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RESEARCH ARTICLE

REVISED Eco-geographic patterns of child malnutrition in India and its association with cereal cultivation: An analysis using demographic health survey and agriculture datasets [version 4; peer review: 1 approved, 2 approved with reservations, 1 not approved]

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Abstract

Background: High prevalence of maternal malnutrition, low birth-weight and child malnutrition in India contribute substantially to the global malnutrition burden. Rural India has disproportionately higher levels of child malnutrition. Stunting and wasting are the primary determinants of child malnutrition and their district-level distribution shows clustering in different geographies and regions. Cereals, particularly millets, constitute the bulk of protein intake among the poor, especially in rural areas in India where high prevalence of wasting persists.

Methods: The previous round of National Family Health Survey (NFHS4) has disaggregated data by district, enabling a more fine-scale characterisation of the prevalence of markers of malnutrition. We used data from NFHS4 and agricultural statistics datasets to analyse relationship of prevalence of malnutrition at the district level and area under cereal cultivation. We analysed malnutrition through data on under-5 stunting and wasting by district.

Results: Stunting and wasting patterns across districts show a distinct

geographical and age distribution; districts with higher wasting showed relatively higher prevalence at six months of age. Wasting prevalence at district level was associated with higher cultivation of millets, with a stronger association seen for jowar and other millets (Kodo millet, little millet, proso millet, barnyard millet and foxtail millet). District level stunting was associated with higher district level cultivation of wheat. In multivariable analysis, wasting was positively associated with women's body mass index and stunting with women's short stature.

Conclusions: Well-designed intervention studies will be required to confirm causal pathways contributing to ecogeographic patterns of child malnutrition. The cultivation of other millets has a strong association with prevalence of wasting. State-of-the-art studies that improve our understanding of bio-availability of amino acids and other nutrients from the prevalent dietary matrices of rural poor communities will be needed to confirm causal pathways contributing to potential eco-geographic patterns.

Keywords
Millets, malnutrition, wasting, stunting, MTORC1 (mechanistic target of Rapamycin complex1), GCN2 (general control non derepressible 2), DSCQ (District subsistence cultivation quantum)

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Introduction

Undernutrition among children less than 5 years is measured by prevalence of stunting (height for age with z score of less than -2), wasting (weight for height with z score less than -2) and underweight (weight for age with z score less than -2). High prevalence of low birth weight (weight less than 2.5kg at birth), is also an important contributor to child undernutrition, and, forms a continuum to it within the first 1000 days[1]. Low pre-pregnancy BMI, low maternal BMI (< 18.5 kg/m2), maternal short stature and maternal micronutrient deficiency or anemia all contribute to small for gestational age, low birth weight and prematurity[2]. Out of the estimated 20.5 million babies born low birth weight annually, 48% are born in South Asia. India alone is estimated to have 100 million adult women with low BMI[1,2]. Globally, the World Health Organization (WHO) estimates that among children under five, about

151 million suffer from stunting and 51 million from wasting with consequent risks of mortality, morbidity and delayed development[3]. The latest stunting trends indicate increases in Africa along with substantial reductions across Asia. However, with regards to wasting, with a regional prevalence of 12%, South Asia accounts for half of all wasted children globally[1,4,5]. India reports 21 % wasting of children under 5 years numbering about 27 million[4]. South Asia is also estimated to have ~45% of the global burden of stunting. The socio-economic gains and poverty reduction of the past decades have not translated into commensurate reduction of stunting and wasting in children, often characterised as, *the Asian enigma*[6–8].

Subsistence farming and millet dependence

Indian states consist of 640 districts (at the time of NFHS4) with wide differences in geography, climate and the main agricultural crops. India has a large and poor rural population (68.9% rural with 25.5 % rural poverty prevalence), and over half (54%) of the working rural population (481.9 million) are cultivators and agricultural labourers[9,10]. Small land-holding farmers (owning less than two hectares of land) and their families constitute more than half the country's population. Only half (96.46 million hectares) of the total area under cultivation (198.36 million hectares) is irrigated[11]. Although, rice and wheat together constitute 75% of total area under food grain cultivation, Jowar (Sorghum) and Bajra (pearl millet) make up a significant 13.8%. However, the distribution of food grain cultivation in irrigated land varies, with rice (60%) and wheat (94.2%), expectedly being grown largely on irrigated land. In contrast, Sorghum (Jowar) and Pearl millet (Bajra) are grown largely in non-irrigated lands, most likely by small land-holding farmers in monsoon-dependent arid or semi-arid regions of the country, which are also among the poorest[12,13]. Cereal cultivation and consequently household food grain consumption and diets in such regions are likely driven by these strong linkages between agro-climatic, edaphic, and eco-geographic factors, more so among poorer households with socio-economic barriers to achieve dietary diversity.

A study based on National Family Health Survey-3, which reported results at the state level for India in 2005–6, demonstrated considerable geographic variation among the states of India with regards to child malnutrition, with higher levels of stunting seen in Uttar Pradesh, Uttaranchal & Gujarat[14]. In contrast, higher wasting levels were seen in Madhya Pradesh, a state in central India. A nutritional survey among preschool children in three tribal regions belonging to different ecological zones in the state of Madhya Pradesh, India, namely Jhabua, Bastar and Sarguja, showed greater extent and severity of malnutrition among children in Jhabua. The staple cereals reported in the study for Jhabua was maize and Sorghum, while for Bastar and Sarguja, it was rice[15]. Sorghum, as staple, has also been linked to endemic pellagra among farm workers in Hyderabad by Gopalan[16]. Subsistence crop cultivation has been linked to seasonal "epidemic" nutritional edema among American farmers in the 1930s[17,18]. Much earlier,at the beginning of last century, nutritional edema among children weaned on a diet of cereal flour was called *Mehlnahrschden* or flour dystrophy in Germany[17]. Cecily Williams in her classic

description of Kwashiorkor attributed it to weaning on a pre-dominantly maize-based staple[19].

The Lancet 2008 series too has brought out this aforementioned pattern of child malnutrition, with areas having similar prevalence of stunting demonstrating substantial differences in wasting[20]. Likewise, low women's BMI (15–49 years age) too, has numerous geographical subnational hotspots in South Asia[1].

Geo-spatial heterogeneity in prevalence of child malnutrition across Indian districts has been reported[21]. The NFHS 4 was conducted in 2015–16 incorporating district-level data for the first time[22]. Based on unpublished field observations of wasting prevalence among populations depending on millet as staple in rural Maharashtra (spanning western and central India), we critically examined the spatial patterns of prevalence of stunting and wasting at the district level across India with the objective of exploring the role of dietary staple cereal consumption pattern using cultivation pattern as a proxy. Ragi (finger millet; *Eleusine coracana*) was excluded because it belongs to a distinct sub-family in the grass family Poaceae and has a relatively better nutritional profile[23–25].

Methods

We analysed district-level secondary data on under-5 stunting and wasting as reported in NFHS4 with district-wise crop cultivation data to assess geo-spatial overlaps and risk relationships between pre-school child malnutrition and cultivation of staple cereal crops. NFHS is a standardised and periodic nationally representative survey. NFHS4 covered 601,509 households, 699,686 women aged 15–49 years and 103,525 men aged 15–54 years that provides comprehensive data on various aspects of maternal and child health[21,26]. NFHS-4 provides unit level data (for each of the 640 districts of India at the time of survey) for download upon request via the demographic health survey data repository[26,27]. We extracted data on population of each district from the 2011 Census[10]. We included other socio-demographic variables with known associations with malnutrition from NFHS4 to assess their relative contribution to childhood wasting and stunting, at district level using multivariable linear regression.

Definitions and data sources

We considered the following cereal crops widely grown and reported in Indian agriculture databases and the Directorate of Millets Development (under Department of Agriculture, Co-operation and Farmers Welfare) in our analysis: rice(*Oryza sativa*), wheat(*Triticum aestivum*), maize(*Zea mays*), jowar (sorghum; *Sorghum bicolor*), bajra (pearl millet; *Pennisetum glaucum*) and other millets (kodo millet: *Paspalum scrobiculatum*, little millet: *Panicum sumatrense*, proso millet: *P. miliaceum*, barnyard millet: *Echinochloa esculenta* and foxtail millet: *Setaria italica*). Henceforth, millets in the text means Jowar, Bajra and other millets combined.

We adopted the definitions of districts with high prevalence of wasting and stunting from district-level malnutrition analysis by Junaid and Mohanty[21], which has considered >46% district-level

stunting prevalence (Z score ≤ -2), and >28% district-level wasting prevalence (Z score ≤ -2) as representing high prevalence districts for stunting and wasting respectively.

We extracted variables of interest from NFHS4 (see variables listed below). For data on cultivation of cereal crops, we used DACNET, a web-based land use statistics information system maintained by the Agriculture Informatics Division of the National Informatics Centre of the Government of India[28].

The following data were extracted to prepare a district-level dataset for analysis[29]:

1. From the 2011 census data, district-wise total and rural population

2. From the NFHS4 data,

   a. using appropriate weights BMI less than 18.5 and short stature less than 145cm of women aged 15–49 years, utilization of Anganwadi, dietary diversity (age 6–23months), women with 10years or more of education, household wealth quintiles (lowest and second), open defecation and rural population.

   b. district-level percentage of wasting and stunting was calculated from the children dataset

   c. percentage of people in household wealth quintiles, open defecation for a given district was calculated from household dataset

3. Various crop data is available in state-wise reports compiled by the Ministry of Agriculture and Farmers Welfare. We extracted district-level area under cultivation of cereals: rice, wheat, maize, ragi, bajra, jowar, and millets (by type as defined above) into a spreadsheet. Data was from the latest state-wise reports available at the time of analysis at DACNET[28] (data for most states ranged for years between 2014–17 except Maharashtra 2002–03, Manipur 2004–05 and Gujarat 2007–08; all data in hectares converted to acres).

Using district names as the common variable in all three datasets, the variables from these three datasets were merged into a single dataset[29]. Any errors due to district spellings and duplicate district names across differing states were handled with caution to ensure proper merging. For each district we estimated the population of poor by multiplying the census figures for population of the district by the proportion of the population in the fourth and fifth wealth quintiles (from NFHS4). This was based on the assumption that subsistence cereal consumption is largely restricted to poor small land-holding farmers[30,31]. Since, Sorghum and other millets are largely cultivated by poor farmers with small land holdings for subsistence purposes with the exception of economically better-off and well-irrigated regions, particularly in northern India[31–33]. District Subsistence Cultivation Quantum (DSCQ) for each district was obtained by multiplying the per capita area (cereal cultivation area in acres/total population) by the proportion of the poor (in the lowest two wealth quintiles as per NFHS) followed by normalising data using logarithmic transformation. The independent

and dependent variables used in scatter plots, bar charts as well as bivariate and multi variable analysis have been enumerated in Table 1.

Analysis

Spatial malnutrition patterns. We assessed overlaps between high prevalence of stunting and/or wasting with cereal cultivation data by generating maps derived from The Database of Global Administrative Areas (GADM)[34]. We merged tabular data (from a spreadsheet file) with geographic data (from a geojson file), chose variables of interest, created map legends dynamically and rendered multiple maps using a custom-built wrapper software written in javascript which internally uses Mapbox GL JS library (version 1.10.0) for rendering maps[35]. Further information on what this software wrapper does and how it works is present in the README file of the source code[36]. As a base layer, DSCQ was shaded using a linear interpolator with manually chosen colour levels for the legend. A transparent layer of outcome variables (stunting and wasting) marked with distinct stripe patterns was overlaid on the base layer for visualizing overlap.

Examining relationship between subsistence millet cultivation, childhood malnutrition and its early onset. For each cereal, we examined its association with district-level prevalence of stunting and wasting and DSCQ (normalised using logarithmic transformation) by linear regression. We also examined the relationship of age with wasting and stunting at the district level by plotting the prevalence percentages by age, from 6 months onwards till 5 years, in both groups of districts, with

high prevalence of stunting and wasting. For multi-variable regression, since cereal cultivation distribution had high variability and was skewed, the logarithm of cultivation area in hectares (with 1 added as a constant), was taken for analysis. For both women 10 or more years of education and toilet facilities, we categorized into binary 1 & 0, with 1 standing for 10 or more years of education and presence of toilet facilities, respectively. For utilization of Anganwadi, the variable was constructed from benefits accrued from Anganwadi centre and frequency of food received during the last 12 months. The information was aggregated at district levels with appropriate sample weights. For dietary diversity this was calculated as per the guide DHS program data guide for dietary diversity.

Results

In all, 107 districts had a high prevalence of stunting (ranging from 46–65% district prevalence) with risk concentrated in poorer states: Uttar Pradesh (31; 29%) Bihar (28; 26%) and Madhya Pradesh (13; 12%) (numbers in brackets are number of districts followed by percentage). Among the 112 districts, those with higher rates of wasting (ranging from 28–47% district prevalence) were in districts with pre-dominantly tribal population in Jharkhand (14; 12.5%), Madhya Pradesh (20; 17.8%), Maharashtra (12; 11%), Rajasthan (11; 9.8%) and Gujarat (10; 9%) (numbers in brackets are number of districts followed by percentage). High stunting areas were concentrated in north and eastern India, whereas areas of high wasting were primarily in central India, which had high prevalence of both childhood stunting and wasting (Figure 1). There were 21 districts with high levels of both stunting and wasting, of which

Table 1. Variables (independent & dependent) used in different analysis.

S.NO	Type of analysis	Independent variable	Dependent variable
1	Maps in Figure 1–Figure 6	DSCQ# of cereals-rice, wheat, jowar, bajra, other millets	High stunting districts (>46%) High wasting districts (>28%)
2	Bivariate analysis (scatter plots) in Figure 2–Figure 6	DSCQ# (normalized using log transformation) of cereals-rice, wheat, jowar, bajra, other millets	Prevalence of stunting and wasting percentage by district
3	Multivariable regression Table 3–Table 4	I. BMI less than 18.5 II. short stature less than 145cm of women aged 15–49 years III. utilization of Anganwadi IV. Dietary diversity (age 6–23months) V. women with 10years or more of education VI. Household wealth quintiles(lowest and second lowest) Vii. open defecation Viii. rural population. IX. Log of district wise area of crops (rice, wheat, jowar, bajra and other millets) in hectares with 1 added as a constant Above variables were controlled for in multivariable regression for prevalence of under 5 stunting and wasting in Table 3 & Table 4	Prevalence of stunting and wasting percentage by district
4	Bar charts Figure 9	Cultivation area in hectare of cereal crops rice, wheat, jowar, bajra, other millets	Percentage of stunting/wasting children under five years of age

#: DSCQ- District Subsistence Cultivation Quantum, calculated for each district by multiplying Per capita Cereal area (Cereal area in acres / Total population of district) with proportion of the poor(in the lowest two wealth quintiles of the district as per NFHS)

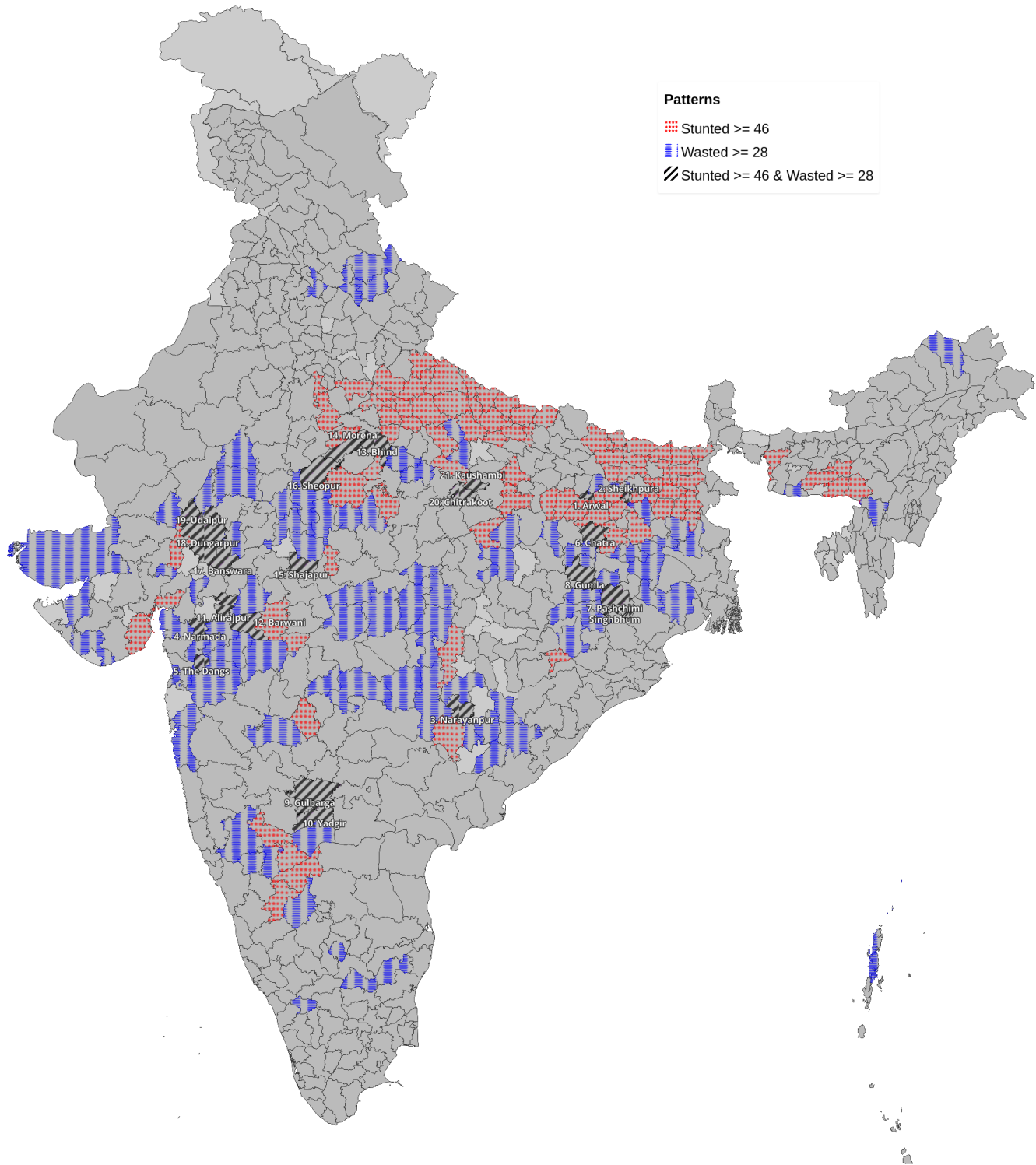**Figure 1. Map of India showing areas with higher prevalence of stunting (>46%) in rows of red dots and those with higher prevalence of wasting (>28%) in columns of blue bars.** Districts with higher prevalence of both stunting and wasting are numbered cross referenced to Table 2 and marked with oblique bars.

