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Agriculture, nutrition and the green revolution in Bangladesh☆

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ABSTRACT

This paper explores agriculture and nutrition linkages in Bangladesh, a country that achieved rapid growth in rice productivity at a relatively late stage in Asia's Green Revolution, as well as unheralded progress against undernutrition. To do so, we first outline a simple conceptual model to identify the different impacts that productivity growth in a food staple(s) might have on child nutrition outcomes, with a particular focus on changes in diets at the household and child level. We then apply this framework to a descriptive overview of the evolution of Bangladesh's food system in recent decades. We show that this evolution is characterized rapid growth in yields and calorie availability, but relatively sluggish diversification in both food production and consumption, despite increasing reliance on imports for dietary diversification. Next, we create a multi-round district level panel that links changes in nutrition survey data with agricultural sample survey data over 1996–2011, a period in which rice yields rose by more than 70%. We then use this panel to more rigorously test for associations between yield growth and various anthropometric and child feeding indicators. Consistent with our descriptive evidence on dietary changes, we find that rice yields predict the earlier introduction of complementary foods to young children (most frequently rice) as well as increases in their weight-for-height, but no improvements in their dietary diversity or height-for-age. Since Bangladesh has one of the highest rates of child wasting in the world, these significant associations between yields and child weight gain are encouraging, but the lack of discernible effects on children's dietary diversity or linear growth is cause for concern. Indeed, it suggests that further nutritional impacts will require diversifying the Bangladeshi food basket through both supply and demand-side interventions.

1. Introduction

Despite a surge of recent interest in identifying the impact of agriculture on maternal and child nutrition, the existing scientific literature has brought little light to bear on the core question of whether large scale agricultural programs – particularly longstanding efforts to increase cereal yields – significantly alter nutrition outcomes (Ruel and Alderman, 2013; Pinstrup-Andersen, 2013). Much of the literature has been confined to cross-sectional studies for which even indirect policy attribution is very difficult (Bhagowalia et al., 2012; Dillon et al., 2014; Hoddinott et al., 2015), or to more experimental studies of small scale livestock or homestead gardening interventions (Berti et al., 2004; Leroy and Frongillo, 2007; Masset et al., 2012).

Yet advocates of agriculture-led development typically have in mind much larger scale agricultural programs and policies in the spirit of Asia's "Green Revolutions" (Bezemer and Headey, 2008; Diao et al., 2010; Hazell, 2009; Mellor, 1976; Pinstrup-Andersen, 2013). These Green Revolutions were led by the research and development (R&D) of improved rice, wheat and maize varieties, which – along with associated policies to promote the expansion of irrigation, fertilizers and other inputs – have contributed to rapid growth in Asian food production over the past 40 years. Rice yields, for example, have increased by around 150% in Bangladesh, northern India, Indonesia and Pakistan since the 1960s, while wheat yields in these countries increased by some 250% (FAO, 2014).

Despite its fundamental contribution to poverty reduction, surprisingly little is known about the impact of Asia's Green Revolution on nutrition, and much of what has been written is speculative at best (see Hazell, 2009 for some review). Optimists have focused on the contributions of Green Revolution investments to household calorie consumption and national food security (Pinstrup-Andersen and Jaramillo, 1991), but no work that we are aware of has directly examined impacts on child level feeding practices (particularly the timing and diversity of complementary feeding) or nutrition outcomes. Pessimists point to the adverse micronutrient consequences of reduced biodiversity in monocropping systems, particularly lower consumption

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of pulses, coarse grains and fish (Bouis, 2000; Shankar et al., 2005), and also to the harmful health and nutritional impacts of excessive use of fertilizers and pesticides (Brainerd and Menon, 2014). Yet no work that we are aware of has examined the impacts of growth in cereal yields on changes in individual nutrition outcomes or diets. This knowledge gap exists because the Green Revolutions of the 1960s, 1970s and 1980s largely preceded the kinds of large, multi-topic surveys that are typically a prerequisite for identifying the welfare impacts of large-scale interventions (Elbers and Gunning, 2013).

