6%. The probability of being wasted also seems to

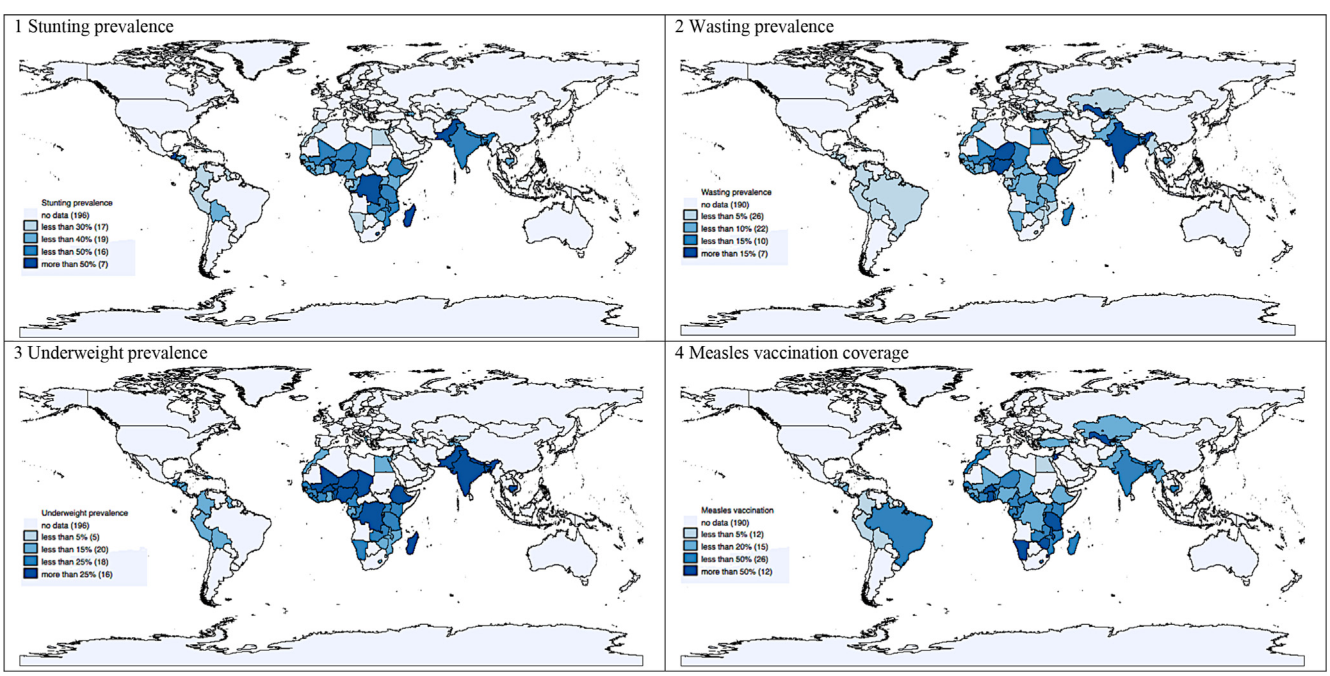

Fig. 2. Global distribution of malnutrition and measles vaccination. Source: Authors' own calculations based on final analysis samples for stunting, wasting, and underweight. Panel 4 uses the joint samples of all three outcomes. For countries with more than one survey, we use the latest available data. Measles vaccination at 12 months of age; stunting, wasting and underweight if z-score is below −2 standard deviations.

Table 1
Descriptive statistics.

Analysis	Stunted		Wasted		Underweight	
	Mean	SD	Mean	SD	Mean	SD
Stunted	0.50	0.50				
Wasted			0.47	0.50		
Underweight					0.49	0.50
Measles	0.25	0.43	0.24	0.43	0.23	0.42
Female	0.50	0.50	0.51	0.50	0.51	0.50
Twin/Multiple birth	0.03	0.18	0.04	0.20	0.04	0.20
Age of child						
1 year	0.30	0.46	0.33	0.47	0.30	0.46
2 years	0.22	0.41	0.21	0.41	0.21	0.41
3 years	0.21	0.41	0.21	0.41	0.21	0.41
4 years	0.27	0.45	0.26	0.44	0.28	0.45
Birth order						
1st child	0.20	0.40	0.20	0.40	0.20	0.40
2nd child	0.25	0.43	0.25	0.43	0.25	0.43
3rd child	0.17	0.38	0.17	0.38	0.17	0.38
4th child	0.12	0.32	0.12	0.32	0.12	0.33
5th child	0.08	0.28	0.09	0.28	0.09	0.28
6th child	0.06	0.24	0.06	0.24	0.06	0.24
7th child or later	0.11	0.31	0.11	0.32	0.11	0.32
Mother's age at child's birth						
<18 years	0.06	0.23	0.06	0.23	0.06	0.23
18–19 years	0.10	0.29	0.10	0.29	0.09	0.29
20–24 years	0.36	0.48	0.36	0.48	0.36	0.48
25–29 years	0.25	0.44	0.26	0.44	0.26	0.44
30–34 years	0.14	0.35	0.13	0.34	0.14	0.34
≥35 years	0.10	0.29	0.09	0.29	0.10	0.29
Education mother						
No education	0.42	0.49	0.53	0.50	0.49	0.50
Primary education	0.30	0.46	0.22	0.42	0.27	0.44
Secondary education or higher	0.28	0.45	0.25	0.43	0.25	0.43
Mother's characteristics						
Has low BMI	0.16	0.37	0.25	0.43	0.20	0.40
Currently pregnant	0.12	0.32	0.12	0.33	0.12	0.33
Currently breastfeeding	0.63	0.48	0.68	0.47	0.66	0.47
Has partner	0.94	0.24	0.96	0.20	0.95	0.22
DPT	0.37	0.48	0.31	0.46	0.32	0.47
N	122,186		61,158		96,411	

Unweighted descriptive statistics of outcomes, exposure, and covariates. Underlying data are the analysis samples for stunting, wasting, and underweight used in the household-fixed-effects regressions. The stunting sample (columns 1 and 2) contains the sample with non-missing stunting information, the wasting sample (columns 3 and 4) contains the sample with non-missing wasting information, the underweight sample (columns 5 and 6) contains the sample with non-missing underweight information.

be reduced by measles vaccination, but the odds ratios are closer to 1 and do not reach statistical significance.

Overall, adding DPT vaccination status as control variable does not change these results. The variable itself does not reach statistical significance in most regressions and the odds ratio is very close to 1. Two exceptions are seen for the outcomes severe stunting and severe underweight, where full DPT vaccination significantly decreases the likelihood of being severely stunted and severely underweight, respectively.

The interaction term between gender and measles vaccination is larger than one and statistically significant at the 1% level for all except the wasting outcomes. Adding this term reduces the odds ratios of the main variable of interest, measles vaccination, in most specifications, but also changes its interpretation. The coefficient of the vaccination variable captures the vaccination effect for boys, while the effect for girls is calculated by testing the linear combination of the coefficients of measles vaccination and the interaction term. The results suggest that the vaccination effect is larger for male than for female children on all outcomes. According to model 3, measles vaccination decreases the probability of being stunted by 18.3% (OR 0.85) and the probability of being underweight by 14.3% (OR 0.88) for boys. While the results point in the same direction for girls, the reductions in the probabilities of stunting, wasting, and underweight, in their moderate and severe form, are not statistically significant.