16 had millets of any type or maize as either the most dominant (n=6) or second most dominant crop (n=10) (Table 2). Of these 21 districts, there were three from Rajasthan, which had more maize cultivation than any other cereal crop: Udaipur (62 %), Banswara (51%), and Dungarpur (47%).

On examining the district-level patterns of subsistence cultivation of jowar by district overlaid over districts having higher prevalence of stunting and wasting, we find that there is an overlap of districts with wasting alone and those with stunting and wasting with higher DSCQ for jowar (Figure 2). Maps of Bajra show areas with higher DSCQ, particularly in parts of Northern and Western India, with no high stunting or wasting prevalence. Similar maps, separately showing overlap of high stunting and high wasting with per-capita cultivation of jowar, wheat, rice, bajra, maize, and other millets are also available[36]. There is an overlap of districts with high wheat and rice cultivation in the well irrigated Gangetic plains (North and Eastern parts) with stunting (Figure 5 & Figure 6). Cultivation of other millets is scattered throughout the country with an overlap with high prevalence of wasting. The large, irrigated

areas in the Northwest & Central India with high DSCQ of Bajra & Jowar also have higher DSCQ of rice and wheat as seen in Figure 2, Figure 3, Figure 5 & Figure 6.

Overall, increase in cultivation of jowar, bajra and other millets is independently associated with increase in prevalence of both stunting and wasting (see Figure 3 – Figure 5). When the association was examined for individual millets, whereas jowar cultivation did show an association with increase in both stunting and wasting, increase in bajra cultivation was associated only with increase in stunting. Increase in cultivation of other millets was associated with increase in wasting only (a reverse trend was seen with stunting). As expected, there was either no change or decrease seen when we examined association between increase in rice or wheat cultivation with wasting (with an increase in stunting associated with increase in rice or wheat cultivation).

On examining the age of children in districts with higher prevalence of stunting and wasting the following observations are evident, as seen in Figure 7 & Figure 8. In 112 districts with high

Table 2. Districts with high prevalence of stunting(>46%) and high prevalence of wasting(>28%) as per the integrated dataset from NFHS4 and agriculture statistics[29].

S.No	District	State	Major crop1	Percentage	Major crop 2	Percentage	Major crop 3	Percentage
1	Arwal	Bihar	Rice	73.64	Wheat	25.21	Maize	0.9
2	Sheikhpura	Bihar	Wheat	49.37	Rice	49.12	Maize	1.5
3	Narayanpur	Chhatisgarh	Rice	87.17	Other millets	7.66	Maize	3.8
4	Narmada	Gujarat	Rice	59.38	Jowar	27.07	Wheat	7.86
5	The Dangs	Gujarat	Rice	64.86	Other millets	16.98	Jowar	16.60
6	Chatra	Jharkhand	Rice	78.44	Maize	11.7	Wheat	8.99
7	Pashchimi Singhbhum	Jharkhand	Rice	98.89	wheat	0.61	Maize	0.47
8	Gumla	Jharkhand	Rice	88.18	Ragi	6.5	Other millets	2.4
9	Gulbarga	Karnataka	Jowar	86.11	Bajra	5.10	Wheat	3.89
10	Yadgir	Karnataka	Rice	62.26	Jowar	24.99	Bajra	12.35
11	Alirajpur	Madhya Pradesh	Maize	42.4	Wheat	21.99	Bajra	14.42
12	Barwani	Madhya Pradesh	Maize	35.02	Wheat	33.77	Jowar	26.04
13	Bhind	Madhya Pradesh	Wheat	67.57	Bajra	22.00	Jowar	4.06
14	Morena	Madhya Pradesh	Wheat	50.46	Bajra	48.11	Rice	0.44
15	Shajapur	Madhya Pradesh	Wheat	99.44	Jowar	0.53	Rice	0.02
16	Sheopur	Madhya Pradesh	Wheat	66.24	Rice	21.57	Bajra	10.58
17	Banswara	Rajasthan	Maize	51.63	Wheat	34.42	Rice	12.17
18	Dungarpur	Rajasthan	Maize	47.50	Wheat	35.06	Rice	13.19
19	Udaipur	Rajasthan	Maize	62.65	Wheat	29.25	Jowar	2.62
20	Chitrakoot	Uttar Pradesh	Wheat	62.43	Bajra	13.36	Rice	11.23
21	Kaushambi	Uttar Pradesh	Wheat	53.69	Rice	35.95	Bajra	6.33

Figure 2. Plots examining relationship between jowar cultivated with stunting and wasting at district level along with map showing the overlap of jowar cultivated with stunting and wasting. A) Scatterplot of stunting v/s district subsistence cultivation quantum (DSCQ) of jowar by poor **B)** Scatterplot of wasting v/s DSCQ of jowar by poor **C)** Geographic distribution of DSCQ of jowar by poor, stunting > 46 & wasting >28.

Figure 3. Plots examining relationship between bajra cultivated with stunting and wasting at district level along with map showing the overlap of bajra cultivated with stunting and wasting. A) Scatterplot of stunting v/s DSCQ of bajra by poor **B)** Scatterplot of wasting v/s DSCQ of bajra by poor **C)** Geographic distribution of DSCQ of bajra by poor, stunting > 46 & wasting >28.
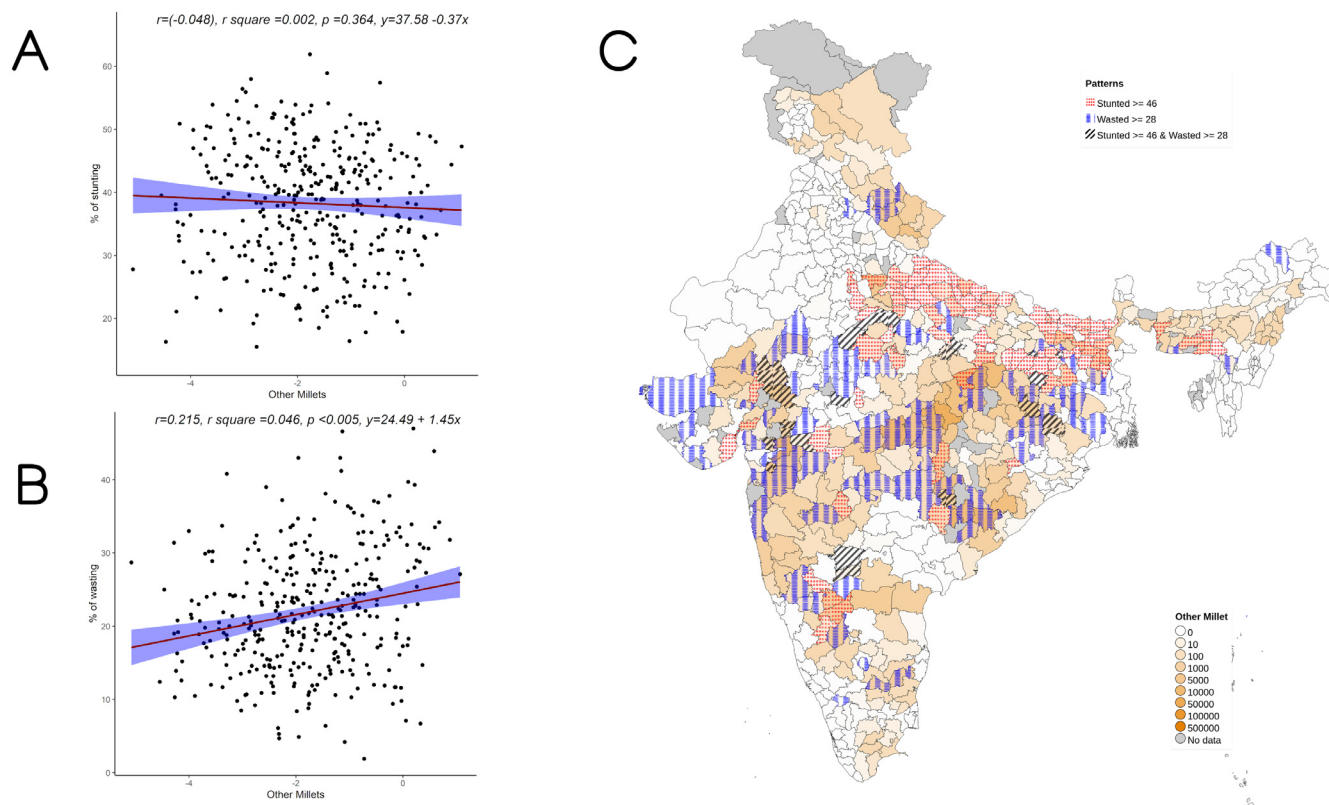
Figure 4. Plots examining relationship between Other millets (kodo millet, little millet, proso millet, barnyard millet and foxtail millet) cultivated with stunting and wasting at district level along with map showing the overlap of Other millets cultivated with stunting and wasting. A) Scatterplot of stunting v/s DSCQ of other millets by poor **B**) Scatterplot of wasting v/s DSCQ of Other millets by poor **C**) Geographic distribution of DSCQ of Other millets by poor, stunting > 46 & wasting >28.

wasting, wasting showed an early onset with highest wasting (40%) at 6 months of age (Figure 7). The age-distribution of stunting was similar for both groups of districts with highest age-specific stunting prevalence at 12 months and a plateau thereafter till five years of age (Figure 7 & Figure 8).

In multiple linear regression the analysis was controlled for confounders which included poor (calculated as belonging to the lower two quintiles of the wealth index), women =>10 years of education, proportion of rural, Open defecation, minimum dietary diversity, utilization of anganwadi, women's short stature (<145 cms) in 15–49 years of age, women's BMI less than 18.5 in the 15–49 years of age group, cultivation of Jowar, Bajra, other millets, rice and ragi and the outcome of interest is under 5 wasting (Table 3) or under 5 stunting (Table 4). In under 5 wasting, statistically significant negative association was seen with proportion of rural, minimum dietary diversity, bajra cultivation and a positive association was seen with women's BMI less than 18.5 as well as open defecation. The cultivation of jowar and other millets was significantly associated positively with wasting, which was consistent with the results of the bivariate analysis seen in Figure 2 & Figure 4 (with r values of jowar & other millets being 0.28 and 0.215

respectively). The R square for the multivariable analysis for under 5 wasting as per model 7 was 0.382 implying that 38% of variance in wasting was attributable to the analyzed factors.

For stunting a significant negative association was seen with women's education of more than 10 years and minimum dietary diversity. A significant positive association was seen with open defecation & women's short stature. Among the crops a positive association was seen with wheat cultivation similar to that seen in bivariate analysis in Figure 6. with an r of 0.151. The R square of multivariable analysis as per model 7 was 0.684 implying that 68% of the variance in stunting was explained by the analyzed variables.

In Figure 9, the area of cereal cultivation among all 640 districts, high stunting only (86) districts and high wasting (112) districts are shown. Figure 9A shows substantially higher cultivation of Jowar, Bajra and other millets in the high wasting districts in comparison to high stunting (only) districts. See contrast in Figure 9B where the cultivated area with respect to rice and wheat indicates greater cultivation of rice and wheat in the 86 high stunting only districts in comparison to the 112 high wasting districts.
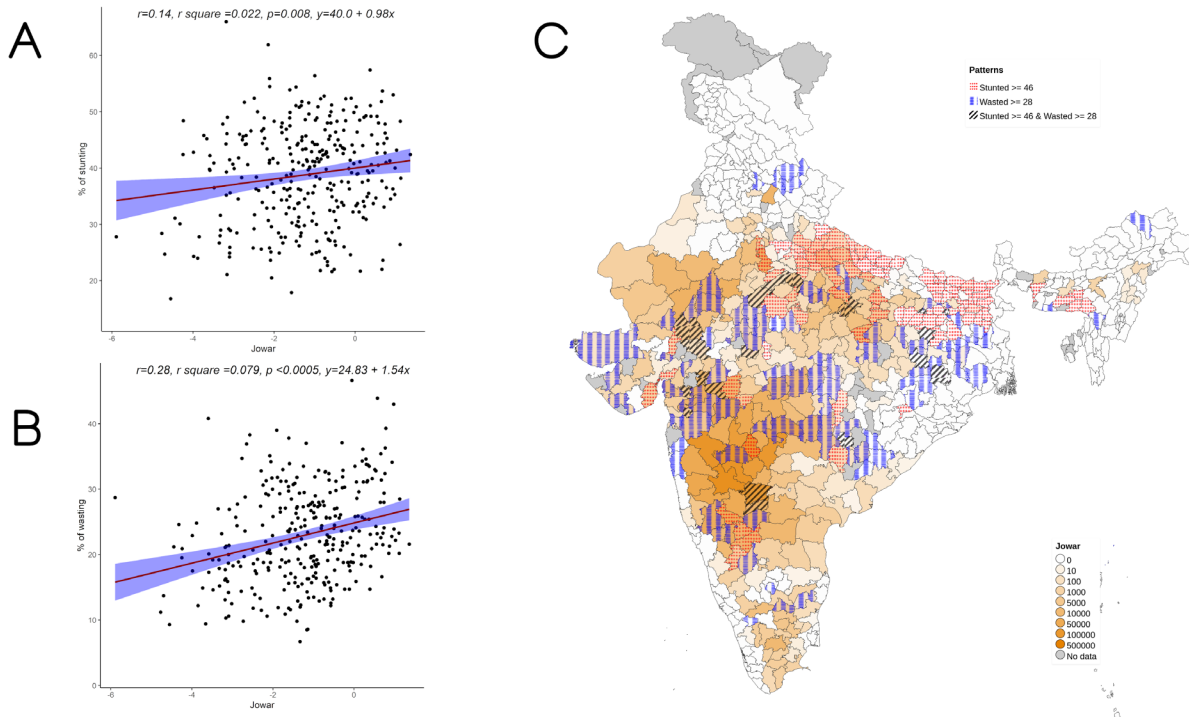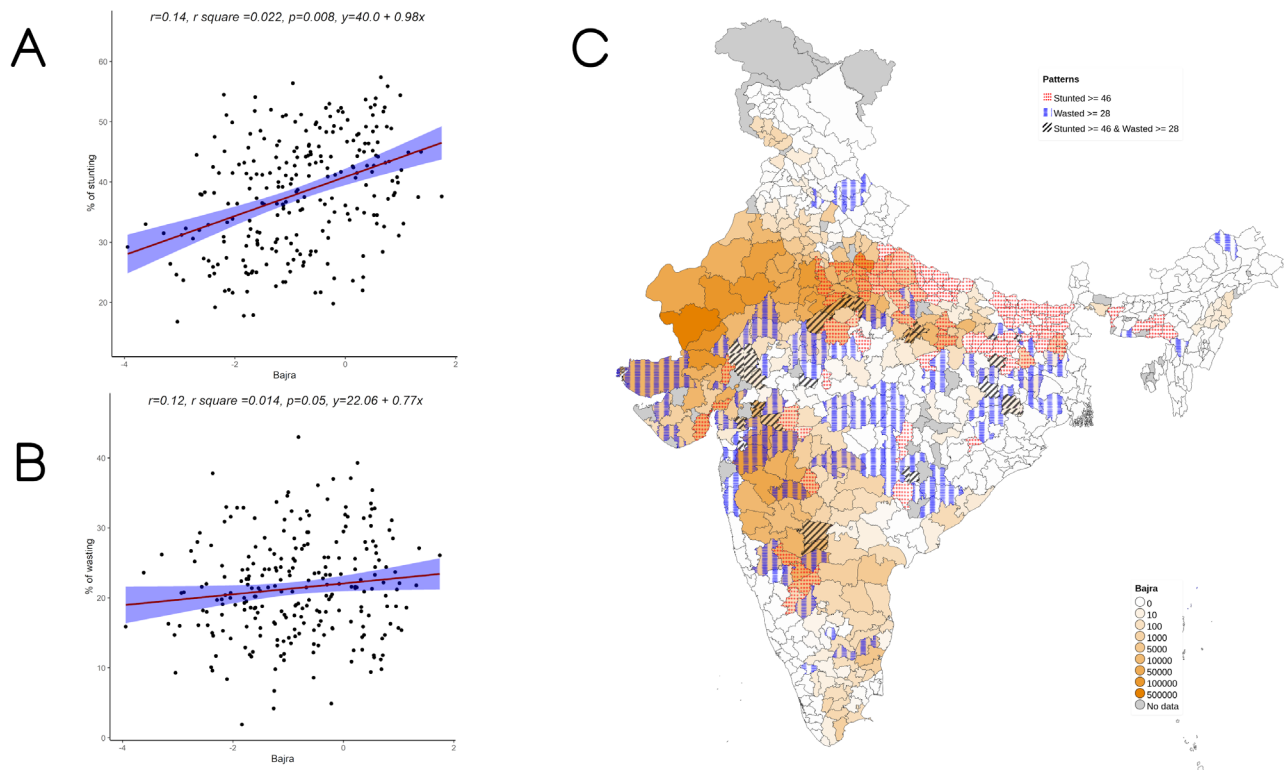
Figure 5. Plots examining relationship between rice cultivated with stunting and wasting at district level along with map showing the overlap of rice cultivated with stunting and wasting. A) Scatterplot of stunting v/s DSCQ of rice by poor **B**) Scatterplot of wasting v/s DSCQ of rice by poor **C**) Geographic distribution of DSCQ of rice by poor, stunting > 46 & wasting >28.