This paper seeks to fill this knowledge gap by exploring the nutritional impacts of rice productivity growth in Bangladesh. Bangladesh is an ideal case study for several reasons. First, for political reasons, Bangladesh was a relatively late adopter of Green Revolution technologies (Evenson and Gollin, 2003), meaning that much of its productivity growth occurred during more recent periods of improved statistical surveillance. From 1997 to 2011 (the period of our analysis) yield growth for rice averaged 3.6% per annum on the back of increased adoption of improved varieties and the rapid expansion of the irrigated dry season rice crop. Second, productivity growth in Bangladesh coincided with substantial improvements in preschooler nutritional status. In 1996/97, rates of preschooler stunting (height-for-age Z scores < -2) and mild wasting (weight-for-height Z scores < -1) were 53 and 54% respectively. These were among the highest rates of undernutrition in the world at that time, although by 2011 rates of moderate stunting and mild wasting had both fallen to around 40% (Headey et al., 2015). Third, Bangladesh has a relatively rich array of nutritional and agricultural data; the dearth of such data has undoubtedly been a constraint to exploring the impacts of agricultural growth on nutrition in other Green Revolution countries.

Our analysis involves three steps. First, we outline a conceptual framework for thinking about the complex linkages between the economic impacts of the Green Revolution (on farm incomes, wages and food prices) and child nutrition outcomes, with a specific focus on child diets/feeding practices as a key impact pathway (Section 2). We then turn to descriptive evidence of how the evolution of agricultural production and trade has influenced national food supply, household diets and child feeding practices in Bangladesh (Section 3). Here we not only describe the well-known drivers of yield growth in Bangladesh rice production (namely the conventional Green Revolution "package" or high yielding varieties, irrigation and chemical inputs), but also the agroecological constraints that have limited Bangladeshi agriculture's capacity to diversify food production away from rice. Imports have provided some imperfect substitution for the lack of diversification in domestic production, but the net result has been a very limited diversification in food consumption, especially among young children.

We then attempt more formal tests of these linkages by constructing a small district-level panel dataset comprised of nutritional indicators from five rounds of the Bangladesh Demographic Health Surveys (over 1996/97 to 2011) and district level data on rice yields from the Bangladesh Bureau of Statistics (the construction of which is described in Section 4). With these data we use difference-in-difference estimates to explore whether growth in rice yields significantly predicts preschool nutritional status and feeding patterns (dietary diversity, and the timing of introducing complementary foods), as well as maternal nutrition outcomes (Section 5). We find that yield growth predicts improvements in child weight gain and an earlier introduction of solid foods (most of which is rice), but does not predict improvements in linear growth (height gain) or improved dietary diversity. We also find no significant associations between yields and maternal body mass.

Given the limitations of our data and the lack of existing evidence on agriculture-nutrition linkages in Bangladesh, our concluding remarks cautiously reflect on these findings. One important limitation of our analysis is that our small district level panel precludes the use of more experimental estimation techniques that might allow us to draw more confident causal inferences. Hence we do not claim to causally identify the nutritional impacts of rice policies and investment per se. This study should instead be viewed as a preliminary exploration into the nutritional impacts of Green Revolution-style agricultural development strategies.

Bearing this important caveat in mind, several of our exploratory findings are economically and biologically plausible, and are certainly pertinent to the important policy question of whether agricultural development strategies should continue to focus on improving the productivity of key staples, or instead leverage agriculture for diversifying diets. We show that Bangladeshi diets remain heavily under-diversified, and that this lack of diversification is likely a major constraint to achieving further reductions in child stunting, as well as various micronutrient deficiencies not directly addressed in this paper. Accelerating dietary diversification will require research and policy experimentation on a wide range of both supply and demand-side interventions.

2. Conceptualizing the linkages between rice productivity growth and child nutrition

How might rapid growth in a staple crop influence child nutrition outcomes? In Fig. 1 we present a simplified framework for thinking through the various connections between rice productivity growth and changes in nutrition. At the top of Fig. 1 we focus on policy-driven growth in rice yields (particularly the combination of agricultural R&D, irrigation expansion and policies that affect other inputs, such as fertilizers). Economic research has demonstrated that growth in staple food production influences farmer incomes directly, but also has indirect effects on the demands for unskilled labor (Mellor, 1976; Hazell, 2009). This influence on labor earnings explains why the rural landless have typically benefited from Asia's Green Revolutions (Hazell, 2009). In partially closed economies an increase in rice production also reduces real rice prices, with important implications for food security (Shahabuddin and Dorosh, 2002). However, the effects of rice productivity growth on the consumption of other foods is ambiguous. Higher