Being female has a negative impact for all health outcomes, increasing the probability of being stunted by 19.8% $[(OR - 1) * 100]$, being wasted by 19.1%, and being underweight by 12.8%. Multiple birth has an even larger significant effect, increasing the probability of being stunted, wasted or underweight by 113.7%, 71.5%, and 133.7%, respectively. The birth order of the child has a significant effect on the likelihood of being stunted and underweight, with an increasingly higher likelihood for all birth order categories compared to the first-born child. The direction is opposite for being wasted, where the probability of being wasted appears lower for the second and third child. Mother's age at birth has a significant effect on stunting and underweight, with a higher age reducing the likelihood of poor health outcomes, but the coefficients are insignificant for wasting. A mother with secondary or higher education, compared to no education, is also associated with odds ratios below 1 for all three child health indicators. Having a mother with a low BMI, in contrast, significantly increases the probability of being wasted and being underweight, while the coefficient is insignificant for the stunting outcome.

Looking at the odds ratio of being severely stunted (see appendix), the coefficient for measles vaccination status is

Table 2
Odds Ratio of being stunted: Household-fixed-effects regressions.

Variables	Model 1			Model 2			Model 3		
	Estimate	(95% CI)	p-value	Estimate	(95% CI)	p-value	Estimate	(95% CI)	p-value
(Reference category : No measles vaccination)									
Measles	**0.897**	**(0.857–0.939)**	**0.000**	**0.895**	**(0.848–0.945)**	**0.000**	**0.845**	**(0.793–0.901)**	**0.000**
Female	1.198	(1.163–1.233)	0.000	1.198	(1.163–1.233)	0.000	1.165	(1.126–1.204)	0.000
Twin/multiple birth	2.137	(1.848–2.471)	0.000	2.137	(1.848–2.471)	0.000	2.138	(1.849–2.473)	0.000
(Reference category: 1 year old)									
2 years old	1.468	(1.406–1.533)	0.000	1.468	(1.406–1.533)	0.000	1.469	(1.407–1.534)	0.000
3 years old	1062	(1.023–1.102)	0.002	1062	(1.023–1.103)	0.002	1062	(1.023–1.103)	0.001
4 years old	0.741	(0.712–0.772)	0.000	0.742	(0.712–0.772)	0.000	0.742	(0.712–0.772)	0.000
(Reference category: Birth order: 1st child)									
2nd child	1.317	(1.260–1.376)	0.000	1.317	(1.260–1.376)	0.000	1.316	(1.260–1.375)	0.000
3rd child	1.541	(1.444–1.645)	0.000	1.541	(1.444–1.645)	0.000	1.540	(1.443–1.644)	0.000
4th child	1.633	(1.500–1.779)	0.000	1.633	(1.500–1.779)	0.000	1.633	(1.499–1.778)	0.000
5th child	1.742	(1.572–1.931)	0.000	1.742	(1.572–1.931)	0.000	1.741	(1.571–1.930)	0.000
6th child	1.929	(1.710–2.176)	0.000	1.929	(1.710–2.176)	0.000	1.928	(1.710–2.174)	0.000
7th child or later	1.958	(1.713–2.238)	0.000	1.958	(1.713–2.238)	0.000	1.958	(1.713–2.238)	0.000
(Reference category: Mother's age at birth: 20–24 years)									
<18 years	1.483	(1.358–1.620)	0.000	1.483	(1.358–1.620)	0.000	1.483	(1.358–1.619)	0.000
18–19 years	1.168	(1.101–1.238)	0.000	1.168	(1.101–1.238)	0.000	1.168	(1.101–1.239)	0.000
25–29 years	0.815	(0.770–0.862)	0.000	0.815	(0.770–0.862)	0.000	0.816	(0.771–0.863)	0.000
30–34 years	0.708	(0.648–0.773)	0.000	0.708	(0.648–0.773)	0.000	0.708	(0.649–0.774)	0.000
≥35 years	0.645	(0.575–0.724)	0.000	0.645	(0.575–0.724)	0.000	0.646	(0.576–0.724)	0.000
(Reference category: Mother's educational attainment: no education)									
Primary	0.952	(0.861–1.053)	0.336	0.952	(0.861–1.053)	0.336	0.951	(0.860–1.052)	0.328
Secondary or higher	0.791	(0.698–0.897)	0.000	0.791	(0.698–0.897)	0.000	0.790	(0.698–0.896)	0.000
(Mother's characteristics)									
BMI below 18.5	1.085	(0.975–1.208)	0.133	1.085	(0.975–1.208)	0.133	1.086	(0.976–1.208)	0.129
Currently pregnant	1.085	(0.984–1.196)	0.102	1.085	(0.984–1.196)	0.102	1.085	(0.984–1.196)	0.101
Currently breastfeeding	1.076	(1.006–1.152)	0.033	1.076	(1.006–1.152)	0.033	1.077	(1.006–1.152)	0.033
Has partner	0.752	(0.672–0.841)	0.000	0.752	(0.672–0.841)	0.000	0.752	(0.673–0.842)	0.000
(Reference category: no full DPT dose)									
DPT				1.003	(0.952–1.056)	0.918	1.003	(0.952–1.056)	0.920
(Interaction term)									
Female*Measles							1.119	(1.045–1.198)	0.001
Observations	122,186			122,186			122,186		
Household FE	YES			YES			YES		

Vaccination variable: at 12 months of age; Outcome variable: stunted if z-score is below −2 standard deviations.

similar at 0.84 in model 1. This means that measles vaccination decreases the likelihood of being severely stunted by 19.0%. The effect is larger for severe underweight, corresponding to a significant reduction by 23.9%. The coefficient points in the same direction but does not reach conventional significance levels for severe wasting.

Results are similar when we control for mother-fixed effects: The probability of being stunted is significantly reduced for children vaccinated at 12 months compared to unvaccinated children of the same mother in all three specifications. The probability of being underweight seems less affected as coefficients are larger and the coefficient is not statistically significant in model 2, while the probability of being wasted is reduced at the 5% significance level only according to model 1.

4. Discussion

We find that childhood measles vaccination significantly reduces the probability of being stunted and being underweight in a large sample of low- and middle-income countries, while effects on wasting are weaker and less consistent. Stunting is an indicator for chronic malnutrition, which starts early in life and is usually not reversible. This justifies our focus on vaccination status at age 12 months, although some countries recommend measles vaccination within the first 18 months. Wasting, on the other hand, describes very recent nutritional problems, which may be attributable to acute food shortage rather than to malnutrition caused by the diseases which could be prevented by the vaccines. It might be driven by other factors than stunting and underweight. This is also suggested by the fact that some of the control variables which appear relevant for stunting and underweight, such as birth order and mother's age at birth, are not found to be significant for the probability of being wasted.

Our findings are similar to those of Anekwe and Kumar, who find a positive effect of immunization on long-term malnutrition, but not on the other anthropometric outcomes [26].