Discussion

The terms stunting and wasting were introduced by John Waterlow in the 1970s to differentiate underweight children with low weight for height, which constitutes wasting and those with low height for age, implying stunting[37]. Stunting and wasting differ in terms of body composition with greater loss in muscle mass and fat in the latter. Adiposity also indirectly affects stature; periods of wasting are followed a few months later by stunting in the same individual, probably mediated by Leptin[38]. The phenomenon of both stunting and wasting together has been named concurrent WaSt[39]. However, most stunting is unrelated to wasting as several populations have high prevalence of stunting in the absence of previous wasting[5]. Gain in height requires skeletal and lean body mass growth with need for additional resources including micronutrients such as Calcium, Magnesium, Phosphorus, Sulphur, Copper and Vitamins C, D and K[38,40]. Absence of the above micronutrients and vitamins can cause children to become stunted with or without adiposity depending on provision of other nutrients[40]. In either wasting or stunting, children are at risk of higher mortality with highest risk being those having both together[38].

Age and geographical patterns of stunting and wasting
On seeing the age profile of children with wasting and stunting (Figure 7 and Figure 8) in the 112 high wasting prevalence and 107 high stunting prevalence districts, wasting at 6 months is higher (40% prevalence) in the high wasting districts, and lower (30% prevalence) in the latter. The mean prevalence of wasting at 6 months for the 640 districts of the country as per the NFHS4 dataset was 31.9%. Prevalence of stunting at 6 months was 20% in both groups of districts which was similar to the national prevalence[22].

A study analysing severe wasting among Indian infants less than 6 months of age using NFHS 4 dataset showed highest prevalence of severe wasting in the relatively prosperous Maharashtra and Gujarat (over 20%), in comparison to less than 15% prevalence in Uttar Pradesh and Bihar which are poorer[41,42]. In a multi-country study utilizing 20 demographic and health survey datasets, wasting under 6 months of age was highest in India (30.5% according to NFHS3 data) followed by Burkina Faso (25%), Nigeria (24.1%), Niger (19.7%) and Mali (18.2%)[43]. Like the states of Maharashtra and Gujarat for India, the above countries too are among the highest millet producing regions in the world[44,45]. We examined and verified this pattern using a composite dataset with FAOSTAT data on agricultural production and prevalence of WaSt, stunting & wasting and wasting at 6 months[45].

Martorell *et al.*[46] compared differences in age patterns of stunting and wasting between India and Guatemala, utilizing NFHS 3 and Reproductive health survey 2008-9 respectively.
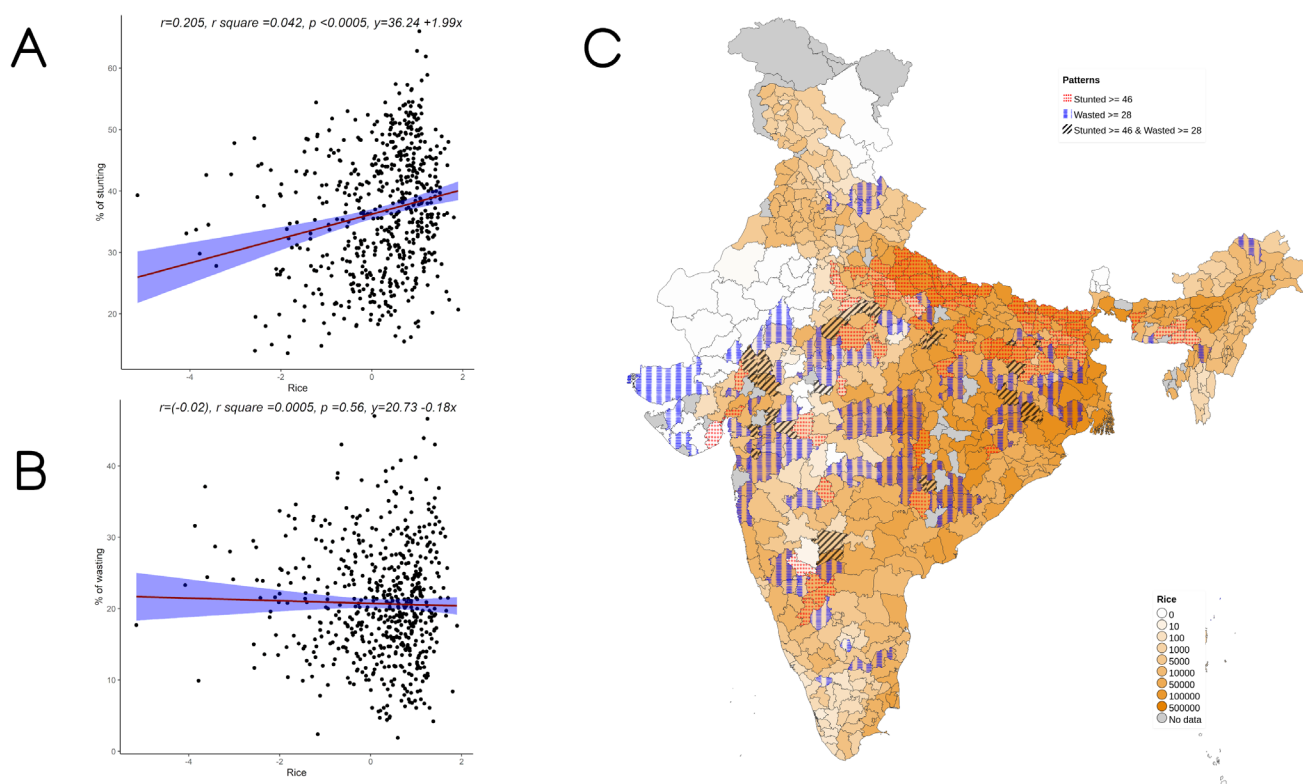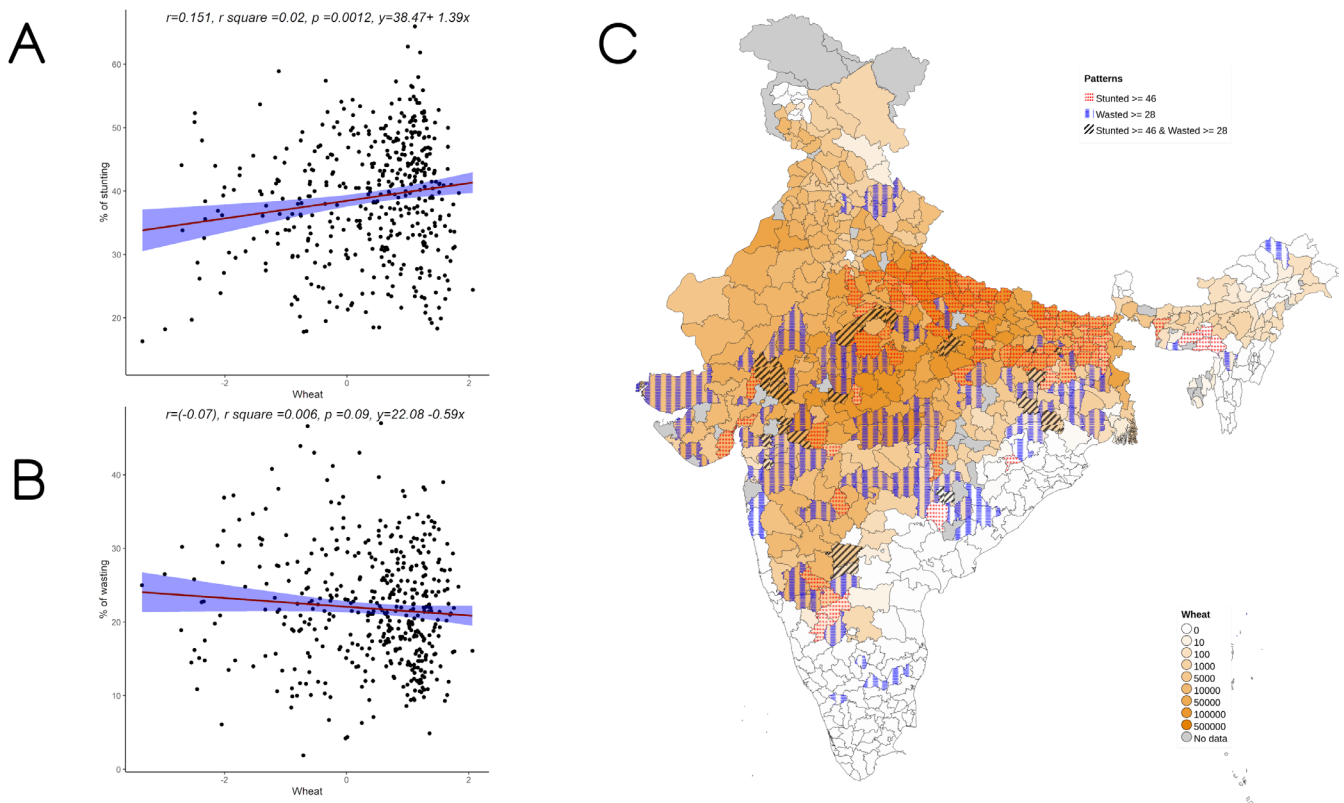
Figure 6. Plots examining relationship between wheat cultivated with stunting and wasting at district level along with map showing the overlap of wheat cultivated with stunting and wasting. A) Scatterplot of stunting v/s DSCQ of wheat by poor **B**) Scatterplot of wasting v/s DSCQ of wheat by poor **C**) Geographic distribution of DSCQ of wheat by poor, stunting > 46 & wasting >28.
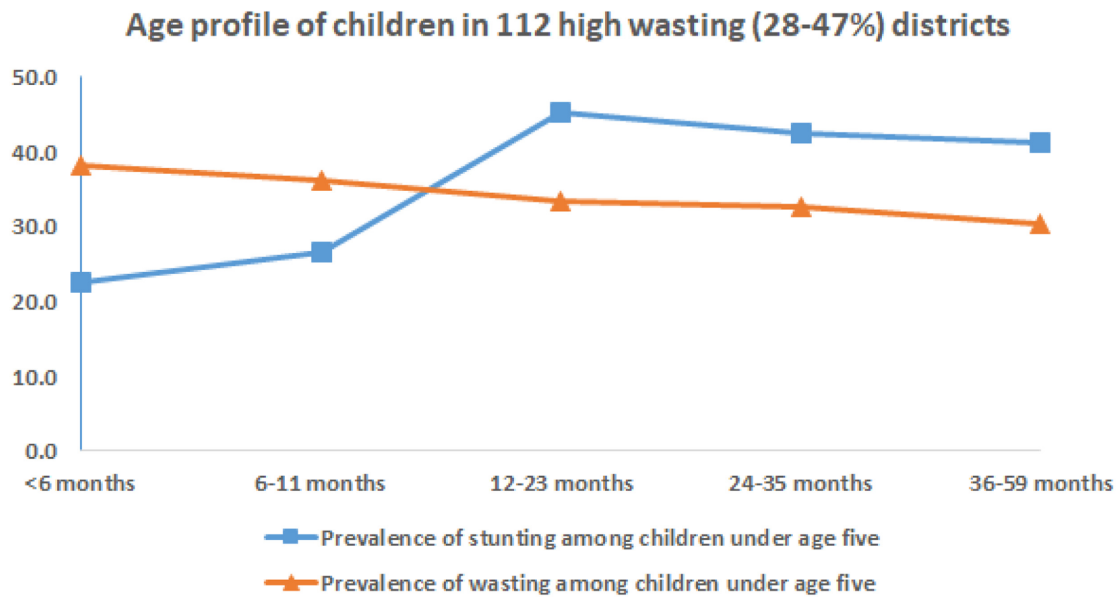
Figure 7. Age profile of stunted and wasted children in 108 high wasting (28–47%) districts.
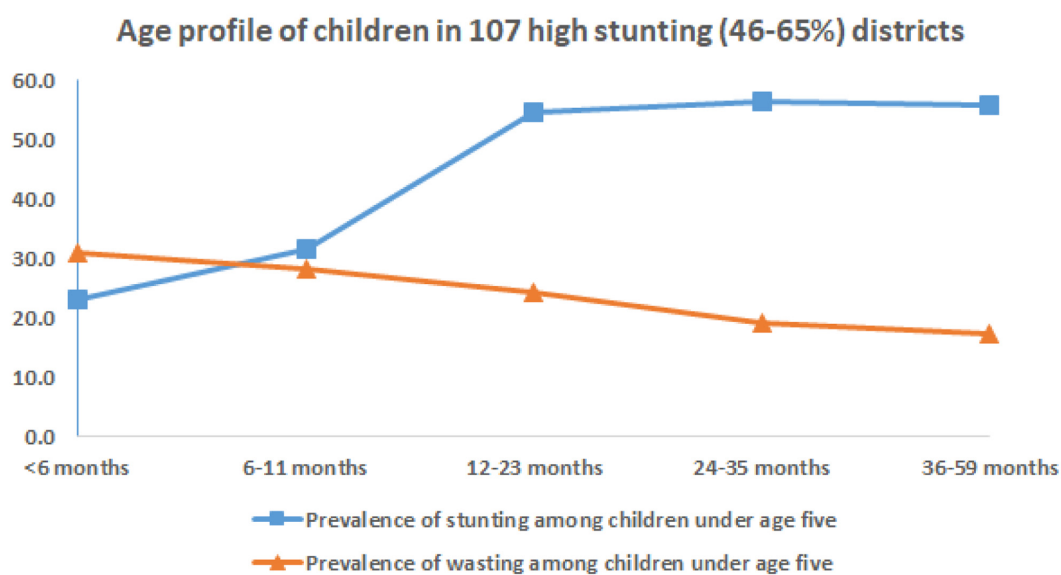
Figure 8. Age profile of stunted and wasted children in 112 high stunting (46–67%) districts.

Table 3. Multivariable Regression models exploring the association between poor, women =>10 years of education, Proportion of rural, Open defecation, Minimum dietary diversity, Utilization of anganwadi, Women's short stature (<145 cms) in 15–49 years of age, Women's BMI less than 18.5 in the 15–49 years of age, cultivation of Jowar, Bajra, other millets, rice and ragi and the outcome of interest is % of under 5 wasting.

Variables	Model-1	Model-2	Model-3	Model-4	Model-5	Model-6	Model-7
	Unadjusted coefficients (95% CI)	Adjusted coefficients (95% CI)	Adjusted coefficients (95% CI)	Adjusted coefficients (95% CI)	Adjusted coefficients (95% CI)	Adjusted coefficients (95% CI)	Adjusted coefficients (95% CI)
Poor	0.073***	-0.029				0.005	-0.025
	(0.050 - 0.095)	(-0.072 - 0.014)				(-0.036 - 0.047)	(-0.072 - 0.022)
women =>10 years of education	-0.074***	-0.007				0.016	0.016
	(-0.105 - -0.042)	(-0.049 - 0.035)				(-0.026 - 0.058)	(-0.027 - 0.058)
Proportion of rural	0.030*	-0.042*				-0.075***	-0.058***
	(0.002 - 0.058)	(-0.075 - -0.008)				(-0.107 - -0.042)	(-0.092 - -0.025)
Open defecation	0.125***	0.157***				0.120***	0.070***
	(0.106 - 0.145)	(0.129 - 0.185)				(0.092 - 0.148)	(0.039 - 0.101)
Minimum dietary diversity	-0.168***		-0.173***			-0.119***	-0.056**
	(-0.206 - -0.129)		(-0.210 - -0.136)			(-0.157 - -0.080)	(-0.099 - -0.014)
Utilization of anganwadi	0.093***		0.098***			0.088***	0.046**
	(0.064 - 0.122)		(0.070 - 0.125)			(0.061 - 0.115)	(0.016 - 0.075)
Women short stature	0.026						
	(-0.073 - 0.125)						
Women BMI less than 18.5	0.372***			0.372***			0.211***
	(0.321 - 0.422)			(0.321 - 0.422)			(0.135 - 0.287)

Variables	Model-1	Model-2	Model-3	Model-4	Model-5	Model-6	Model-7
	Unadjusted coefficients (95% CI)	Adjusted coefficients (95% CI)	Adjusted coefficients (95% CI)	Adjusted coefficients (95% CI)	Adjusted coefficients (95% CI)	Adjusted coefficients (95% CI)	Adjusted coefficients (95% CI)
Jowar	0.620***				0.670***		0.326***
	(0.482 - 0.757)				(0.500 - 0.840)		(0.163 - 0.488)
Bajra	0.228**				-0.306***		-0.194*
	(0.085 - 0.371)				(-0.481 - -0.131)		(-0.366 - -0.022)
Wheat	0.363***				0.365***		0.135
	(0.243 - 0.483)				(0.243 - 0.488)		(-0.003 - 0.272)
Other millets	6.689***				4.299***		3.372***
	(4.472 - 8.905)				(2.185 - 6.412)		(1.404 - 5.341)
Rice	0.052						
	(-0.128 - 0.233)						
Ragi	0.490***				0.488***		0.237*
	(0.296 - 0.684)				(0.303 - 0.674)		(0.057 - 0.418)
Observations	640	640	640	640	640	640	640
R-squared		0.218	0.167	0.247	0.221	0.299	0.382

*** p<0.001, ** p<0.01, * p<0.05

Table 4. Multivariable Regression models exploring the association between poor, women =>10 years of education, Proportion of rural, Open defecation, Minimum dietary diversity, Utilization of anganwadi, Women short stature (<145 cms) in 15–49 years age, Women's BMI less than 18.5, cultivation of Jowar, Bajra, other millets, rice and ragi and the outcome of interest is % of under 5 stunting.

Variables	Model-1	Model-2	Model-3	Model-4	Model-5	Model-6	Model-7
	Unadjusted coefficients (95% CI)	Adjusted coefficients (95% CI)	Adjusted coefficients (95% CI)	Adjusted coefficients (95% CI)	Adjusted coefficients (95% CI)	Adjusted coefficients (95% CI)	Adjusted coefficients (95% CI)
Poor	0.248***	0.052*				0.062**	0.031
	(0.225 - 0.271)	(0.010 - 0.093)				(0.023 - 0.102)	(-0.014 - 0.076)
women =>10 years of education	-0.335***	-0.197***				-0.137***	-0.104***
	(-0.367 - -0.304)	(-0.237 - -0.156)				(-0.177 - -0.097)	(-0.143 - -0.065)
Proportion of rural	0.164***	-0.044**				-0.030	-0.012
	(0.130 - 0.198)	(-0.077 - -0.012)				(-0.061 - 0.001)	(-0.043 - 0.019)
Open defecation	0.235***	0.146***				0.132***	0.086***
	(0.214 - 0.257)	(0.119 - 0.173)				(0.106 - 0.159)	(0.057 - 0.114)
Minimum dietary diversity	-0.339***		-0.336***			-0.149***	-0.082***

Variables	Model-1	Model-2	Model-3	Model-4	Model-5	Model-6	Model-7
	Unadjusted coefficients (95% CI)	Adjusted coefficients (95% CI)	Adjusted coefficients (95% CI)	Adjusted coefficients (95% CI)	Adjusted coefficients (95% CI)	Adjusted coefficients (95% CI)	Adjusted coefficients (95% CI)
	(-0.384 - -0.294)		(-0.381 - -0.292)			(-0.186 - -0.113)	(-0.121 - -0.043)
Utilization of anganwadi	-0.058**		-0.048**			-0.068***	-0.038**
	(-0.096 - -0.019)		(-0.081 - -0.015)			(-0.093 - -0.042)	(-0.065 - -0.011)
Women short stature	0.902***			0.612***			0.474***
	(0.796 - 1.007)			(0.512 - 0.712)			(0.376 - 0.571)
Women BMI less than 18.5	0.571***			0.427***			0.065
	(0.511 - 0.631)			(0.368 - 0.487)			(-0.005 - 0.134)
Jowar	0.511***				0.265*		0.079
	(0.328 - 0.694)				(0.053 - 0.476)		(-0.072 - 0.230)
Bajra	0.467***				-0.052		0.146
	(0.285 - 0.648)				(-0.274 - 0.170)		(-0.011 - 0.304)
Wheat	0.964***				0.901***		0.315***
	(0.825 - 1.103)				(0.749 - 1.052)		(0.191 - 0.439)
Other millets	2.039						
	(-0.875 - 4.954)						
Rice	0.420***				0.361***		-0.102
	(0.191 - 0.650)				(0.153 - 0.570)		(-0.258 - 0.055)
Ragi	-0.222						
	(-0.475 - 0.030)						
Observations	640	640	640	640	640	640	640
R-squared		0.557	0.266	0.473	0.246	0.617	0.684

*** p<0.001, ** p<0.01, * p<0.05

India had much higher levels of wasting and similar levels of stunting with respect to Guatemala[46]. This comparison was triggered by the use of WHO growth charts since 2007 in place of the older NCHS charts. The WHO growth charts had values of healthy breast fed babies (having relatively faster growth in the first 6 months than bottle fed babies), whereas NCHS represented bottle fed babies[46]. Switching over to the WHO values resulted in lower weights for length at less than 6 months (and much higher values of wasting) among Indian babies, majority of whom paradoxically are breast fed. The paper also reported much higher levels of low BMI and anaemia in mothers as well as higher low birth weights in India when compared to Guatemala. The authors acknowledged absence of a satisfactory explanation apart from poor status of women, poor dietary quality, poor nutritional parameters or the "thin fat Indian baby" phenotype[46,47]. On examining the composite FAOSTAT dataset we created, Guatemala has maize as

the top crop in contrast to India[45]. Interestingly, like Guatemala, high stunting and lower wasting is also seen in Burundi and Timor-Leste which also have maize as top staple cultivated. Probably, proximate dietary factors hold the clues to these differences in spatiotemporal prevalence patterns of malnutrition between geographies within India and between nations.

Ecogeographic patterns of clustering in India

There appears to be a discernible clustering of districts with stunting distinct from wasting in the country (Figure 1). Greater stunting prevalence is mostly seen in the populous Northern states, which account for more than 80% stunted children in the country[42]. High stunting prevalence was seen in Bihar and Uttar Pradesh at prevalence rates of 48.2% and 46.3% respectively[42]. Areas with high prevalence of wasting are seen predominantly clustered in Central and Western Indian states of Gujarat, Maharashtra, Jharkhand, Madhya Pradesh and
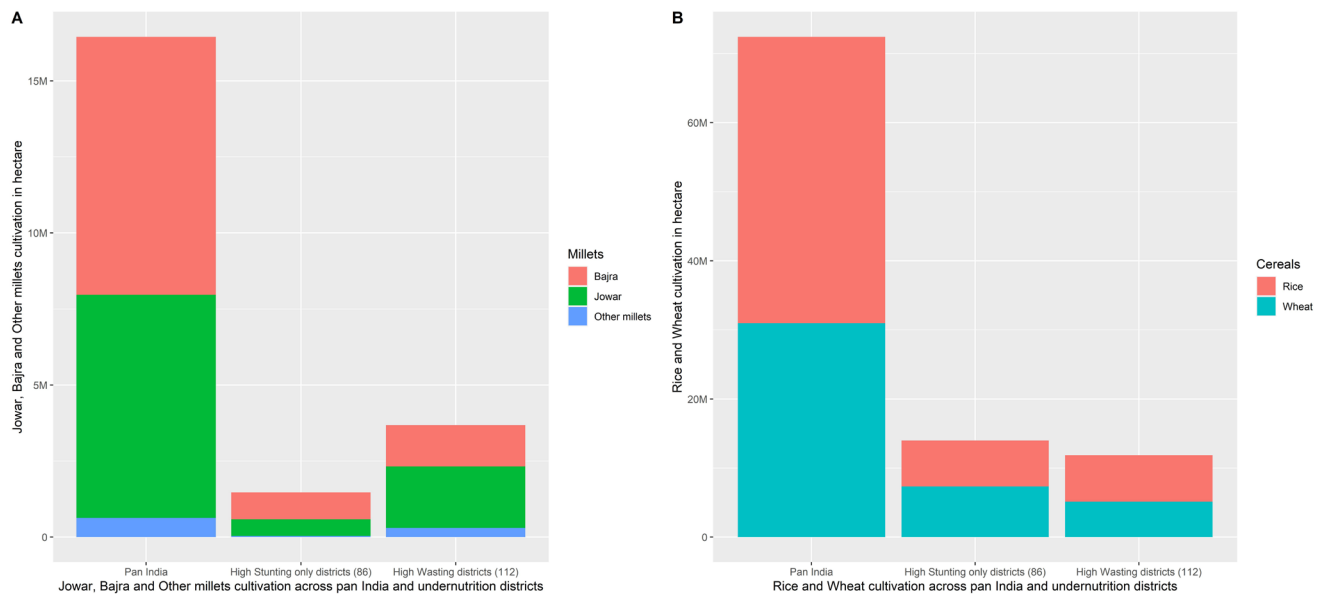
Figure 9. A. Cultivation of Jowar, Bajra and Other millets all over India, high stunting (only) districts and high wasting districts. **B**. Cultivation of rice and wheat all over India, high stunting (only) districts and high wasting districts.

Rajasthan with greater dependence on rainfed agriculture[48]. In India, child malnutrition prevalence, particularly stunting, has been explored spatiotemporally at household, village, block/*taluk*, district, parliament and legislative constituency levels[49–54]. It has been studied with respect to clustering related to poverty, wealth inequality, low birth weight, maternal stature or low BMI[55–59]. However, these studies do not satisfactorily explain the contrasting clustering patterns of wasting vis-à-vis stunting across districts and states.

Cesar Victora in 1992 demonstrated that stunting and wasting are not necessarily co-occurring to a similar extent across geographies; regions with comparable stunting may in fact report several fold variations with corresponding wasting prevalence indicating diverse pathways to these two conditions[60,61]. Frongillo *et al.* analysed these differences between regions with stunting and wasting and found that they were eliminated when social, demographic and economic factors were taken into account[61]. Both Victora and Frongillo *et al.* studies concluded that stunting and wasting could have different causes[60,61]. However, when comparing India and Bangladesh with respect to wasting, Frongillo *et al.* concluded that India had higher than expected and Bangladesh, on the contrary, had a lower than expected prevalence. They conclude that other factors not incorporated in their study possibly explained this difference[61]. More than two decades later the differences with respect to under 5 wasting between India and its South Asian neighbours have remained persistently high, with India recording 21.04 % (as per NFHS4) wasting while others have figures ranging from 9.48% to 14.36%[4].

Individual and geographic co-occurrence patterns of stunting and wasting

Presence of both stunting and wasting concurrently is called WaSt and its wide prevalence has been increasingly recognised recently[39,62–65]. In our study 21 districts were identified to have high prevalence of both stunting and wasting (Table 2). This is not WaSt *per se* but districts/populations reporting high prevalence of both *separately*. These 21 districts were from the high prevalence central and north-western states of Gujarat, Madhya Pradesh, Rajasthan and Jharkhand with only two each from Uttar Pradesh and Bihar. On examining the staple cereals cultivated in these districts, majority either cultivated Maize, Jowar (sorghum), other millets or Bajra (pearl millet) as one among the top two crops (Table 2). However, among the four Uttar Pradesh and Bihar districts, one cultivated Bajra (Chitrakoot) as the second common crop but the others were predominantly rice and wheat cultivators.

Similar to the Indian cultivation patterns, a spate of recent studies on areas with WaSt also show predominant millet and sorghum cultivation. A prevalence survey of Karamoja region in Uganda, with Sorghum and maize as staple, showed a WaSt prevalence of 5%[65,66]. A recent study of children under 2 years in Madaraounfa in rural Niger, also with millet and sorghum as staple, showed 80% stunting, 14% wasting and 12% having concurrent wasting and stunting[62]. Garenne *et al.* studied concurrent wasting and stunting among under 5 children in Niakhar, Senegal, which too has millet as staple[39,67]. Concurrent WaSt was found prevalent to the tune of 6.2% with a peak at 18 months in the study[39]. A meta-analysis of prevalence

of WaSt in 84 countries showed prevalence above 5% in 9 countries with three from Asia (India, Timor-Leste and Yemen) and six from sub-Saharan Africa (Niger, Djibouti, Burundi, Chad, Sudan and South Sudan)[63]. On assessing them for crop cultivation or production, the highest ranking crops by area or production were Millet or Sorghum for Niger, Chad, Sudan, South Sudan and Yemen[45]. For Djibouti, Burundi and Timor-Leste the top crop produced was Maize. India had by far the highest production of Sorghum and millet among all countries in the group, but these cereals trailed behind the figures for rice and wheat[45]. We hypothesise that subsistence cereal cultivation in areas with high wasting and its use as staple particularly by pregnant and breast feeding mothers could account for this pattern.

The longitudinal study on WaSt of four decades of growth data in rural Gambia showed that wasting earlier increased the odds to stunting later after 3 months by a factor of 3.2[64]. In contrast, the odds to stunting associated with wasting after 3 months, was 1.6[64]. Hence, the stunted and wasted districts are more likely to have wasted children who later developed stunting. So we analysed the differences in quantity of crops cultivated between the high prevalence of wasting and high prevalence of stunting (only) districts, after excluding the 21 stunting and wasting districts from the list of high prevalence of stunting districts. The bar charts (Figure 9A) clearly show the greater cultivation of coarse cereals (Bajra, Jowar and other millets) in the 112 high wasting districts in comparison to the 86 high stunting (only) districts.

Cereal-based diets are known to be associated with malnutrition and have been linked to Pellagra especially diets exclusively dependent on Sorghum and maize[16,68–70]. Our results linking district-level wasting prevalence with cultivation of Jowar (Sorghum) and Other millets, and district-level stunting with wheat (rice cultivation did not significantly affect either stunting or wasting prevalence at district level) in the background of the discussion above indicate the need for household-level type of cereal consumption data to explain the malnutrition patterns. On the other hand, our study shows a negative association of bajra with under 5 wasting in Punjab and Haryana which needs explaining, given the overall pattern of district level wasting association with millet cultivation. Unlike other high millet cultivating regions which are semi-arid and practice rain-dependent agriculture, these states on the other hand are well irrigated and possibly grow Bajra for non-food purposes (feed, fodder and fine grain alcohol). This is estimated to be to the tune of 60% of total production of the country[31]. The significant negative association of wheat with stunting could be due to reduced zinc intake linked to high phytates in wheat[71–73].

The dietary diversity scores and maternal education levels are expectedly negatively associated with prevalence of stunting and wasting like reported earlier[53,74–77]. Negative association was seen with rural residence for wasting which is contrary to the results of Harding et al[4]. This could be a result of our choice of variables which modified the effect of rural residence. However, in a study comparing undernutrition in urban poor neighborhoods with rural areas in Maharashtra, wasting

prevalence was higher in urban neighborhoods[78]. Low women's BMI was expectedly positively associated with under 5 wasting which is consistent with several other studies[21,79–81]. Similarly women's short stature was positively associated with stunting as reported earlier[80–83]. Open defecation and poverty too has been shown in various studies to be associated with under 5 wasting and stunting[21,57,59,75,76]. However, in our study on adjusting for multiple variables, the association with poverty for both stunting and wasting was not statistically significant. A study done among Anganwadi centres (AWC) in North East India documented higher rates of stunting, wasting and underweight among 510 randomly selected children suggesting greater food insecurity among those utilizing AWCs[84]. Food insecurity and access sought by food insecure families to AWC services could explain the positive association seen in our analysis with utilization of AWCs for under 5 wasting.