Theoretically, a randomisation approach would be optimal to identify causal effects. However, due to ethical reasons it is not possible to randomize measles vaccination between individuals. Household- and mother-fixed-effects regressions that control for a large part of observed and unobserved confounders represent a strong alternative to detect causal relations between measles vaccination and health outcomes. This approach has also been used by Anekwe et al. in their analysis of the effect of childhood measles

Table 3
Odds Ratio of being wasted: Household-fixed-effects regressions.

Variables	Model 1			Model 2			Model 3		
	Estimate	(95% CI)	p-value	Estimate	(95% CI)	p-value	Estimate	(95% CI)	p-value
(Reference category : No measles vaccination)									
Measles	**0.950**	**(0.887–1.018)**	**0.143**	**0.960**	**(0.880–1.047)**	**0.361**	**0.922**	**(0.836–1.016)**	**0.101**
Female	1.191	(1.143–1.241)	0.000	1.191	(1.143–1.241)	0.000	1.168	(1.115–1.224)	0.000
Twin/multiple birth	1.715	(1.441–2.041)	0.000	1.716	(1.442–2.042)	0.000	1.717	(1.443–2.043)	0.000
(Reference category: 1 year old)									
2 years old	0.552	(0.522–0.585)	0.000	0.552	(0.521–0.584)	0.000	0.552	(0.522–0.584)	0.000
3 years old	0.376	(0.356–0.398)	0.000	0.376	(0.355–0.397)	0.000	0.376	(0.356–0.398)	0.000
4 years old	0.379	(0.358–0.401)	0.000	0.378	(0.357–0.401)	0.000	0.378	(0.357–0.401)	0.000
(Reference category: Birth order: 1st child)									
2nd child	0.881	(0.825–0.941)	0.000	0.881	(0.825–0.940)	0.000	0.880	(0.824–0.940)	0.000
3rd child	0.849	(0.771–0.934)	0.001	0.849	(0.771–0.934)	0.001	0.848	(0.771–0.934)	0.001
4th child	0.917	(0.816–1.031)	0.148	0.917	(0.816–1.031)	0.148	0.917	(0.815–1.031)	0.146
5th child	0.995	(0.867–1.142)	0.946	0.995	(0.867–1.142)	0.944	0.995	(0.867–1.142)	0.942
6th child	1.039	(0.886–1.218)	0.639	1.039	(0.886–1.218)	0.641	1.038	(0.886–1.218)	0.643
7th child or later	1.017	(0.852–1.215)	0.851	1.017	(0.851–1.215)	0.852	1.016	(0.851–1.214)	0.857
(Reference category: Mother's age at birth: 20–24 years)									
<18 years	0.989	(0.871–1.123)	0.862	0.989	(0.871–1.123)	0.863	0.989	(0.871–1.124)	0.867
18–19 years	0.976	(0.892–1.068)	0.597	0.976	(0.892–1.068)	0.595	0.976	(0.891–1.068)	0.592
25–29 years	0.990	(0.914–1.072)	0.805	0.990	(0.914–1.072)	0.805	0.990	(0.915–1.073)	0.814
30–34 years	0.885	(0.786–0.997)	0.044	0.885	(0.786–0.997)	0.044	0.885	(0.786–0.997)	0.044
≥35 years	0.952	(0.813–1.115)	0.540	0.952	(0.813–1.114)	0.539	0.953	(0.814–1.116)	0.548
(Reference category: Mother's educational attainment: no education)									
Primary	0.933	(0.813–1.071)	0.326	0.933	(0.813–1.071)	0.327	0.934	(0.813–1.071)	0.328
Secondary or higher	0.767	(0.639–0.919)	0.004	0.767	(0.639–0.920)	0.004	0.767	(0.640–0.920)	0.004
(Mother's characteristics)									
BMI below 18.5	1.414	(1.269–1.575)	0.000	1.414	(1.269–1.576)	0.000	1.414	(1.269–1.576)	0.000
Currently pregnant	1.022	(0.896–1.164)	0.749	1.022	(0.896–1.165)	0.746	1.022	(0.897–1.165)	0.742
Currently breastfeeding	1.104	(0.999–1.220)	0.051	1.104	(0.999–1.220)	0.051	1.104	(0.999–1.220)	0.052
Has partner	0.726	(0.608–0.867)	0.000	0.727	(0.609–0.868)	0.000	0.728	(0.609–0.869)	0.000
(Reference category: no full DPT dose)									
DPT				0.982	(0.905–1.066)	0.667	0.982	(0.905–1.066)	0.669
(Interaction term)									
Female*Measles							1.084	(0.983–1.195)	0.105
Observations	61,158			61,158			61,158		
Household FE	YES			YES			YES		

Vaccination variable: at 12 months of age; Outcome variable: wasted if z-score is below −2 standard deviations.

vaccination on educational attainment in South Africa [49]. Such fixed-effects regressions require large sample sizes to permit the detection of significant effects. The sample used in this analysis is large, even on the level of mother-fixed effects. For each outcome, the cases included in the regressions slightly differ. However, even when we restrict our sample to include only those cases that are used in all three analyses, results are qualitatively similar: effects are weakest in size and p-values are highest for wasting (see appendix).

The weaker effect of measles vaccination on female compared to male children warrants further investigation in future studies. It is plausible that it is related to a generally higher susceptibility of boys to morbidity, making vaccination a more important protection for their immune system. Alternatively, it is possible that girls face structural or cultural disadvantages in many communities, which inhibit the potential effects of vaccination on growth outcomes to fully manifest themselves. Future research, including mixed-methods studies, should examine the potential reasons for the gender heterogeneity in vaccination effects, as well as identify potential interventions to overcome potential female disadvantages blocking the benefits of vaccination among girls.

This study has several limitations. The first is that a large number of observations is excluded because of missing vaccination dates, leading to a large proportion of information being lost. This loss of information is critical especially for the fixed-effects regressions, which require a large sample size to detect significant effects. However, this information cannot be inferred from other variables and since timing of the measles vaccination according to the recommendations is important, we cannot ignore vaccination dates. Apart from reducing the sample size, missing data on vaccination date, outcome variables or covariates make the final sample non-representative of the full sample with regard to the prevalence of malnutrition and other characteristics.

Secondly, our analysis does not specifically capture herd effects. Children without measles vaccination might benefit from the vaccination of others. Fixed effects partly control for herd effects as they control for the living environment of a child, which is unlikely to differ between children of the same household. However, the overall causal impact of measles vaccination on child health may be larger than the effect size estimated here. Our estimates should be interpreted as a lower bound of the true benefit of measles vaccination, especially in settings where measles vaccination coverage

Table 4
Odds Ratio of being underweight: Household-fixed-effects regressions.