Food processing and nutrient availability of cereals

In India both Sorghum and pearl millet are consumed by milling followed by bran removal and dry heating[85]. This is known to adversely affect cereal protein availability, particularly in Sorghum, by Maillard reaction and Lysino-alanine like product formation[86]. However, soaking overnight and boiling to 90 degree C can yield high percentage availability of available lysine for both pearl millet and Sorghum[87,88]. Unlike the practices in India, Maize is consumed in Latin America after nixtamalization[89]. Indeed, cereal processing practices could contribute to high stunting and wasting seen in some districts with maize as staple (Table 1).

The lower lysine scores of coarse cereals could be the key to higher levels of wasting and stunting in areas where they are staple. This could be mediated by molecular mechanisms[90]. On comparing the digestible indispensable amino acid scores (DIAAS) of rice and wheat vis-à-vis millets and Sorghum, Lysine scores are higher in the former (table by Hans Henrik Steyn reproduced in our composite dataset)[45]. With regards to micronutrient availability coarse cereals have higher micronutrient content than rice and wheat[45,68]. However, there is a known association of Jowar and Maize with Pellagra[16,69]. Clearly, there is marked variability in nutritional availability of glucose, amino acids, zinc, iron and other micronutrients among cereals[45,70–73]. This warrants closer scrutiny of the dietary matrices of populations whose diet is mainly cereal based. See for instance, the nutritional benefit from ready to use therapeutic foods (RUTF) in children with acute malnutrition. RUTF formulations made from soya-maize-sorghum (SMS) show similar efficacy for malnutrition only when they are supplemented with free amino acids[91–93]. While millets and Sorghum's lower glycaemic indices are suitable for elderly users their lower provision of amino acids and glucose could be detrimental for growth during the first 1000 days of life[90,94,95]. This could be mediated by protein kinases, the mechanistic target of Rapamycin (MTORC1) or General control nonderepressible 2 (GCN2) as seen in the placenta in the case of intra-uterine growth retardation[95]. Of these, MTORC1 has also been postulated as a possible cellular mechanism for stunting[90,95–97]. A plausible hypothesised pathway on mechanisms of stunting and wasting through cereal based diets has been separately prepared[45].

Study limitations

An important limitation of our analysis is the limited fine scale data on food grain consumption (as opposed to cultivation) which would have allowed for confirmation of our hypothesis at household level. One of the reasons for this is that the NFHS and other country/regional demographic health surveys record cereal consumption without paying attention to type of cereal. Moreover, consumption is likely to be guided by choice and availability through food subsidy or open-market access to other cereals and food staples, apart from those cultivated for subsistence. Our analysis indicates the need for NFHS and demographic health surveys worldwide to include type of cereal consumption to gain better understanding of pathways to malnutrition. The use of cereal cultivation as a proxy for consumption too is likely to have introduced substantial errors, as some of the cultivation is for non-human use. Factors leading to lack of dietary diversity like poverty, prevalence of infections like worm infestations or tuberculosis and other possible unaccounted confounding factors could also be contributing to these patterns. The data on availability of nutrients from cereal consumption from nutritional assays (stable isotope-based) is also meagre to the best of our efforts in reviewing peer-reviewed evidence-base. Such data from cereal consumption could help in linking the dietary matrix to the effects described above.

Conclusion

Higher wasting and stunting prevalence among children in India has an ecogeographic pattern with plausible links of pre-dominant millet consumption to higher prevalence of wasting. The type of cereal consumed should be incorporated in NFHS and all global demographic surveys to enable better assessment of nutritional intake. State of the art research in nutrient sensing should be integrated with agriculture, food science, delivery systems and dietary matrix for translational benefits to accrue to the wider population.

Data availability

Underlying data

Figshare: Dataset used to assess relationship between millet cultivation and malnutrition patterns in India at district level. https://doi.org/10.6084/m9.figshare.12236789.v2[29]

This project contains the following underlying data:

- malnutrition_dataset_for_publication.xlsx (Dataset used for analysis described in the paper)

- Malnutrition and millets – India – DACNET NFHS 4.docx (Word document explaining how the dataset was prepared)

Extended data

Figshare: Plots examining relationship between type of millet cultivated with stunting and wasting at district level along with map showing the overlaps for each type of millet with stunting and wasting. https://doi.org/10.6084/m9.figshare.12206135.v6[98]

This project contains the following extended data:

- Malnutrition_millets and malnutrition.pdf (PDF file with panel of seven plots and maps, each showing relationship between type of millet cultivated with stunting and wasting at district level and the corresponding map showing the overlaps of each type of millet with stunting and wasting)

Figshare: Plots examining relationship between low BMI and short stature in women 15–49 with stunting and wasting at district level along with map showing the overlaps for each type of millet with low BMI and short stature in women (15–49). https://doi.org/10.6084/m9.figshare.12206264.v4

This project contains the following extended data:

- malnutrition_bmi_short_status.pdf (PDF file with panel of seven plots and maps, wach showing relationship between low BMI and short stature in women 15–49 with stunting and wasting at district level alogn with maps showing overlaps for each type of millet with low BMI and short stature in women (15–49))

Data are available under the terms of the Creative Commons Attribution 4.0 International license (CC-BY 4.0).

Software availability

Source code available from: https://gitlab.com/asdofindia/malnutrition-crops-maps

Archived source code at time of publication: http://doi.org/10.5281/zenodo.5976145[36]

License: MIT license

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Open Peer Review

Current Peer Review Status: ✓ ✗ ? ?

Version 4

Reviewer Report 13 June 2022

https://doi.org/10.21956/wellcomeopenres.19560.r50740

? **Ilana Cliffer** (iD)

Harvard T.H. Chan School of Public Health, Boston, MA, USA

Overall comments:
This is a creative paper that uses district-level data to link area used for cereal cultivation of different types of cereals to wasting or stunting prevalence, using cereal cultivation area as a proxy for cereal consumption. The findings are interesting and relevant, however, the authors do not present a clear message as to the implications of their descriptive findings, nor do they sufficiently discuss the limitations of such ecological analyses based on many assumptions about the relationship between cereal cultivation and consumption.

Two major points are missing, in my opinion:

Is it possible that areas that cultivate one cereal over another may also have similar climatological features (temperature, precipitation) that impact the soil quality and type and also the prevalence of infectious disease? While I think the DSCQ is an interesting and clever metric, it is hard to separate any potential effects of cereal consumption from the underlying reasons why some areas cultivate one grain in favor of the other, and whether these factors could be related to other determinants of nutritional status. This merits discussion and exploration in this paper.

The authors need to spend some time explaining why cereals were the only crops/dietary factors examined. No mention at all is made of vegetables, or other more nutrient-dense crops. What about livestock keeping? Animal-source foods? It seems impossible to draw conclusions even about associations with type of cereal without considering other dietary factors that may be equally or even more important.

Several more specific comments follow, as well:

Abstract
    1. Background
           1. Does the high prevalence of maternal malnutrition and child malnutrition include only undernutrition, or also overweight/obesity? Please clarify or use the term

undernutrition if that is more accurate.

2. Rural India has disproportionately high levels of child malnutrition compared to where? Urban India? Rest of the world?

3. Stunting and wasting are not determinants of child malnutrition, they are indicators

4. The background section of the abstract needs to explain the motivation behind the study better. It goes from stating that there is a high burden of malnutrition that is not evenly geographically distributed to talking about how cereals make up the bulk of protein intake, but doesn't state the proposed connection between the two. It needs to be clarified why the authors are mentioning cereals as a proportion of the diet.

2. Methods
   1. Methods section of abstract does not mention statistical techniques used – this would be helpful to mention

   2. Please also add sample size to methods (how many districts are included?)

   3. State in the methods of the abstract how under-5 stunting and wasting prevalence was disaggregated by age, since this comes up in the results

   4. Please also state in the methods of the abstract what cereals are analyzed (millets, wheat, etc.) or at least state that the investigation is of the relationship between prevalence of undernutrition and area under cultivation of several different cereals.

3. Results:
   1. Districts with higher prevalence of wasting – please define what this means. Would be useful to include a few specific statistics. Perhaps the range of prevalence in the highest vs lowest prevalence regions?

   2. Was the prevalence of wasting only higher among infants of 6 months old in districts with higher prevalence of wasting, or was it higher at all age ranges and especially at 6 months? Please make sure this is clear. Also what age ranges is this compared to? (All other children under 5?)

   3. When comparative phrases such as "stronger" or "higher" are used, it is hard to interpret without knowing what the comparison is. For example, the phrase stating that wasting prevalence has a stronger association seen for jowar and other millets, it would be helpful to know what this is compared to. Either that, or make the statement absolute.

   4. "District level stunting was associated with higher…". Does this mean higher district level stunting was associated with higher district level cultivation of wheat?

   5. Does higher cultivation of cereals means more area under cultivation? It could be better to use more specific terms for what higher cultivation means.

6. Saying wasting was positively associated with women's body mass index is confusing, because what you actually mean is with women's body mass index <18.5, correct? Please specify, otherwise it looks like in districts where women's BMI was higher, there was *more* child wasting, which is not the case.

4. Conclusions

○ It seems to me that prior to a statement about what future studies are needed, the authors should summarize the main findings and their implications.

Introduction

1. Overall, the focus of the paper/study is not very clear, nor is the motivation to do the study. This needs to be more clearly defined and explained in the introduction. One thing that could help is if the introduction had a more logical organizational flow. For example, the authors may first want to discuss the high prevalence of undernutrition in South Asia (or India) compared to other regions (what is currently the last paragraph of the first section of the intro), then discuss its uneven distribution across the different districts (currently the second paragraph under the "subsistence farming and millet dependence" sub-heading, and phrase about hot-spots of low women's BMI), and then discuss potential reasons for these disparities (differential cereal availability - the first paragraph in the "subsistence farming and millet dependence" sub-heading and the last paragraph about geospatial heterogeneity). Then the authors can state the research problem and specific research question in the last paragraph, and include a phrase about why answering this question will be beneficial.

2. The discussion of low birth weight in the first paragraph of the introduction seems out of place to me. Unless a link is made that explicitly discusses intergenerational transmission, talk of birth weight can be left out of the introduction since birth weight is not included as an outcome of interest in the study.

3. In the first line of the introduction, I suggest specifying that *population-level* undernutrition is indicated by prevalence of stunting, wasting, underweight.

4. Perhaps clarify how reference to the 2008 Lancet series on child malnutrition which mentions that areas with similar levels of stunting have different prevalence of wasting is relevant to the research question.

5. Please provide more specifics about what kind of subsistence crop cultivation was linked to seasonal epidemic nutritional edema among American farmers in the 1930s. Was the type of crop important in these studies from the 1930s?

6. Last phrase of the introduction about Ragi can be moved to the methods section.

Methods

1. Please clarify the year that data were collected for the NFHS4

2. Could the effects of DSCQ on district-level prevalence of stunting and wasting be modified by age? Was the age distribution even across all districts?

Table 1

○ Variables like diet diversity could be a mean, so it should be clarified that all variables in this table are proportions of binary variables. (And/or call it minimum diet diversity in this table, as is done elsewhere).

Results

○ "Wasting showed an early onset with highest wasting (40%) at 6 months of age". I would suggest changing the wording from early onset, which implies that the data were longitudinal, to "wasting was highest among the youngest children (6 months of age) at the time of measurement".

Discussion

1. The discussion should start with a clear summary (not repetition) of the results – a few phrases that summarize the main findings before moving on to put them into context of previous research and/or hypothesis related to the mechanisms behind their findings. The first paragraph of the discussion seems out of place to me. It can be shortened and worked into the section on individual and geographic co-occurrence patterns of stunting and wasting. The authors also do not really explain how cereal consumption in itself would be related to the relationship between stunting and wasting.

2. As it is written, the discussion is hard to follow, with many seemingly irrelevant details presented outside the context of the objective of the paper. It would be good if the discussion first outlined how the results in this paper are related to previous findings or not, and then discussed potential explanations for the findings, including mechanisms through which millet consumption may be associated with higher stunting or wasting prevalence. While there is some discussion at the very end about potential mechanisms through which millet consumption may be related to higher levels of stunting and/or wasting, this section is confusing and it is unclear how exactly millet consumption would be inferior, given statements about processing of rice or maize that would seemingly make those the inferior grains to consume.

3. A lot of the discussion is re-stating results instead of providing context and explanation for the results. For example, the age and geographical patterns of stunting and wasting section starts off with a paragraph stating specific results that could be summarized in one phrase and then merged into discussion that couches the findings in the literature and discusses implications.

4. "Probably, proximate dietary factors hold the clues to these differences in spatiotemporal prevalence patterns...". This is a strong statement and a stretch in my opinion. It is possible, but saying that it is probable overstates a relationship based solely on correlations and understates/doesn't explore other potential explanatory factors. In fact, the authors need to stress and respect that they cannot make causal inferences from these analyses, given their study design but also the fact that they use cereal cultivation as a proxy for consumption.

5. The limitation of using cereal cultivation as a proxy for consumption needs to be afforded much more discussion, as this is based on a lot of assumptions and is a major limitation to interpretation of these findings.

6. Authors could comment in the limitations section on how it may impact their results that census data were from 2011, the NFHS4 data were from (2015-2016?), and the crop data ranged from 2002-2017.

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and is the work technically sound?
Partly

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Partly

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
No

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: maternal and child nutrition, child growth, seasonality, food systems

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Reviewer Report 04 April 2022

https://doi.org/10.21956/wellcomeopenres.19560.r48847

✔ **Edward J.M. Joy** [iD]
Faculty of Epidemiology and Population Health, London School of Hygiene & Tropical Medicine, London, UK

Thanks to the authors for their further revisions to the article.

Is the work clearly and accurately presented and does it cite the current literature?
No

Is the study design appropriate and is the work technically sound?

No

Are sufficient details of methods and analysis provided to allow replication by others?
No

If applicable, is the statistical analysis and its interpretation appropriate?
No

Are all the source data underlying the results available to ensure full reproducibility?
No

Are the conclusions drawn adequately supported by the results?
No

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Dietary micronutrient assessment, population micronutrient assessment

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

- -

Version 3

Reviewer Report 10 November 2021

?

Edward J.M. Joy (iD)
Faculty of Epidemiology and Population Health, London School of Hygiene & Tropical Medicine, London, UK

- In the abstract, the authors suggest that 'better data' are required to confirm a causal pathway. What is actually required is a well-designed intervention study. Please revise.

- In the methods, the authors write "Other socio-demographic variables included in our analysis have been listed above…". It would be clearer to specify them here, and the authors should also specify whether these variables were controlled for in the multivariate regression analysis.

- In the methods where the outcome variables are specified, the z-scores should be 'negative 2'

○ In the study limitations, the authors write "The use of cereal cultivation as a proxy for consumption too is a source of noise in our data…". I don't think 'noise' is the right term. It is likely to introduce substantial error and is a major limitation of the study.

Is the work clearly and accurately presented and does it cite the current literature?
No

Is the study design appropriate and is the work technically sound?
No

Are sufficient details of methods and analysis provided to allow replication by others?
No

If applicable, is the statistical analysis and its interpretation appropriate?
No

Are all the source data underlying the results available to ensure full reproducibility?
No

Are the conclusions drawn adequately supported by the results?
No

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Dietary micronutrient assessment, population micronutrient assessment

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 22 Feb 2022
Prashanth N Srinivas, Institute of Public Health Bengaluru, Bengaluru, India

Thank you for your review.

Regarding suggestion on revision of abstract, the revised abstract addresses this comment.

Regarding the clarification on variables, listing them and on the details of controlling for them in the multivariable regression, the variables have been listed in Table 1 and mention has been made of them being controlled in multivariable regression.

The error regarding z-scores is regretted and fixed.

Amendments pointed out In the study limitations has been addressed.

In addition to this, extensive revisions have now been made in the Discussion section to address other reviewer concerns as well and we hope these have comprehensviely addressed the observations in the reviews.

Competing Interests: None declared

Reviewer Report 26 October 2021

https://doi.org/10.21956/wellcomeopenres.18904.r46243

?   **Nicholas J. Kassebaum** (iD)

Institute for Health Metrics and Evaluation, University of Washington, Seattle, WA, USA

This study reports on associations between grain cultivation patterns and patterns of HIGH wasting and HIGH stunting prevalence. This is a useful addition to the field of nutrition and child anthropometrics, which ironically has not focused as much on food supply as on other factors. However, I have a few concerns:

Small points:
1. Opening sentence of intro is very difficult to read. After several tries, I'm still not sure what it is trying to say.

2. Last sentence of intro says NFHS4 was "published" in 2015. Wasn't it conducted in 2015-2016 and published in 2018?

More substantial comments:
1. Figure 1- the legend is so similar for the three categories that it is very difficult to tell them apart. Suggest to revise to increase legibility.

2. Birth weight data for children <5 were routinely collected in NFHS-4. The authors state that this is "unavailable." Please explain.

3. Choice of "high" vs. "low" is a bit arbitrary. There is nothing in the paper by Khan and Mohanty (other than their making severity classifications in a table), or indeed in the NFHS-4 anthropometrics data itself, that suggests a particular inflection point where the authors of this study have defined "high" wasting / stunting. Stunting/ wasting/ underweight are already over-simplified to be dichotomous. Further dichotomizing to high vs. low prevalence locations may be a simplification that makes the analysis easier, but it substantially weakens the broad applicability of the findings of the paper. Can the authors comment on why they were unable to perform this as an analysis where the dependent variable was not also/ instead chosen to be continuous z score?

4. Discussion doesn't talk at all about the results of the paper and its implications, instead focusing on nutrition science. Suggest to revise and focus on this paper. Summarize the biology/ clinical information much more briefly and refer interested readers to where they can find this additional information. The tables and figures in the discussion do not add to the narrative. Figure 9 in particular – these don't look substantially different; if there is an important difference to show, this needs to be a different visual (and moved to the results).

5. The most important finding of this analysis has largely been glossed over in both the results and the discussion. This is presented in Table 2 and Table 3, where the authors' multivariate analysis suggests that the previously described association between sociodemographic factors (poverty, education, rural status, open defacation) are all actually [potential] proxies for dietary diversity as evidenced by dramatically reduced – or reversed – beta coefficients in multivariate regressions. What is the authors interpretation of this finding? This contradicts, or at least refines, the findings of Khan and Mohanty (cited by authors, ref 18) and many others. If true, the implications of this are potentially profound. What are the potential policy implications? What does the literature say about the mechanistic association between sociodemographics and food supply – is it more effective to target education/ poverty/ living conditions? Or more effective to target food supply and dietary diversity? What would be the next steps in gathering data to answer this question if unknown?

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and is the work technically sound?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Partly

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: child health, epidemiology, health metrics

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 22 Feb 2022

Prashanth N Srinivas, Institute of Public Health Bengaluru, Bengaluru, India

Thank you for your detailed review.
On the minor points you have highlighted:

1. We have made suitable edits to improve readability. Regarding teh

2. Error related to year of NFHS4 regretted and corrected**.**

Response to major/substantive comments below; extensive changes made in v4 to address these:

1. Figure 1 has been re-done the figures to improve visual contrast of the pattern**.**

2. References to birth weight data from NFHS have now been removed as we do not use it in our analysis.

3. On the assertion regarding arbitrariness of "high" vs. "low" stunting/wasting districts: In the paper by Junaid and Mohanty, the districts were classified as low stunting (less than 26%), medium stunting (prevalence 26.1-46%) and high stunting (prevalence higher than 46%) based on mean and standard deviation, as per their results. Highest wasting prevalence districts were categorised as more than 28%. We utilised this classification for illustrating the districts with high prevalence of stunting, wasting as well as both high stunting and wasting in the maps. However, Z scores of less than -2 SD have been used for stunting & wasting cut off to assess prevalence in NFHS4. Their prevalence in districts (without distinction into high and low) have been used for the scatter plots and multivariable regression. A table (table 1) indicating different variables used in the maps and other results is shown for clarity in this version. We accept that our choosing of these cut-offs will affect the wider applicability of these findings. However, in the lack of a globally comparable standard, we have chosen this. Furthermore, this categorisation is only applicable to our map-based visualisations. The multivariable analysis indeed uses district-level percentages of stunting and wasting.

4. On the points raised in Discussion that are not in the results: We have re-written the Discussion section to focus better on the results reported. WE have now removed any tables and figures from our discussion and have modified earlier figure 9, a pie chart into a bar and moved it up to the results. The figure showing pathways to nutrition and information about mechanisms through MTORC1 has been only referred to and all narrative/figures on the pathway have now been shifted out of the paper.

5. On the reviewers points about findings presented in Table 2 and Table 3: Thank you for the opportunity to clarify this further and thank you for your comments on the potential applications of our findings. In our revision, we have attempted to address these important comments to the extent possible. However, some of these comments being policy and practice implications of the underlying hypotheses we are examining, we have been unable to comprehensively address them even in our revised discussion. Moreover, many of these important observations by the reviewer are in age-groups outside of our analysis (nonetheless having important implications). We hope that our paper shall contribute to expanding the literature on the points raised by the reviewer. However, given the importance of these points, we attempt to provide some response hereunder to those aspects that are yet not addressed in our revised discussion. We hope to develop these further once this

analysis achieves peer acceptability.

6. The literature and evidence on food security potentially connects socio-demographic factors mechanistically to food supply. One definition of food security is "Access by all people at all times to sufficient food and nutrition for a healthy and productive life"[1] . The opposite term, food insecurity has been defined by one source as "A person is food insecure when they lack regular access to enough safe and nutritious food for normal growth and development and an active and healthy life "[2]. Moderate food insecurity, like seen among the poor in high-income countries, is also associated with obesity[3] . Severe food insecurity is associated with hunger. A study based on data suitable for measuring food security from Maharashtra, India indicated that food insecurity is no longer associated with statistically significant stunting, wasting or underweight, when controlled for dietary diversity and all other child, maternal or household characteristics implying the importance of dietary diversity as a determinant of malnutrition[4].

7. The Lancet 2013 series clearly brought that the Nutrition specific interventions , when brought up to scale of over 90% could help tackle about 20% of global burden of malnutrition[8]. Noticeably, the emphasis in the Lancet series of both 2008 & 2013 was on the first 1000 days as far as Nutrition specific interventions are concerned[8,9]. However, longitudinal studies point to the fact that children both become stunted and recover in growth, from infancy through adolescence, thereby extending the period of intervention for healthy growth from the first 1000 days till adolescence [10,11]. Greater persistent stunting after 5 years till 15 years, in one study in India and Ethiopia vis-à-vis Peru and Vietnam, points to an environmental context in the former countries[11]. India also has the largest number of low birth weight among countries in the world, a reflection on the health and nutrition of women through their lives[12]. A study analysing secular trends in improvement of child malnutrition indices in Vietnam and Bangladesh, attributed rapid improvements in HAZ scores to changes in underlying determinants like socioeconomic status, maternal education, hygiene and food security[13]. Changes in maternal nutritional knowledge and child dietary diversity were associated with only 20% of the total change[12]. A cross country study about drivers of nutritional change suggested four factors which predict reduction in undernutrition as, women's secondary education, reduction in fertility, increased access to health services and increase in household assets[14]. Clearly, a combination of nutrition sensitive and specific measures as per context would be the way forward [15].

8. The Integrated Child Development Services (ICDS) of India covers a wide range of services involving teenage nutrition, pre-school feeding, health and education as well as nutrition of pregnant & breast feeding mothers, conducted through 1.3 million Anganwadi centres all over India [16,17]. In 2006, the ICDS was scaled up substantially following a Supreme Court directive[18]. There was a significant improvement in ICDS coverage as seen through comparison of NFHS 3 & 4 after this scaling up. A threefold increase in percentage of women and children receiving food supplementation during pregnancy, lactation and early childhood was noted during the period[17,18] .There were also significant improvements recorded in breast feeding practices, antenatal coverage, immunization, age of marriage, women's education and several other health related practices [18]. Concomitantly, a 10 percentage reduction in stunting in children aged 0-5 years was recorded in 2016 vis-à-vis 2006 ,as per NFHS

data[17,18]. The improvement is heterogenous across states of India, with intra-state disparities seen particularly among the poor and lower castes. However, in IYCF practices, complementary feeding and minimal meal frequency showed decline in 2016 over 2006. Clearly, the ICDS is a work in progress and there is much room for improvement with respect to coverage and efficacy[17,18].

9. A meta-analysis on school feedings showed significant improvements in height and weight over 12 months , compared to controls[19]. A recent study has clearly indicated substantial benefits of India's mid-day meal (MDM) scheme, in estimated improvement in stunting up to 0.4 SD among children born to mothers with greater exposure to MDM[20]. This points to the intergenerational benefits of school feeding apart from its multisectoral economic benefits which extend from health, social protection, education, fertility reduction to local agriculture[20,21].A closer look at countries which have shown impressive declines in stunting and other mother and child nutrition related parameters, such as China and Peru , show presence of robust school feeding programs including provision of milk , over the last few decades[22,23]. Improving the quality of school feeding (coupled with deworming , nutrition education etc)   and extending it to include adolescents could arguably bring about undernutrition reduction substantially by synergising the nutrition specific and sensitive nature of interventions involved.

10. A practice like eating down in pregnancy, wherein mothers eat less for fear of labour related complications due to a large baby is not unheard of in many parts of rural India[24]. Health care systems should be made more accessible and effective, particularly in terms of priority areas like vaccination services, as well as obstetric and child care. This will also help deal with hidden issues like maternal depression as well as common infectious causes of child wasting such as tuberculosis, Malaria, diarrhoeas and respiratory infections[25,26]. Replacement of iron folate to multiple micronutrient supplements, targeted balanced energy micronutrient supplements to pregnant mothers with low BMI have been recommended[8] .This could be extended to breast feeding mothers given the high rates of malnutrition in early infancy in India. The MDM should be expanded to include older children with provision of a breakfast with milk to start the day. Greater emphasis on play at ICDS and school should address both child stunting and rising prevalence of obesity(twin burdens of malnutrition) well. Conditional cash transfers for poorer households like the Oportunidades in Mexico[27], could be used to improve dietary diversity among women and children of the poorer states through encouraging use of Nutrition, education and health services. Optimum resource allocation for multisectoral improvements in both nutrition specific and sensitive areas with close monitoring of benefits to the targeted population nation-wide, could bring about transformational benefits.

11. Dietary matrix data like studies by Kurpad et al on commonly consumed food preparations by the poor with a focus on means to enhance nutrient availability through simple measures can be utilised for better quality nutritional advice or education[28]. The effect of cereal type on the variability in nutrient(s) availability will have to be factored while designing/ recommending appropriate diets. Well-designed biofortification on a large scale could be explored to improve micronutrient levels in a population. Quality of breast milk , nutrient availability in the breast milk and maternal depression among mothers consuming different dietary matrices(like, say,

by using different cereal types) would be immensely beneficial to focus on type of diets needed by lactating mothers in different ecogeographic areas . Given that most of the countries with high rates of malnutrition in early infancy have high cultivation of coarse cereals (our observation), it would be relevant and important to explore the relationship between type of cereal consumed and foetal growth restriction in communities with low dietary diversity and a cereal based diet. Considering that one third of Indian women in NFHS report never consuming eggs and 11% never consuming dairy products, research in optimal diet to support this group for the first 1000 days is urgently needed[29]. Use of mobile services for personalised dietary advise to the general population is another unexplored avenue. Research into quality of India's preschool services should be extended to states with poorer indicators of performance with an aim to translate best practices consistently across the states [30,31].

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Competing Interests: None disclosed.

Version 2

Reviewer Report 09 June 2021

https://doi.org/10.21956/wellcomeopenres.18006.r41339

❌   **Suparna Ghosh-Jerath**
        Indian Institute of Public Health-Delhi, Public Health Foundation of India, Gurgaon, Haryana, India

I would request you to kindly transfer this paper for a second round of review by another reviewer for the following reasons:

- ○ I have gone through the responses provided by the authors. Though the authors have tried to respond to some of the concerns raised by both the reviewers, the core concern related to the basic hypothesis remains. The authors seem to be making the classic mistake of assuming causality from correlations with erroneous and troublesome conclusions. Further, these conclusions are based on several assumptions especially translating production into consumption, limited exploration of intra-household food distribution, access to other food sources (dietary diversity), nutrition sensitive factors and a simple fact that a nutritious diet cannot be constituted or assessed based on "only cereals", one needs to look at the diet in totality and production and access to a diverse food basket. If this message is disseminated without further scrutiny, it may give strong negative messages countering the benefits of cultivating nutrient rich, climate friendly millets, that are sometimes grown as mixed cropping with other pulses/legumes and cereals, and are incidentally produced by several of the nutritionally vulnerable, marginalized, economically backward communities of India.

- ○ Unfortunately, the authors fail to understand that production of cereal cannot be a proxy to actual consumption, which along with several other intervening factors (both nutritional as

well as non nutritional) are resulting in poor nutritional status of vulnerable communities in question.

○ Most of the responses are deviating from the queries raised. Removing a nutrient rich millet from the analysis and assuming that the underlying cause of wasting could be coarse cereals seems somewhat indefensible.

○ In case they wish to continue with the coarse cereal /millets and wasting argument, they need to highlight in discussion that pre-processing can address most concerns about the anti-nutritional effects e.g. as given in many papers, instead of trying to dissuade millet cultivation and use. (https://fppn.biomedcentral.com/articles/10.1186/s43014-020-0020-5)

○ In case the authors extensively revise the paper, they need to focus on all components of infant and young child feeding practices in totality along with other nutrition sensitive factors rather than focusing on "cereals only" and exploring association of wasting with cultivation of specific coarse cereals in isolation

○ At its current status, the paper cannot be accepted for indexing.

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Is the work clearly and accurately presented and does it cite the current literature?

Partly

Is the study design appropriate and is the work technically sound?

Partly

Are sufficient details of methods and analysis provided to allow replication by others?

Partly

If applicable, is the statistical analysis and its interpretation appropriate?

Partly

Are all the source data underlying the results available to ensure full reproducibility?

Partly

Are the conclusions drawn adequately supported by the results?

Partly

Competing Interests: No competing interests were disclosed.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for

reasons outlined above.

Author Response 25 Jun 2021

Prashanth N Srinivas, Institute of Public Health Bengaluru, Bengaluru, India

In the paper we analyse data in order to explore the possible link between type of cereal consumed and the occurrence of child malnutrition, given that cereals constitute upwards of 70% of diet in the rural areas where malnutrition is the highest. We maintain that this is a novel exploratory study, as we have not come across a study that has explored this relationship.

In the interest of advancing critical inquiry at the heart of the scientific process, we believe that overwhelming existing evidence should NOT be a reason for non-acceptance of new kinds of evidence demonstrating plausibility if not causation. A reasonable approach in our opinion for anyone with differences from the line of thought that we pursue here would be to demonstrate mistakes in our analysis and/or over-reach of conclusions (which in fact was pointed out by RI and has been significantly revised in our version 2).

The reviewer repeatedly brings out the argument that millets are nutritious and in the same breath says that malnutrition is more common in communities consuming millets (see for eg. R2 assertion in response to v1 ""It's not surprising that households with high coarse cereals consumption have high wasting and malnutrition") This is in fact the relationship that we attempt to explain (we do not attempt to causally link the two). Such an explanation requires reaching across disciplines ranging from cellular pathways, agriculture and nutrition which we attempt in this paper.

It is the dietary matrix and how it impacts on the absorption of various nutrients that is important as opposed to making millet a singular causal candidate. Our approach is that since there is substantial variability in the dietary availability of various key nutrients in different cereals there are likely to be differences in their effects in different populations. The low glycaemic index of some millets which may be advantageous to the obese diabetic may be a disadvantage to the unborn of a pregnant adolescent with poor dietary diversity. We have indicated in our version2 that most millets indeed have greater micronutrient levels in comparison to rice & wheat which could be contributory to stunting in areas where they are predominantly consumed. Our contention is that the lower amino acid availability could be similarly causing wasting in areas where millets are consumed. To emphasize this aspect, we have brought out the Digestible ingested amino acid scores(DIAAS), as acceptable by WHO, of different cereals from published literature. The correct approach mitigate this lack of nutritional availability by pre-processing like nixtamalization or fermentation or to supplement above by appropriate changes in the matrix or with added nutritional supplements in the way Iron and Folate is supplemented in pregnancies in most developing countries.

So what we are asking is for a closer scientific scrutiny into the nutritional availability of key components in commonly consumed diets by rural Indians. To reject the question itself, as the reviewer has done in conclusion, demonstrates the lack of engagement with our analysis and results presented possibly due to an overwhelming reliance on the existing

> assertions about nutritious value of millets rather than an openness to engage with evidence critical of a given hypothesis.
>
> We believe that our assertions are reasonably demonstrated by the evidence we present and were hoping to be proved wrong by demonstrating errors in our analysis or conclusions. In the lack of that, we shall continue working harder on communicating our findings better to the scientific community.
>
> ***Competing Interests:*** None declared.

Reviewer Report 12 January 2021

https://doi.org/10.21956/wellcomeopenres.18006.r41340

?