Variables	Model 1			Model 2			Model 3		
	Estimate	(95% CI)	p-value	Estimate	(95% CI)	p-value	Estimate	(95% CI)	p-value
(Reference category : No measles vaccination)									
Measles	**0.904**	**(0.857–0.953)**	**0.000**	**0.924**	**(0.867–0.984)**	**0.015**	**0.875**	**(0.811–0.944)**	**0.001**
Female	1.128	(1.091–1.166)	0.000	1.128	(1.091–1.166)	0.000	1.100	(1.060–1.142)	0.000
Twin/multiple birth	2.337	(2.010–2.719)	0.000	2.339	(2.011–2.720)	0.000	2.339	(2.011–2.720)	0.000
(Reference category: 1 year old)									
2 years old	1.103	(1.052–1.157)	0.000	1.102	(1.051–1.155)	0.000	1.103	(1.052–1.156)	0.000
3 years old	0.765	(0.734–0.798)	0.000	0.763	(0.732–0.796)	0.000	0.764	(0.732–0.797)	0.000
4 years old	0.722	(0.690–0.754)	0.000	0.720	(0.688–0.752)	0.000	0.720	(0.688–0.753)	0.000
(Reference category: Birth order: 1st child)									
2nd child	1.076	(1.023–1.132)	0.004	1.076	(1.023–1.132)	0.004	1.076	(1.023–1.132)	0.005
3rd child	1.181	(1.095–1.273)	0.000	1.181	(1.095–1.273)	0.000	1.180	(1.095–1.273)	0.000
4th child	1.311	(1.193–1.440)	0.000	1.311	(1.193–1.440)	0.000	1.311	(1.193–1.441)	0.000
5th child	1.426	(1.275–1.595)	0.000	1.426	(1.274–1.595)	0.000	1.427	(1.275–1.596)	0.000
6th child	1.538	(1.350–1.751)	0.000	1.537	(1.350–1.751)	0.000	1.538	(1.350–1.752)	0.000
7th child or later	1.727	(1.492–1.998)	0.000	1.726	(1.492–1.997)	0.000	1.727	(1.493–1.999)	0.000
(Reference category: Mother's age at birth: 20–24 years)									
<18 years	1.292	(1.169–1.430)	0.000	1.292	(1.168–1.429)	0.000	1.292	(1.168–1.429)	0.000
18–19 years	1.175	(1.096–1.259)	0.000	1.175	(1.096–1.259)	0.000	1.175	(1.096–1.259)	0.000
25–29 years	0.855	(0.802–0.911)	0.000	0.855	(0.802–0.911)	0.000	0.855	(0.802–0.911)	0.000
30–34 years	0.763	(0.692–0.841)	0.000	0.763	(0.692–0.842)	0.000	0.762	(0.691–0.841)	0.000
≥35 years	0.724	(0.639–0.821)	0.000	0.724	(0.639–0.821)	0.000	0.724	(0.639–0.821)	0.000
(Reference category: Mother's educational attainment: no education)									
Primary	0.884	(0.789–0.991)	0.035	0.884	(0.789–0.991)	0.035	0.883	(0.788–0.990)	0.033
Secondary or higher	0.677	(0.585–0.784)	0.000	0.677	(0.585–0.785)	0.000	0.677	(0.585–0.784)	0.000
(Mother's characteristics)									
BMI below 18.5	1.385	(1.235–1.553)	0.000	1.386	(1.236–1.553)	0.000	1.386	(1.236–1.553)	0.000
Currently pregnant	1.067	(0.959–1.187)	0.236	1.067	(0.959–1.187)	0.233	1.066	(0.958–1.186)	0.243
Currently breastfeeding	1.089	(1.006–1.178)	0.035	1.089	(1.006–1.179)	0.034	1.088	(1.006–1.178)	0.036
Has partner	0.754	(0.657–0.865)	0.000	0.754	(0.658–0.866)	0.000	0.754	(0.657–0.866)	0.000
(Reference category: no full DPT dose)									
DPT				0.964	(0.907–1.025)	0.244	0.964	(0.907–1.025)	0.240
(Interaction term)									
Female*Measles							1.112	(1.029–1.201)	0.007
Observations	96,411			96,411			96,411		
Household FE	YES			YES			YES		

Vaccination variable: at 12 months of age; Outcome variable: underweight if z-score is below −2 standard deviations.

is relatively high and herd effects may play a relevant role. In our data, however, vaccination rates are very low and do not come close to rates that could lead to herd immunity.

A third limitation is that our fixed-effects model relies on variation in vaccination status among siblings and includes only observations from households, or mothers in the mother-fixed-effects model, with more than one child. It does not consider the causal effect of measles vaccination on health among families with only one child. This is one main factor reducing the sample size available for analysis. The sub-sample of cases from households with more than one child and variation in vaccination status among those children, that is used in the fixed-effects regressions, differs from the full sample in two dimensions. Prevalence rates of stunting, but especially of underweight and wasting, are considerably higher in the smaller sample, and mother's education is lower. This points in the direction that the cases included in our analysis consists of children from the poorer, less educated households, linking back to the non-representative of the final samples. Moreover, the control group in our estimation strategy are unvaccinated children who have at least one sibling who is vaccinated against measles. The control group therefore benefits from a cross-sibling herd effect [50] and the siblings' vaccination status partially protects the child from measles infection. Consequently, the estimated effect sizes should be interpreted as a lower bound on the true effect size for children in families with only unvaccinated children. The reason for discordance in vaccination status between siblings is unknown. One factor could be the availability of providers at the right time for a child's vaccination. Another factor could be underlying preferences of one child over another. If this is the case, a caregiver could not only be selective in giving vaccination to a child but also in distributing nutrition and other aspects of care. In this scenario, the coefficient on measles vaccination would also capture general care received by a child. However, after controlling for gender and birth order, there is no apparent reason why this should present a severe concern for our results.

A fourth limitation is that putting all countries together into one analysis masks differences between countries. The effect of vaccination on child growth might be larger in communities with high underlying levels of undernutrition, because chronic malnutrition weakens the immune system and can aggravate the severity of measles infection and complications [35]. Country-specific effect sizes might therefore deviate from our estimates of a general relationship.

Although the DHS provide a rich dataset, they nevertheless have data limitations. There is no information on the vaccination status of dead children, even if they may have died of measles or related complications. For the included cases, no data is available on their history of measles or whether vaccination led to actual immunization against measles. Data on traditional risk factors associated with malnutrition are also limited.

Child health is an essential factor for developing countries since it affects cognitive development and later outcomes in adult life [24]. Stunting in particular, capturing child growth, is a cumulative indicator of child health and has been shown to predict educational achievement later in life [51]. High rates of stunting in a population lead to an accumulation of negative effects and generate considerable economic losses [52]. Our analysis provides evidence that immunisation against measles, a cost-effective health intervention, has a positive impact on child growth, an effect beyond the proven protection from infection and death due to measles-related complications. For the purpose of saving lives and preventing disease it is desirable to achieve universal coverage with vaccinations. In addition, we show that universal coverage may have further-reaching implications for child growth and consequently long-term economic development. This represents another piece of evidence suggesting a strengthening of efforts to further increase vaccination coverage in order to achieve targets set for the SDGs. Future research should investigate the herd effects of vaccination more closely and develop identification strategies that consider vaccination effects on children without siblings.

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Declaration of Competing Interest

We declare no conflict of interest.

Appendix

see Tables A2–A7.

Table A1
List of surveys included in household-fixed-effects regressions.