Edward J.M. Joy (iD)

Faculty of Epidemiology and Population Health, London School of Hygiene & Tropical Medicine, London, UK

The authors have made substantial revisions which have largely addressed my earlier comments. I would prefer the authors to expand on the study limitations, which are inherent in a cross-sectional, ecological study design.

The multi-variate analysis is a better approach. It appears that the association between wheat consumption and wasting is similarly strong as for jowar consumption, which I suppose illustrates the potential pitfalls with over-interpreting the findings and implying causality via a specific metabolic pathway driven by (anti-)nutritional factors in millets. It would be consistent with an underlying driver of poverty/wealth which will determine not only access to diverse diets but also other risk factors of undernutrition.

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and is the work technically sound?
Partly

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Partly

Are all the source data underlying the results available to ensure full reproducibility?
Partly

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Dietary micronutrient assessment, population micronutrient assessment

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

- -

Version 1

Reviewer Report 27 July 2020

https://doi.org/10.21956/wellcomeopenres.17478.r39290

✗ **Suparna Ghosh-Jerath**
Indian Institute of Public Health-Delhi, Public Health Foundation of India, Gurgaon, Haryana, India

The manuscript provides insight on impact of production of coarse cereals (selective millets) on the nutritional status of women and children in India.

I have the following concerns with the methodology and conclusions drawn in this manuscript
1. Title: The title has issues in terms of including food (cereals) and nutrients (proteins and micronutrients) in the same basket, which is not clear.

2. Hypothesis: According to the manuscript, families depending on subsistence farming and growing millets may have higher levels of wasting in under 5 children and malnourishment in women. Assessing causality by relating production of millets to nutritional status without looking at actual consumption and other factors [underlying and basic factors (ref to UNICEF conceptual framework of Causes of maternal and child malnutrition)] may be flawed.

3. The issue of assuming causality from correlations with perhaps erroneous conclusions is a major concern in this manuscript. It is crucial to look at dietary consumption data, from NSSO and NNMB and it is also important to adjust for all the other factors like SES, endemicity to diseases, access to potable water before superimposing millet cultivation and

prevalence of malnutrition in women and wasting in children. These communities are poverty stricken and have limited access to several resources mentioned above. So the yield of crop is questionable as well. What % of their farming are millets? What % of their food plate are millets? All these need to be explored before drawing conclusions. It's not surprising that households with high coarse cereals consumption have high wasting and malnutrition. To assume that the underlying cause of wasting is coarse cereals (and that wasting would be less without coarse cereals) seems erroneous and perhaps indefensible. Comparing similar households with and without coarse cereal consumption could be a convincing way to draw conclusion in the present manuscript.

4. Why have the authors excluded Ragi (finger millets) from the analysis, which is one of the most nutritious millets?

5. With Public distribution system (PDS) , a food security program in India distributing majorly rice and wheat throughout the country at subsidized rates, it might be difficult to conclude that the millet growing communities, who have access to PDS are only consuming millets and hence have poor nutritional status?

6. The authors mention that at 6 months, the wasting in children is the highest, does the data say that disaggregated data on millet cultivation and wasting at 6 months has the most significant association?

7. It is somewhat worrisome to see the concluding line stating that "Policies and programs targeting malnutrition need to address type of cereal consumed in order to impact childhood malnutrition in parts of India where subsistence cultivation of millets for staple consumption is prevalent." The millet consumption can actually add diversity to the Indian diets and the presence of anti-nutrients can be assessed in the light of anti-nutrient and micronutrient molar ratio (e.g. phytate: iron molar ration before concluding that the millets can lead to malnutrition.

 Recommendation: In its current state, this manuscript may be rejected.

Is the work clearly and accurately presented and does it cite the current literature?
No

Is the study design appropriate and is the work technically sound?
No

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
No

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?

No

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Food systems research, assessment of nutritional status, nutrient analysis, nutritional status of indigenous communities of India

I confirm that I have read this submission and believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.

Author Response 09 Oct 2020
Prashanth N Srinivas, Institute of Public Health Bengaluru, Bengaluru, India

Thank you for your careful review of our submission and for raising important concerns. We have now comprehensively revised the paper and hope that the revised version has adequately responded to your concerns raised. We first provide a comprehensive overview of the main arguments underlying our revision and subsequently provide point-by-point response to the specific concerns raised. We kindly point you to review substantive responses we have made in response to reviewer 1 under the following headings which are also relevant to concerns raised by you: *(a) On protein and amino acid content of cereals, (b) On the matter of why some cereals such as millet and sorghum have lower digestibility, (c) Protein quality in the first 1000 days of conception, (d) On the micronutrient content in cereals*

On the choice of title: There have been questions linked to our choice of the title by both reviewers. Overall, there are 108 districts each with higher prevalence of stunting and wasting, with an overlap of both in 18 districts (Figure 1 showing overlaps between two sets of districts in response to reviewer 1). Undeniably, cereals constitute upwards of 70% protein consumption in rural India and malnutrition has a strong rural preponderance worldwide[1,2,3]. Looking from the prism of predominantly cereal based diets, the wide range of protein (or amino acid) and micronutrient availabilities among cereals (as explained in our overarching response above) could well determine both wasting and stunting. Furthermore the results provided in the revised version strengthen the evidence-base for an association of wasting and low BMI with millet cultivation (as a proxy for consumption).

On the hypothesis: Our hypothesis is based on the distinct patterns of higher prevalence of stunting and wasting as well as the wide diversity in the cultivation and nutritional values of both micronutrients and proteins among cereals. We agree that other factors linked to poverty like dietary diversity, infections, low birth weight could well be contributing to malnutrition. This emphasizes is a need for well-designed studies to look for the contribution of cereals consumed to the patterns of malnutrition. But, given that some states with higher poverty (e.g., UP and Bihar) with relatively lower levels of low BMI and wasting than states in peninsular (or central) India (also see Table 1 in response to Reviewer 1 and the section titled *On the early onset of malnutrition in India and ecogeographic patterns & *section titled *On the micronutrient content of cereals*) points to other factors.

On the exclusion of *ragi*(finger millet): As mentioned in the text we excluded *ragi* from the

millets because of its purported nutritional richness and its distinct subfamily in the grass family *Poaceae*[4,5,6]. This is also corroborated by patterns in the African continent where the countries which had the highest production of ragi (Uganda and Tanzania) are in the highlands of East Africa with lower prevalence of wasting when compared to other millet-growing regions in the continent[4,7].The figure showing the distribution of Ragi in eastern highlands is available from p.42 (Link); the geo-spatial analysis of prevalence of malnutrition in low- and middle-income countries by Kinyoki et. al figure 2 showing low prevalence of wasting in areas having pre-dominant *ragi* cultivation is available (Link).

About Poverty, PDS and food security in India and its effects on our findings (see table uploaded on Figshare as tables are not allowed in response to reviewers)**:** That the Public Distribution system (PDS) is invaluable in managing food security in the country is undeniable. The share of rice or wheat consumption from PDS in different states indicates that the percentage is quite less (ranging from 7.6% in Gujarat to 34.3% in Chhattisgarh) . The percentage of improvement in PDS use from 2004-5 to 2011-12 has not led to a commensurate decline in undernutrition in the country[8,9]. Moreover, the coverage of PDS is much higher in hill-states of northern India and in South Indian states as compared to other regions where malnutrition prevalence is higher[9]. Hence, the likelihood of effects of PDS especially in the regions that we analyse in this paper by the marginal farmers and rural poor is likely to be low with subsistence cultivation continuing to play an important part, especially among the poorest communities.

About validity of data for study purposes: The major nutrition surveys completed in this decade are summarised by Rathi et. al. (see table 1; Link to journal) [7] . The Comprehensive National Nutrition Survey 2016-18 has data by state and their respective urban/rural areas and not by districts[10]. The district level household survey 4 (DLHS4 in 2012-14) covered only 336 districts among 640 present at that time. The minimum disaggregation available on such a scale is at the district level only. The malnutrition data in our study was extracted from NFHS4 which is a nationwide survey encompassing all districts [11,12]. The Hemalatha et al[13] study uses multiple data inputs with the latest being,NFHS4 and India Urban Nutrition Survey Data 2015-2016. As seen from table 4 above taken from Rathi et al [14]NFHS4 is the only nationwide survey encompassing all districts completed in the present decade. The food consumption data too has dietary groups with cereals aggregated in a group, as grains, roots and tubers. For the purposes of our study we needed separate consumption of cereal (by type) in each district which is not available in CNNS or NFHS4.The older NSSO (NSS 55) has data on type of cereals consumed but that too is not available by district but by 77 ecogeographic zones[15] .

Point-by-point response to review observations

- ○ Title: The title has issues in terms of including food (cereals) and nutrients (proteins and micronutrients) in the same basket, which is not clear.

Thank you for bringing the title to attention. We have explained above under the heading "*on the choice of the title*".

- ○ Hypothesis: According to the manuscript, families depending on subsistence farming and growing millets may have higher levels of wasting in under 5 children and malnourishment in women. Assessing causality by relating production of millets to

nutritional status without looking at actual consumption and other factors [underlying and basic factors (ref to UNICEF conceptual framework of Causes of maternal and child malnutrition)] may be flawed.

We accept that obtaining actual consumption would have been ideal for establishing or negating such a hypothesis. In the version 2 of our paper, we have attempted to include other factors pertinent to malnutrition (available through nationwide surveys) in our analysis . We have explained this in detail under the sections *On the hypothesis* and *On the validity of data for study purposes*. Please also see the more extended multivariate analysis in version 2.

- ○ The issue of assuming causality from correlations with perhaps erroneous conclusions is a major concern in this manuscript. It is crucial to look at dietary consumption data, from NSSO and NNMB and it is also important to adjust for all the other factors like SES, endemicity to diseases, access to potable water before superimposing millet cultivation and prevalence of malnutrition in women and wasting in children. These communities are poverty stricken and have limited access to several resources mentioned above. So the yield of crop is questionable as well. What % of their farming are millets? What % of their food plate are millets? All these need to be explored before drawing conclusions. It's not surprising that households with high coarse cereals consumption have high wasting and malnutrition. To assume that the underlying cause of wasting is coarse cereals (and that wasting would be less without coarse cereals) seems erroneous and perhaps indefensible. Comparing similar households with and without coarse cereal consumption could be a convincing way to draw conclusion in the present manuscript.

We have strengthened the analysis in the revised version as well has edited the language implying causality. We, in fact do not want to attribute causality but wish to describe a consistent pattern and provide a plausible hypothesis in the epidemiology of malnutrition in India. Hence, we have placed the pathway incorporating the mechanisms of causation in discussion rather than results in version 2 . We have incorporated few of the variables pertaining to causation of malnutrition in a multivariate analysis as well. Dietary consumption data from nationwide surveys have limitations as mentioned under the section *About validity of data for study purposes.* We concede that well designed field studies are required to come to a clear position on this issue.

- ○ Why have the authors excluded Ragi (finger millets) from the analysis, which is one of the most nutritious millets?

We have dwelt on this under the above section titled *On the exclusion of ragi(finger millet).*

- ○ With Public distribution system (PDS) , a food security program in India distributing majorly rice and wheat throughout the country at subsidized rates, it might be difficult to conclude that the millet growing communities, who have access to PDS are only consuming millets and hence have poor nutritional status?

This has been explained in the section above titled *About Poverty, PDS and food security in   India and its effects on our findings.*

○ The authors mention that at 6 months, the wasting in children is the highest, does the data say that disaggregated data on millet cultivation and wasting at 6 months has the most significant association?

In Fig 5 of version 1 and Figs 9 & 10 of version 2 the age profile of children in the 108 high stunting and 108 high wasting districts is plotted. The districts with higher wasting (which have higher cultivation of millets as brought out in the results) have higher wasting at 6 months. However, data are unavailable to establish this at the household level due to lack of data on type of cereal consumed (which we have elaborated under the discussion).

○ It is somewhat worrisome to see the concluding line stating that "Policies and programs targeting malnutrition need to address type of cereal consumed in order to impact childhood malnutrition in parts of India where subsistence cultivation of millets for staple consumption is prevalent." The millet consumption can actually add diversity to the Indian diets and the presence of anti-nutrients can be assessed in the light of anti-nutrient and micronutrient molar ratio (e.g. phytate: iron molar ration before concluding that the millets can lead to malnutrition.

We have indeed taken note of this suggestion and changed the manuscript in version 2 accordingly. We have taken into consideration the diversity of nutritional profiles of various cereals and brought out tables (Table 3 & 4) to highlight this. Further detailed explanation has been given under the headings *On protein and amino acid content of cereals, Protein quality in the first 1000 days of conception and On the micronutrient content in cereals* in the response to reviewer 1. The concluding line as stated in the comment has been removed in version 2.

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Competing Interests: None declared

Reviewer Report 21 July 2020

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❌   **Edward J.M. Joy** 🆔

Faculty of Epidemiology and Population Health, London School of Hygiene & Tropical Medicine, London, UK

The authors assess whether staple cereal consumption patterns in India underlie malnutrition patterns. They test this through an association between District-level production of staple cereals, and prevalence of stunting/wasting in children or low BMI/short stature in adult women.

The article is quite clearly written and I appreciate that the authors have made the datasets and

analysis code available for reviewers/readers. This is commendable.

However, there are a number of areas that concern me about the study:

The study title calls this an exploratory analysis, and if this is to be indexed I think the interpretation of the results and framing of the whole paper needs to be consistent with this. For example, the authors currently write "Policies and programs targeting malnutrition need to address type of cereal consumed in order to impact childhood malnutrition in parts of India where subsistence cultivation of millets for staple consumption is prevalent". I don't think such a statement is justified based on the findings of this paper, given the exploratory nature of the analysis, quite apart from the methodological shortcomings.

The title also specifies wasting, where 4 different anthropometric outcomes were assessed.

There are several methodological shortcomings to the analysis, in my opinion. The following shortcomings are noted by the authors:
1. Cereal production is not equivalent to cereal consumption, so testing the hypothesis using cereal production data is problematic. Can the authors explain why 'consumption ' data were not used, e.g. from the Comprehensive National Nutrition Survey?

2. Data are integrated at the District-level. This level of aggregation is likely to mask the true effect, if there is indeed an effect, between millet consumption and risk of malnutrition.

The following shortcomings are not reported in the paper:
○ The authors propose a biochemical pathway through which consumption of millets and sorghum might negatively affect nutritional status of women and children. However, they ignore wider contextual factors that are likely to be related both to the likelihood of producing millets and to the risk of malnutrition. These factors include, for example, socioeconomic status and likelihood of drought. There are multiple pathways linking such environmental and socioeconomic factors to nutritional status, mostly operating outside specific biochemical pathways. The proposed pathways (Figure 6) should at most be included in the discussion (not results), with acknowledgement that it may explain a small proportion of the observed association...if at all.

○ The relationship between millet production and prevalence of malnutrition outcomes (displayed in Figures 3 & 4) is messy. This is not necessarily inconsistent with the hypothesis, considering the District-level nature of the data and the multiple and complex factors underlying nutritional status. However, do the authors really find sufficient evidence with appropriate statistical certainty to reject the null hypothesis, that there is no association between the independent and dependent variables? The authors need to present a more comprehensive assessment of the associations they find, including appropriate p-values. NB I found this hard to review as the statistical test of association was not specified in the methods. Relatedly, the axes in Figures 3 & 4 need units.

○ As above, assuming production closely predicts consumption is a major limitation of the study. But this could be partially addressed through limiting the analysis to rural households only. This might avoid any associations being driven by highly-urban Districts where there is both low millet production and better-than-average nutritional status.

○ The authors pick out particular micronutrients and amino acids which are apparently lower in concentration or bioavailability in millets than in other staple cereals, and suggest this offers a mechanism which might underlie the observed associations. I am not clear how the authors came to select these micronutrients and amino acids. There are others, for example calcium, which are present at much greater concentrations in millets (especially finger millet) than other staple cereals. The idea that a diet with greater millet consumption is less nutritious is not supported by the evidence.

Other comments:

○ Are the estimates of malnutrition prevalence consistent with others? E.g. Hemalatha et al (2020), The Lancet[1].

From visual analysis of the figures, it appears there are some discrepancies. The authors could discuss this.

○ The pattern of increased stunting and wasting prevalence around 12 mo of age (Figure 5) is consistent with other settings and is likely due to poor IYCF practices and high rates of diarrhoea when moving from exclusive breastfeeding to complementary feeding

○ The authors could consider using a different base colour for Figure 1. The current colouring might not translate well to presentations or black and white printing. Also, the hatched areas represent areas with 'higher prevalence' of stunting or wasting, but it's not clear what they are higher than, i.e. what's the comparator.

Overall, I suggest the authors re-consider the framing of the paper and presentation of findings.

References

1. India State-Level Disease Burden Initiative CGF Collaborators: Mapping of variations in child stunting, wasting and underweight within the states of India: the Global Burden of Disease Study 2000-2017.*EClinicalMedicine*. 2020; **22**: 100317 PubMed Abstract | Publisher Full Text

Is the work clearly and accurately presented and does it cite the current literature?

Partly

Is the study design appropriate and is the work technically sound?

No

Are sufficient details of methods and analysis provided to allow replication by others?

Yes

If applicable, is the statistical analysis and its interpretation appropriate?

No

Are all the source data underlying the results available to ensure full reproducibility?

Yes

Are the conclusions drawn adequately supported by the results?

No

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Dietary micronutrient assessment, population micronutrient assessment

I confirm that I have read this submission and believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.

Author Response 09 Oct 2020

Prashanth N Srinivas, Institute of Public Health Bengaluru, Bengaluru, India

Comments of Dr Joy

Thank you for your careful review of our submission and for raising important concerns. We have now comprehensively revised the paper and hope that the revised version has adequately responded to your concerns raised. We first provide a comprehensive overview of the main arguments underlying our revision and subsequently provide point-by-point response to the specific concerns raised.

On protein and amino acid content of cereals: Cecily D Williams, in her pathbreaking description of Kwashiorkor in 1933 commented[1]: *"As maize is the only source of supplementary food , some amino acid or protein deficiency cannot be excluded as a cause."* The understanding about proteins being relevant to the causation of stunting and Intrauterine growth restriction(IUGR) through the MTOR pathway has been extensively studied[2,3,4,5]. Since proteins are absorbed through the ileum after breakdown into amino acids or short peptide chains, and, MTOR being exquisitely sensitive to amino acids, we incorporate the MTOR pathway in hypothesizing about the purported differences in wasting prevalence between northern and peninsular India (see figure 1). Further, as per the 2011 FAO Expert Consultation on Protein Quality Evaluation in Human Nutrition[6], it is recommended that " *dietary amino acids be treated as individual nutrients and that wherever possible data for digestible or bioavailable amino acids be given in food tables on an individual amino acid basis*". Due to paucity of human data it was further stated that "*Where human data are lacking it is recommended that true ileal amino acid digestibility values from the growing pig be used, and where these data are not available from the growing laboratory rat.*" [6] This consideration is underlying our use of ileal digestibility data in pig (Table 5 in the revised version). In a recent paper Swaminathan, Vaz & Kurpad while analysing protein intakes in India[7],highlight lower protein quality of a predominantly cereal based rural and tribal diet, particularly in pregnancy. There are small but significant differences in the Lysine contents across cereals in their analysis (table2 in Swaminathan S et al[7]). This is in line with earlier more global evidence-base[8]. These differences are germane to the differences in malnutrition patterns between northern and peninsular India.

On the matter of why some cereals such as millet and sorghum have lower digestibility, Millward implicates tougher plant cell walls prevalent in millets; others have implicated anti-nutrient factors as well [8,9,10,11]. This is corroborated by measures such as the Digestible indispensable amino acid scores(DIAAS) of cooked cereals (including rice and wheat) which are the lowest for foxtail and proso millet[12]. Other independent analyses to determine the standardised ileal digestibility(SID) among eight cereal grains using DIAAS scores also have shown highest values for rice but the lowest for maize, rye and Sorghum[13]. Furthermore, excess Leucine in Sorghum has been implicated in Pellagra reported among people who

consume Sorghum as a staple in India[14]. There are few studies that compare ileal digestibility across various complementary foods in India. In a comparison of standardized ileal digestibility(%) of amino acids between Sorghum, pearl millet and different varieties of corn, Sorghum was the lowest followed by pearl millet. The different corn varieties were higher than both[15]. The digestibility of pearl millet protein has been suspected to be less than other major grains[16]. While evaluating the protein quality of complementary foods using dual isotope tracer method in comparing the true ileal digestibility of rice, finger millet (*ragi*) and egg, finger millet and mung dal had the lowest[13]. Studies are ongoing for other millets but are currently unavailable (email communication with corresponding author[17]).

Protein quality in the first 1000 days of conception. Pregnant women in fact need an additional 1, 9 and 31 gm per day in first, second and third trimester respectively[18]. This lack of protein (and energy quality) is linked to low maternal BMI and Intrauterine growth restriction[18]. As per the standard FAO reference source on millets and sorghum, Lysine amino acid score of pearl millet is variable (26-69)[8]. Barnyard millet, little millet and Sorghum had the lowest Lysine scores among millets[8]. The lower glycaemic index of millets vis-à-vis rice and wheat (which is indeed beneficial for elderly Diabetics), on the other hand for pregnant women on pre-dominant millet-based diet could contribute to low birth weight and wasting since glucose along with amino acids is an important upstream regulator for MTOR[4,19]. In fact the FAO asserts that exclusive millet diets are not adequate to meet the growth requirements of infants and young children[8]. In table 5 (of the revised version of our paper) we provide Lysine scores of cereals and their references in studies conducted in University of Illinois, Urbana-Champaign and elsewhere. The table is extracted from a compendium curated by Hans-Henrik Stein from published data.

Based on these arguments and evidence presented in our paper further supported by extensive published data, we submit that monotonous cereal based diets of the rural poor wherever they are not supplemented with good quality protein from other sources could drive wasting, as is seen in monotonous millet-based diets.

On the micronutrient content in cereals: Micronutrient availability in rice and wheat, on the contrary, is worse off than in millets (see table 6 of revised paper). This could be underlying the higher prevalence of stunting in rice and wheat growing areas of northern India (possibly related to Zinc deficiency). Review evidence too corroborates the other reviewer's observation that high phytate and phytate to mineral molar ratios in plant based diets as contributing to deficiencies of Iron, zinc and Calcium[20,21,22,23]. The higher Iron, Zinc and Calcium content in millets (especially pearl millet, Sorghum and other millets) could be offsetting the phytate and phenol inhibitors in comparison to rice and wheat (Table 6 data from Indian Food Composition Table 2017[24]). This underlies our assertion "Lower lysine, high phytates with lowered micronutrients like zinc and iron in cereal based diet in wheat and rice growing areas with poor dietary diversity could lead to stunting" (as per caption of pathway figure in version 1; now figure 11). Zinc has a known association with linear growth and supplementation in developing countries has been beneficial in marginal gain of length [25,26]. There has been a decline in the zinc & Iron molar ratios with phytates, in India over the last four decades, attributed to lesser consumption of millets and sorghum [21,22]. Characterising micronutrient availabilities *in vivo* (particularly Zinc, Vitamin D, Magnesium,

Phosphate, Selenium) in different cereal based meals will require state-of-the-art laboratory techniques like stable isotope studies. Iodine is another micronutrient critical for foetal and child growth ,but, unlikely to be of consequence in view of universal Iodization of common salt in India. Iodine availability of different cereals is however unavailable in IFCT 2017.

Malnutrition prevalence related to micronutrients are available only at state level and with no district level data and have been compiled by us from different sources in table 1 below. The state-level data do not reproduce intuitive patterns. For example, poorer states (higher poverty rates) are better off with respect to prevalence of low BMI among women in 10-19 years age group when compared with richer states which report higher coarse cereal cultivation (Rajasthan, Maharashtra, Karnataka and Gujarat highlighted in red). Similarly, lesser degree of low zinc prevalence was seen in 1-4 year age groups in Rajasthan and Maharashtra (see discussion above on better off micronutrient profile of coarse cereals) in comparison to Uttar Pradesh and Bihar. However, these patterns are not consistent (for example Karnataka which reports higher low zinc prevalence in 1-4 year age group despite having relatively high coarse cereal consumption). Nevertheless, a study comparing zinc levels among preschool children across five states of India too showed higher prevalence in Orissa(51.3%) followed by Uttar Pradesh(48,1%), Gujarat(44.2%), Madhya Pradesh(38.9%) and Karnataka(36.2%)[27]. The latter three have a higher production of coarse cereals in comparison to others as seen in the table (since tables are not allowed here, this table curated by us has been uploaded on figshare)

On the early onset of malnutrition in India and ecogeographic patterns: The timing of onset of malnutrition in India has been reported in earlier studies. The paper titled *The Asian Enigma* by UNICEF in 1996 brought it to the forefront with a discussion about higher proportion of low birth weights in India (and Bangladesh) with its linkages to womens' health in general and maternal nutrition in particular[28]. Cesar Victora et al[29] have demonstrated this with India having the lowest weight for age Z scores at 1 month of age. This aspect was emphasized by Martorell et al in the comparisons between stunting and wasting prevalence as well as their respective age of occurrence between India and Gautemala[30]. Figure 1 in the paper by Martorellillustrates this comparison indicating earlier onset of wasting in India.

In our analysis the stunting prevalence comparison between the districts with high stunting and high wasting showed a similar pattern as seen in figures 9 and 10 (in the revised version), with higher and earlier onset of wasting in the 108 high wasting districts. That is likely to be attributable to maternal nutritional factors during pregnancy, lactation and low birth weight. However, granular data on low birth weight by district in India not being available, this remains a hypothesis to be tested when better data becomes available.

Further evidence of ecogeographic patterning of malnutrition is also available in the landmark Lancet 2008 series on malnutrition [31] where it is asserted "*Furthermore, stunting and severe wasting are not necessarily associated on a geographical or ecological basis—ie, countries with a similar stunting prevalence can have a several-fold difference in the prevalence of severe wasting.*" This phenomenon has also been written about by Cesar Victora in 1992 [32] . What we are attempting to posit here is that, in a diverse country like India, such differences are likely to be important in addressing malnutrition.

Point-by-point response to review observations

- ○ The authors assess whether staple cereal consumption patterns in India underlie malnutrition patterns. They test this through an association between District-level production of staple cereals, and prevalence of stunting/wasting in children or low BMI/short stature in adult women. The article is quite clearly written and I appreciate that the authors have made the datasets and analysis code available for reviewers/readers. This is commendable.

Thank you.

- ○ The study title calls this an exploratory analysis, and if this is to be indexed I think the interpretation of the results and framing of the whole paper needs to be consistent with this. For example, the authors currently write "Policies and programs targeting malnutrition need to address type of cereal consumed in order to impact childhood malnutrition in parts of India where subsistence cultivation of millets for staple consumption is prevalent". I don't think such a statement is justified based on the findings of this paper, given the exploratory nature of the analysis, quite apart from the methodological shortcomings. The title also specifies wasting, where 4 different anthropometric outcomes were assessed.

There have been questions linked to our choice of the title by both reviewers. Overall, there are 108 districts each with higher prevalence of stunting and wasting, with an overlap of both only in 18 districts (see Junaid et. al.; reference number 33). Undeniably, cereals constitute upwards of 70% protein consumption in rural India and malnutrition has a strong rural preponderance worldwide[7]. Looking from the prism of predominantly cereal based diets, the wide range of protein (or amino acid) and micronutrient availabilities among cereals (as explained in our overarching response above) could well determine both wasting and stunting. Furthermore the results provided in the revised version strengthen the evidence-base for an association of wasting and low BMI with millet cultivation (as a proxy for consumption).

- ○ There are several methodological shortcomings to the analysis, in my opinion. The following shortcomings are noted by the authors: Cereal production is not equivalent to cereal consumption, so testing the hypothesis using cereal production data is problematic. Can the authors explain why 'consumption ' data were not used, e.g. from the Comprehensive National Nutrition Survey? Data are integrated at the District-level. This level of aggregation is likely to mask the true effect, if there is indeed an effect, between millet consumption and risk of malnutrition.

This is an important shortcoming of the paper. However, no consumption data are currently available. Detailed explanation for this is provided in response to reviewer 2 under the heading *About validity of data for study purposes*.

- ○ The following shortcomings are not reported in the paper: The authors propose a biochemical pathway through which consumption of millets and sorghum might negatively affect nutritional status of women and children. However, they ignore wider contextual factors that are likely to be related both to the likelihood of producing millets and to the risk of malnutrition. These factors include, for example, socioeconomic status and likelihood of drought. There are multiple pathways linking such environmental and socioeconomic factors to nutritional status, mostly operating

outside specific biochemical pathways. The proposed pathways (Figure 6) should at most be included in the discussion (not results), with acknowledgement that it may explain a small proportion of the observed association...if at all.

We agree with the reviewer observation about the need to integrate other known co-variates of malnutrition which is now done in version 2. Furthermore as suggested the implications of our findings are moved to the discussion (figure 11 relating to plausible pathways is now moved to discussion).

- ○ The relationship between millet production and prevalence of malnutrition outcomes (displayed in Figures 3 & 4) is messy. This is not necessarily inconsistent with the hypothesis, considering the District-level nature of the data and the multiple and complex factors underlying nutritional status. However, do the authors really find sufficient evidence with appropriate statistical certainty to reject the null hypothesis, that there is no association between the independent and dependent variables? The authors need to present a more comprehensive assessment of the associations they find, including appropriate p-values. NB I found this hard to review as the statistical test of association was not specified in the methods. Relatedly, the axes in Figures 3 & 4 need units.

Thank you for these observations. We have now reported the details of our statistical analysis. Corresponding changes have also been made in erstwhile figures 3 and 4 which have now been broken up into figures 3-5 & 6-8 in the revised version along with appropriate p-values.

- ○ As above, assuming production closely predicts consumption is a major limitation of the study. But this could be partially addressed through limiting the analysis to rural households only. This might avoid any associations being driven by highly-urban Districts where there is both low millet production and better-than-average nutritional status.

The multivariate analysis has now taken into the account the effect of rural population proportion in the district.

- ○ The authors pick out particular micronutrients and amino acids which are apparently lower in concentration or bioavailability in millets than in other staple cereals, and suggest this offers a mechanism which might underlie the observed associations. I am not clear how the authors came to select these micronutrients and amino acids. There are others, for example calcium, which are present at much greater concentrations in millets (especially finger millet) than other staple cereals.

This has now been comprehensively addressed in our overarching response above (see particularly discussion under sub-heading *On the matter of why some cereals such as millet and sorghum have lower digestibility* and *On micronutrient availability in cereals*. Please see also section *On the exclusion of ragi* in response to reviewer 2).

- ○ The idea that a diet with greater millet consumption is less nutritious is not supported by the evidence.

This has been addressed in the revisions made. Please also refer to section above titled *On micronutrient availability in cereals.*

○ Are the estimates of malnutrition prevalence consistent with others? E.g. Hemalatha et al (2020), The Lancet[66].

Hemalatha et. al.[66] have used multiple data sources for their analysis, of which the only comprehensive dataset that comprises district-level malnutrition data for the entire country is NFHS4 (which we have used in our anlaysis). Other datasets used in their paper do not provided district-level data for the entire country. Our estimates of malnutrition prevalence at the district level are reproducible and are consistent with analysis of NHFS4.

○ From visual analysis of the figures, it appears there are some discrepancies. The authors could discuss this.

The maps have been reproduced with better contrast and legends for clarity. The few instances of lack of overlaps between millet cultivation and wasting (e.g., bajra in north India) are now discussed in the revised version.

○ The pattern of increased stunting and wasting prevalence around 12 mo of age (Figure 5) is consistent with other settings and is likely due to poor IYCF practices and high rates of diarrhoea when moving from exclusive breastfeeding to complementary feeding

We have extensively discussed the early onset of malnutrition in India above.

○ The authors could consider using a different base colour for Figure 1. The current colouring might not translate well to presentations or black and white printing. Also, the hatched areas represent areas with 'higher prevalence' of stunting or wasting, but it's not clear what they are higher than, i.e. what's the comparator.

Thank you for these suggestions. The revised figures address these concerns. We took the levels of districts having higher prevalence of stunting >45% and wasting >27% based on cut-offs suggested by Junaid et al article[33]. We used levels of > = 30% and >= 15% as high prevalence of women's BMI (<18.5) and short stature(< 145 cms) respectively.

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Competing Interests: Nil

Comments on this article

Version 4

Reader Comment 08 Apr 2022

Sagar Lad, Jehangirhospital, pune, India

Looks very informative study
Especially applicable to Indian village culture
This will definitely improve nutritional outcome and health outcome of children

Competing Interests: No competing interests were disclosed.

Version 3

Reader Comment 06 Jan 2022

Vidya Ramkumar, Sri Ramachandra Institute of Higher Education and Research (Deemed to be University), Chennai, India

The use of geomaps in this article was of interest to me. Upon reading I was intrigued by some of the concepts that forms the basis of the understanding of malnutrition.

Presumably, the authors chose to look at cereal cultivation owing to the large-scale nature of its production. Would things have been different if we grew more (proportionately), fruits, vegetables and nuts? Considering a plethora of micro and macro nutrients are available from these sources and can also increase overall sustainable eating and food habits. Nourishing food has to be easy, local, sustainable for it become a part of routine consumption. A study mapping consumption of natural, local foods and nutrition of children/mothers would be interesting.

Competing Interests: None