Country	Year	Number of observations		
		Stunting	Wasting	Underweight
Albania	2008–09	70	24	26
Armenia	2000	87	11	13
Armenia	2005	63	9	17
Armenia	2015–16	4	4	
Azerbaijan	2006	199	35	103
Bangladesh	1996–97		331	
Bangladesh	1999–00		256	
Bangladesh	2004	621	350	603
Bangladesh	2007	492	307	504
Bangladesh	2011	612	354	609
Bangladesh	2014	467	276	493
Burkina Faso	1992–93		440	
Burkina Faso	1998–99		521	
Burkina Faso	2003	1753	1146	1689
Burkina Faso	2010	1200	604	1055
Benin	1996		91	
Benin	2001	750	270	608
Benin	2006	1950	708	1580
Benin	2011–12	1463	728	1292
Bolivia	1993–94		12	
Bolivia	1998		56	
Bolivia	2003–04	1136	83	393
Bolivia	2008	665	58	232
Brazil	1996		34	
Burundi	2010–11	464	131	432
Congo	2007	568	184	481
Congo	2013–14	1369	434	1202
Central African Republic	1994–95		53	
Congo (Brazzaville)	2005	455	157	297
Congo (Brazzaville)	2011–12	602	156	413
Cote d'Ivoire	1994		141	
Cote d'Ivoire	1998–99		103	
Cote d'Ivoire	2011–12	484	124	324
Cameroon	1998		27	
Cameroon	2004	502	164	333
Cameroon	2011	835	206	519
Colombia	1995		37	
Colombia	2000	374	33	138
Colombia	2004–05	834	103	353
Colombia	2009–10	915	89	304
Dominican Republic	1991		54	
Dominican Republic	1996		37	
Dominican Republic	2013	78	19	45
Dominican Republic	2013	11	2	11

(*continued on next page*)

Table A1 (*continued*)

Country	Year	Number of observations		
		Stunting	Wasting	Underweight
Egypt	1992–93		233	
Egypt	1995–96		450	
Egypt	2000	1265	175	247
Egypt	2003	576	143	289
Egypt	2005	1314	236	313
Egypt	2008	997	254	332
Egypt	2014	895	411	448
Ethiopia	2000	1095	656	1067
Ethiopia	2005	497	239	473
Ethiopia	2012–11	1241	630	1138
Ethiopia	2016	101	68	78
Gabon	2000–01		109	
Gabon	2012	524	90	233
Ghana	1993–94		33	
Ghana	1998–99		125	
Ghana	2003	336	104	262
Ghana	2008	261	77	138
Ghana	2014	237	54	157
Gambia	2013	760	346	668
Guinea	1999		267	
Guinea	2005	456	181	356
Guinea	2012	527	236	411
Guatemala	1995		231	
Guatemala	1998–99		86	
Guatemala	2014–15	961	40	729
Guyana	2009	173	40	108
Honduras	2005–06	952	77	564
Honduras	2011–12	663	56	394
Haiti	1994–95		173	
Haiti	2000	777	227	518
Haiti	2005–06	283	103	238
Haiti	2012	371	96	249
India	1998–99		502	
India	2005–06	5338	3285	5140
India	2015–16	28,712	18,317	27,452
Jordan	1997		90	
Jordan	2002	432	72	175
Jordan	2007	470	206	242
Jordan	2012	413	106	163
Kenya	1993		269	
Kenya	1998		26	
Kenya	2003	614	173	430
Kenya	2008–09	700	257	542
Kenya	2014	996	271	634
Cambodia	2000	368	193	360
Cambodia	2005–06	393	123	348
Cambodia	2010–11	349	155	318
Cambodia	2014	346	130	267
Kazakhstan	1995		2	
Kazakhstan	1999		5	
Comoros	1996		16	
Comoros	2012	307	143	220
Kyrgyz Republic	1997		6	
Kyrgyz Republic	2012	339	36	81
Liberia	2006–07	626	174	451
Liberia	2013	515	120	356
Lesotho	2004–05	115	14	93
Lesotho	2009–10	165	30	87
Lesotho	2014	88	14	48
Morocco	1992		94	
Morocco	2003–04	461	206	223
Moldova	2005	41	9	14
Madagascar	1997		35	
Madagascar	2003–04	550	345	580
Madagascar	2008–09	619		
Mali	1995–96		173	
Mali	2001	1305	671	1248
Mali	2006	1934	1128	1843
Mali	2012–13	874	334	715
Myanmar	2015–16		72	
Maldives	2009	163	87	178
Malawi	1992		118	
Malawi	2000	1000	228	798
Malawi	2004–05	856	233	680

Table A1 (*continued*)

Country	Year	Number of observations		
		Stunting	Wasting	Underweight
Malawi	2010	577	88	368
Malawi	2015–16	39	7	31
Mozambique	1997		41	
Mozambique	2003–04	1065	217	786
Mozambique	2011	1307	265	635
Nicaragua	1997–98		111	
Nicaragua	2001	698	90	327
Nigeria	1999		25	
Nigeria	2003	635	318	663
Nigeria	2008	3168	1491	2886
Nigeria	2013	4002	2388	3835
Niger	1992		583	
Niger	1998		179	
Niger	2006	738	381	733
Niger	2012	1008	652	1054
Namibia	1992		154	
Namibia	2006–07	324	134	294
Namibia	2013	159	45	135
Nepal	1996		76	
Nepal	2001	882	427	965
Nepal	2006	618	373	661
Nepal	2011	221	123	240
Nepal	2016–17	56	27	37
Peru	1991–92		101	
Peru	1996		135	
Peru	2000	1127	88	447
Peru	2003–08	788	45	306
Peru	2009	679	35	249
Peru	2010	576	31	203
Peru	2011	578	37	223
Peru	2012	1764	74	580
Pakistan	2012–13	560	239	586
Rwanda	2000	666	200	459
Rwanda	2005	496	100	362
Rwanda	2010–11	448	62	257
Rwanda	2014–15	312	29	119
Sierra Leone	2008	261	98	193
Sierra Leone	2013	599	222	392
Senegal	1992–93		514	
Senegal	2005	593	299	457
Senegal	2010–11	1018	463	918
Sao Tome & Principe	2008–09	142	58	82
Swaziland	2006–07	245	15	54
Chad	1996–97		527	
Chad	2004	828	473	784
Chad	2014–15	1618	1029	1522
Togo	1998		125	
Togo	2013–14	450	155	349
Tajikistan	2012	741	272	467
Timor Leste	2009–10	1270	783	1512
Turkey	1993		65	
Turkey	1998		33	
Turkey	2003–04		26	
Tanzania	1991–92		357	
Tanzania	1996		257	
Tanzania	2004–05	998	190	665
Tanzania	2009–10	1064	252	634
Tanzania	2015–16	223	71	151
Uganda	1995		108	
Uganda	2000–01	694	157	526
Uganda	2006	412	110	297
Uganda	2011	300	51	184
Uzbekistan	1996		19	
Zambia	1992		254	
Zambia	1996–97		174	
Zambia	2001–02	713	208	635
Zambia	2007	749	181	456
Zambia	2013–14	1524	345	1013
Zimbabwe	1994		23	
Zimbabwe	1999	222	66	126
Zimbabwe	2005–06	329	81	213
Zimbabwe	2010–11	284	44	148
Zimbabwe	2015	44	6	27

List of surveys included in household-fixed-effects regressions with included number of observations.
Separately for stunting sample, wasting sample, underweight sample.

Table A2
Odds Ratio of being severely stunted: Household-fixed-effects regressions.

Variables	Model 1			Model 2			Model 3		
	Estimate	(95% CI)	p-value	Estimate	(95% CI)	p-value	Estimate	(95% CI)	p-value
(Reference category : No measles vaccination)									
Measles	**0.840**	**(0.795–0.888)**	**0.000**	**0.902**	**(0.843–0.965)**	**0.003**	**0.840**	**(0.775–0.910)**	**0.000**
Female	1.258	(1.215–1.303)	0.000	1.258	(1.215–1.303)	0.000	1.221	(1.173–1.271)	0.000
Twin/multiple birth	2.259	(1.916–2.664)	0.000	2.269	(1.924–2.675)	0.000	2.274	(1.928–2.681)	0.000
(Reference category: 1 year old)									
2 years old	1.470	(1.396–1.548)	0.000	1.466	(1.392–1.544)	0.000	1.467	(1.393–1.545)	0.000
3 years old	0.892	(0.853–0.933)	0.000	0.886	(0.847–0.927)	0.000	0.887	(0.848–0.928)	0.000
4 years old	0.622	(0.592–0.653)	0.000	0.616	(0.587–0.647)	0.000	0.617	(0.587–0.648)	0.000
(Reference category: Birth order: 1st child)									
2nd child	1.371	(1.296–1.449)	0.000	1.370	(1.296–1.449)	0.000	1.371	(1.296–1.449)	0.000
3rd child	1.692	(1.559–1.837)	0.000	1.693	(1.559–1.837)	0.000	1.692	(1.559–1.837)	0.000
4th child	1.749	(1.578–1.939)	0.000	1.750	(1.579–1.940)	0.000	1.750	(1.578–1.939)	0.000
5th child	1.842	(1.631–2.081)	0.000	1.843	(1.631–2.081)	0.000	1.843	(1.632–2.082)	0.000
6th child	1.968	(1.707–2.269)	0.000	1.969	(1.708–2.271)	0.000	1.969	(1.708–2.271)	0.000
7th child or later	2.053	(1.750–2.407)	0.000	2.054	(1.752–2.409)	0.000	2.055	(1.752–2.410)	0.000
(Reference category: Mother's age at birth: 20–24 years)									
<18 years	1.520	(1.364–1.694)	0.000	1.517	(1.362–1.691)	0.000	1.516	(1.361–1.690)	0.000
18–19 years	1.212	(1.125–1.305)	0.000	1.212	(1.125–1.305)	0.000	1.211	(1.124–1.305)	0.000
25–29 years	0.854	(0.798–0.913)	0.000	0.853	(0.798–0.912)	0.000	0.854	(0.798–0.913)	0.000
30–34 years	0.720	(0.648–0.800)	0.000	0.719	(0.647–0.799)	0.000	0.719	(0.647–0.798)	0.000
≥35 years	0.661	(0.576–0.758)	0.000	0.661	(0.576–0.759)	0.000	0.662	(0.576–0.759)	0.000
(Reference category: Mother's educational attainment: no education)									
Primary	0.904	(0.803–1.017)	0.093	0.904	(0.803–1.017)	0.094	0.901	(0.801–1.015)	0.086
Secondary or higher	0.763	(0.656–0.888)	0.000	0.765	(0.658–0.891)	0.001	0.765	(0.658–0.890)	0.001
(Mother's characteristics)									
BMI below 18.5	1.213	(1.093–1.346)	0.000	1.214	(1.094–1.348)	0.000	1.213	(1.093–1.346)	0.000
Currently pregnant	1.192	(1.060–1.342)	0.003	1.195	(1.062–1.344)	0.003	1.194	(1.061–1.344)	0.003
Currently breastfeeding	1.143	(1.050–1.243)	0.002	1.145	(1.052–1.246)	0.002	1.145	(1.053–1.246)	0.002
Has partner	0.814	(0.699–0.948)	0.008	0.817	(0.701–0.951)	0.009	0.816	(0.700–0.950)	0.009
(Reference category: no full DPT dose)									
DPT				0.890	(0.835–0.949)	0.000	0.891	(0.835–0.950)	0.000
(Interaction term)									
Female*Measles							1.148	(1.057–1.247)	0.001
Observations	83,520			83,520			83,520		
Household FE	YES			YES			YES		

Vaccination variable: at 12 months of age; Outcome variable: stunted if z-score is below −3 standard deviations (see Table A1).

Table A3
Odds Ratio of being severely wasted: Household-fixed-effects regressions.

Variables	Model 1			Model 2			Model 3		
	Estimate	(95% CI)	p-value	Estimate	(95% CI)	p-value	Estimate	(95% CI)	p-value
(Reference category : No measles vaccination)									
Measles	**0.959**	**(0.868–1.059)**	**0.410**	**0.956**	**(0.847–1.080)**	**0.471**	**0.975**	**(0.845–1.124)**	**0.725**
Female	1.351	(1.269–1.437)	0.000	1.351	(1.269–1.437)	0.000	1.363	(1.270–1.462)	0.000
Twin/multiple birth	1.744	(1.344–2.263)	0.000	1.743	(1.344–2.262)	0.000	1.744	(1.344–2.262)	0.000
(Reference category: 1 year old)									
2 years old	0.603	(0.554–0.657)	0.000	0.603	(0.554–0.657)	0.000	0.603	(0.554–0.657)	0.000
3 years old	0.386	(0.356–0.420)	0.000	0.387	(0.356–0.420)	0.000	0.386	(0.356–0.420)	0.000
4 years old	0.297	(0.272–0.323)	0.000	0.297	(0.272–0.324)	0.000	0.297	(0.272–0.324)	0.000
(Reference category: Birth order: 1st child)									
2nd child	0.914	(0.833–1.004)	0.060	0.914	(0.833–1.004)	0.060	0.914	(0.833–1.004)	0.060
3rd child	0.908	(0.788–1.046)	0.181	0.908	(0.788–1.046)	0.181	0.908	(0.788–1.046)	0.183
4th child	1.053	(0.884–1.254)	0.561	1.053	(0.884–1.255)	0.560	1.054	(0.885–1.255)	0.557
5th child	1.007	(0.820–1.236)	0.947	1.007	(0.820–1.236)	0.946	1.008	(0.821–1.237)	0.942
6th child	1.062	(0.843–1.339)	0.608	1.063	(0.843–1.340)	0.607	1.063	(0.843–1.341)	0.603
7th child or later	1.203	(0.928–1.561)	0.163	1.203	(0.928–1.561)	0.163	1.204	(0.928–1.563)	0.161

Table A3 (*continued*)

Variables	Model 1			Model 2			Model 3		
	Estimate	(95% CI)	p-value	Estimate	(95% CI)	p-value	Estimate	(95% CI)	p-value
(Reference category: Mother's age at birth: 20–24 years)									
<18 years	0.933	(0.763–1.141)	0.501	0.933	(0.763–1.141)	0.500	0.932	(0.762–1.140)	0.495
18–19 years	0.987	(0.862–1.130)	0.848	0.987	(0.862–1.130)	0.848	0.987	(0.862–1.130)	0.847
25–29 years	0.908	(0.811–1.018)	0.098	0.908	(0.811–1.018)	0.098	0.908	(0.810–1.017)	0.097
30–34 years	0.770	(0.646–0.918)	0.004	0.770	(0.646–0.918)	0.004	0.770	(0.646–0.918)	0.004
≥35 years	0.763	(0.603–0.966)	0.025	0.763	(0.603–0.966)	0.024	0.762	(0.603–0.964)	0.024
(Reference category: Mother's educational attainment: no education)									
Primary	0.821	(0.662–1.019)	0.074	0.821	(0.662–1.019)	0.074	0.822	(0.663–1.020)	0.076
Secondary or higher	0.742	(0.575–0.957)	0.022	0.741	(0.574–0.957)	0.022	0.742	(0.575–0.958)	0.022
(Mother's characteristics)									
BMI below 18.5	1.210	(1.032–1.420)	0.019	1.210	(1.032–1.420)	0.019	1.210	(1.031–1.419)	0.019
Currently pregnant	0.982	(0.811–1.190)	0.856	0.982	(0.811–1.190)	0.855	0.982	(0.811–1.190)	0.855
Currently breastfeeding	1.134	(0.982–1.310)	0.087	1.134	(0.982–1.310)	0.087	1.134	(0.982–1.310)	0.087
Has partner	0.783	(0.614–1.000)	0.050	0.783	(0.614–1.000)	0.050	0.783	(0.614–1.000)	0.050
(Reference category: no full DPT dose)									
DPT				1.005	(0.893–1.130)	0.938	1.005	(0.893–1.131)	0.931
(Interaction term)									
Female*Measles							0.964	(0.828–1.121)	0.632
Observations	23,998			23,998			23,998		
Household FE	YES			YES			YES		

Vaccination variable: at 12 months of age; Outcome variable: wasted if z-score is below −3 standard deviations.

Table A4
Odds Ratio of being severely underweight: Household-fixed-effects regressions.

Variables	Model 1			Model 2			Model 3		
	Estimate	(95% CI)	p-value	Estimate	(95% CI)	p-value	Estimate	(95% CI)	p-value
(Reference category : No measles vaccination)									
Measles	**0.807**	**(0.746–0.874)**	**0.000**	**0.892**	**(0.810–0.982)**	**0.020**	**0.817**	**(0.729–0.914)**	**0.000**
Female	1.145	(1.093–1.199)	0.000	1.146	(1.094–1.200)	0.000	1.109	(1.054–1.166)	0.000
Twin/multiple birth	2.570	(2.094–3.154)	0.000	2.586	(2.106–3.174)	0.000	2.585	(2.106–3.173)	0.000
(Reference category: 1 year old)									
2 years old	1.015	(0.949–1.086)	0.658	1.009	(0.944–1.080)	0.787	1.011	(0.945–1.081)	0.751
3 years old	0.643	(0.606–0.682)	0.000	0.636	(0.599–0.675)	0.000	0.637	(0.601–0.676)	0.000
4 years old	0.493	(0.463–0.527)	0.000	0.487	(0.457–0.520)	0.000	0.488	(0.457–0.520)	0.000
(Reference category: Birth order: 1st child)									
2nd child	1.160	(1.076–1.251)	0.000	1.160	(1.075–1.251)	0.000	1.161	(1.077–1.252)	0.000
3rd child	1.342	(1.202–1.497)	0.000	1.341	(1.201–1.497)	0.000	1.341	(1.202–1.497)	0.000
4th child	1.503	(1.312–1.722)	0.000	1.506	(1.314–1.725)	0.000	1.507	(1.315–1.726)	0.000
5th child	1.665	(1.416–1.956)	0.000	1.666	(1.417–1.959)	0.000	1.669	(1.420–1.962)	0.000
6th child	1.835	(1.524–2.210)	0.000	1.838	(1.526–2.214)	0.000	1.843	(1.531–2.220)	0.000
7th child or later	1.993	(1.623–2.448)	0.000	1.996	(1.625–2.451)	0.000	2.001	(1.629–2.457)	0.000
(Reference category: Mother's age at birth: 20–24 years)									
<18 years	1.343	(1.159–1.555)	0.000	1.340	(1.157–1.552)	0.000	1.341	(1.158–1.554)	0.000
18–19 years	1.150	(1.043–1.267)	0.005	1.147	(1.040–1.265)	0.006	1.148	(1.041–1.265)	0.006
25–29 years	0.778	(0.711–0.852)	0.000	0.777	(0.710–0.851)	0.000	0.778	(0.711–0.851)	0.000
30–34 years	0.628	(0.545–0.725)	0.000	0.629	(0.545–0.725)	0.000	0.628	(0.545–0.725)	0.000
≥35 years	0.597	(0.499–0.713)	0.000	0.596	(0.499–0.712)	0.000	0.595	(0.498–0.711)	0.000
(Reference category: Mother's educational attainment: no education)									
Primary	0.798	(0.666–0.958)	0.015	0.797	(0.664–0.957)	0.015	0.798	(0.665–0.956)	0.014
Secondary or higher	0.504	(0.376–0.676)	0.000	0.504	(0.375–0.678)	0.000	0.506	(0.379–0.674)	0.000
(Mother's characteristics)									
BMI below 18.5	1.557	(1.365–1.777)	0.000	1.557	(1.365–1.777)	0.000	1.559	(1.367–1.778)	0.000
Currently pregnant	1.102	(0.950–1.279)	0.201	1.106	(0.953–1.283)	0.186	1.103	(0.950–1.280)	0.198
Currently breastfeeding	1.182	(1.055–1.324)	0.004	1.185	(1.057–1.328)	0.004	1.183	(1.056–1.326)	0.004
Has partner	0.832	(0.669–1.036)	0.100	0.832	(0.667–1.036)	0.101	0.829	(0.665–1.032)	0.094

(*continued on next page*)

Table A4 (*continued*)

Variables	Model 1			Model 2			Model 3		
	Estimate	(95% CI)	p-value	Estimate	(95% CI)	p-value	Estimate	(95% CI)	p-value
(Reference category: no full DPT dose)									
DPT				0.853	(0.780–0.933)	0.000	0.854	(0.781–0.934)	0.001
(Interaction term)									
Female*Measles							1.184	(1.048–1.339)	0.007
Observations	46,149			46,149			46,149		
Household FE	YES			YES			YES		

Vaccination variable: at 12 months of age; Outcome variable: underweight if z-score is below −3 standard deviations.

Table A5
Odds Ratio of being stunted: Mother-fixed-effects regressions.

Variables	Model 1			Model 2			Model 3		
	Estimate	(95% CI)	p-value	Estimate	(95% CI)	p-value	Estimate	(95% CI)	p-value
(Reference category : No measles vaccination)									
Measles	**0.908**	**(0.861–0.957)**	**0.000**	**0.902**	**(0.848–0.960)**	**0.001**	**0.850**	**(0.790–0.914)**	**0.000**
Female	1.207	(1.167–1.247)	0.000	1.207	(1.167–1.247)	0.000	1.173	(1.128–1.219)	0.000
Twin/multiple birth	2.284	(1.907–2.735)	0.000	2.283	(1.907–2.734)	0.000	2.284	(1.907–2.735)	0.000
(Reference category: 1 year old)									
2 years old	1.842	(1.747–1.942)	0.000	1.842	(1.747–1.942)	0.000	1.843	(1.748–1.943)	0.000
3 years old	1.667	(1.569–1.771)	0.000	1.668	(1.569–1.773)	0.000	1.670	(1.571–1.775)	0.000
4 years old	1.372	(1.273–1.478)	0.000	1.373	(1.274–1.479)	0.000	1.374	(1.275–1.480)	0.000
(Reference category: Birth order: 1st child)									
2nd child	1.929	(1.813–2.051)	0.000	1.928	(1.813–2.051)	0.000	1.928	(1.813–2.051)	0.000
3rd child	3.463	(3.098–3.872)	0.000	3.462	(3.096–3.871)	0.000	3.463	(3.097–3.871)	0.000
4th child	5.573	(4.729–6.567)	0.000	5.570	(4.726–6.564)	0.000	5.575	(4.731–6.569)	0.000
5th child	9.361	(7.522–11.65)	0.000	9.355	(7.517–11.64)	0.000	9.370	(7.530–11.66)	0.000
6th child	16.92	(12.85–22.29)	0.000	16.91	(12.84–22.27)	0.000	16.94	(12.87–22.31)	0.000
7th child or later	29.04	(20.86–40.42)	0.000	29.01	(20.84–40.39)	0.000	29.09	(20.90–40.50)	0.000
(Reference category: no full DPT dose)									
DPT				1.011	(0.951–1.074)	0.731	1.011	(0.951–1.074)	0.731
(Interaction term)									
Female*Measles							1.124	(1.042–1.212)	0.003
Observations	93,242			93,242			93,242		
Mother FE	YES			YES			YES		

Vaccination variable: at 12 months of age; Outcome variable: stunted if z-score is below −2 standard deviations.

Table A6
Odds Ratio of being wasted: Mother-fixed-effects regressions.

Variables	Model 1			Model 2			Model 3		
	Estimate	(95% CI)	p-value	Estimate	(95% CI)	p-value	Estimate	(95% CI)	p-value
(Reference category : No measles vaccination)									
Measles	**0.914**	**(0.845–0.988)**	**0.024**	**0.931**	**(0.844–1.028)**	**0.160**	**0.904**	**(0.809–1.011)**	**0.076**
Female	1.211	(1.156–1.269)	0.000	1.211	(1.156–1.269)	0.000	1.194	(1.132–1.260)	0.000
Twin/multiple birth	1.742	(1.406–2.159)	0.000	1.744	(1.407–2.162)	0.000	1.744	(1.408–2.162)	0.000
(Reference category: 1 year old)									
2 years old	0.573	(0.534–0.614)	0.000	0.572	(0.534–0.614)	0.000	0.573	(0.534–0.614)	0.000
3 years old	0.411	(0.377–0.447)	0.000	0.410	(0.376–0.446)	0.000	0.410	(0.377–0.447)	0.000
4 years old	0.438	(0.397–0.484)	0.000	0.437	(0.396–0.483)	0.000	0.437	(0.396–0.483)	0.000
(Reference category: Birth order: 1st child)									
2nd child	0.941	(0.863–1.026)	0.169	0.941	(0.864–1.026)	0.169	0.941	(0.863–1.026)	0.167
3rd child	0.991	(0.851–1.153)	0.903	0.991	(0.851–1.154)	0.909	0.991	(0.851–1.154)	0.908
4th child	1.228	(0.986–1.528)	0.066	1.229	(0.988–1.530)	0.065	1.229	(0.988–1.530)	0.064
5th child	1.579	(1.186–2.103)	0.002	1.581	(1.187–2.105)	0.002	1.582	(1.188–2.107)	0.002
6th child	2.079	(1.458–2.963)	0.000	2.081	(1.460–2.967)	0.000	2.084	(1.462–2.970)	0.000
7th child or later	2.647	(1.722–4.067)	0.000	2.650	(1.724–4.074)	0.000	2.653	(1.726–4.078)	0.000
(Reference category: no full DPT dose)									
DPT				0.968	(0.879–1.065)	0.503	0.968	(0.880–1.065)	0.505
(Interaction term)									
Female*Measles							1.061	(0.948–1.187)	0.303
Observations	46,470			46,470			46,470		
Mother FE	YES			YES			YES		

Vaccination variable: at 12 months of age; Outcome variable: wasted if z-score is below −2 standard deviations.

Table A7
Odds Ratio of being underweight: Mother-fixed-effects regressions.

Variables	Model 1			Model 2			Model 3		
	Estimate	(95% CI)	p-value	Estimate	(95% CI)	p-value	Estimate	(95% CI)	p-value
(Reference category : No measles vaccination)									
Measles	**0.928**	**(0.874–0.986)**	**0.015**	**0.948**	**(0.882–1.020)**	**0.150**	**0.889**	**(0.816–0.968)**	**0.007**
Female	1.143	(1.102–1.187)	0.000	1.143	(1.102–1.187)	0.000	1.111	(1.064–1.159)	0.000
Twin/multiple birth	2.388	(1.967–2.899)	0.000	2.389	(1.968–2.900)	0.000	2.390	(1.969–2.902)	0.000
(Reference category: 1 year old)									
2 years old	1.316	(1.242–1.394)	0.000	1.314	(1.241–1.392)	0.000	1.316	(1.242–1.394)	0.000
3 years old	1.051	(0.984–1.123)	0.138	1.049	(0.982–1.121)	0.158	1.051	(0.983–1.123)	0.144
4 years old	1.183	(1.092–1.282)	0.000	1.180	(1.089–1.279)	0.000	1.181	(1.090–1.280)	0.000
(Reference category: Birth order: 1st child)									
2nd child	1.406	(1.314–1.506)	0.000	1.407	(1.314–1.506)	0.000	1.407	(1.314–1.506)	0.000
3rd child	2.118	(1.871–2.399)	0.000	2.120	(1.872–2.401)	0.000	2.122	(1.873–2.402)	0.000
4th child	3.371	(2.823–4.027)	0.000	3.374	(2.825–4.030)	0.000	3.382	(2.831–4.039)	0.000
5th child	5.641	(4.453–7.146)	0.000	5.648	(4.459–7.155)	0.000	5.671	(4.477–7.183)	0.000
6th child	9.671	(7.206–12.98)	0.000	9.683	(7.215–13.00)	0.000	9.723	(7.245–13.05)	0.000
7th child or later	18.97	(13.30–27.07)	0.000	19.00	(13.32–27.11)	0.000	19.09	(13.39–27.24)	0.000
(Reference category: no full DPT dose)									
DPT				0.963	(0.898–1.033)	0.296	0.963	(0.898–1.033)	0.294
(Interaction term)									
Female*Measles							1.135	(1.041–1.237)	0.004
Observations	73,456			73,456			73,456		
Mother FE	YES			YES			YES		

Vaccination variable: at 12 months of age; Outcome variable: underweight if z-score is below −2 standard deviations.

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