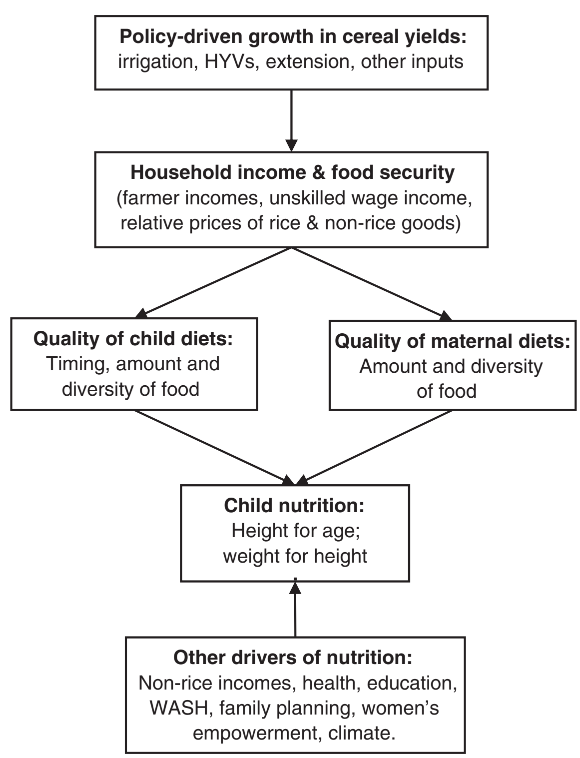

Fig. 1. The linkages between yield growth, dietary changes and nutrition outcomes. Notes: WASH refers to water, sanitation and hygiene.
Source: Authors' construction.

incomes should raise the demand for more nutrient-rich foods (e.g. meat, eggs, fish and fruits and vegetables), but unless there is an adequate supply response this increase in demand may increase prices (Bouis, 2000), which will constrain consumption of these foods. As we discuss below, in Bangladesh there are likely to be basic agroecological constraints to diversifying agricultural production. Imports can partially play a role in strengthening supply response, though imports of highly perishable foods like vegetables, eggs and dairy products, will likely be highly constrained. These supply constraints, perhaps in combination with cultural factors that inhibit demand for nutrient-rich foods, likely explain the limited diversification of the Bangladeshi diet despite real income gains.

The next step in this framework is to consider how household level increases in incomes, rice consumption, and dietary diversity translate into improvements in the nutrition outcomes of young children, either via improvements in the diets of those children or in the diets of their mothers. A well-established nutritional literature has shown that linear growth (height for age) largely manifests itself in the first 1000 days of life (in utero and in the first 24 months of childhood), after which there is substantial stabilization in heights (Victora et al., 2009). Improvements in maternal diets can therefore influence child nutrition through growth in utero or, secondarily, via improved breastfeeding outcomes. Postnatal growth is more a function of child feeding practices, as well as exposure to infections that can curtail nutrient utilization.

Thus, in addition to direct tests of the relationships between nutrition outcomes and growth in rice yields, it is also important to explore the relationships between rice yields and maternal nutrition, and rice yields and child feeding outcomes. In terms of the latter we distinguish between the timing at which complementary (solid or semi-solid) foods are introduced (the WHO recommends 6 months, but many South Asian children start much later than this, and the diversity of foods given to young children. We hypothesize that the timing at which solid food is introduced may be a rough proxy for calorie intake at this critical age of accelerated faltering in both weight and height gain, since related indicators (feeding frequency) have been shown to be reasonable proxies for calorie intake (Working Group on IYCF Indicators, 2006). A child's dietary diversity may also proxy for calorie intake, but is likely more strongly linked to micronutrient intake. This indicator has also been empirically linked to linear growth in young children (Arimond and Ruel, 2006).

Finally, while Fig. 1 is a simplified framework designed to focus on the dietary aspects of agriculture-nutrition linkages, we note that: (1) productivity growth in agriculture might also have some negative non-dietary impacts on nutrition; and (2) many other factors may influence nutrition, and perhaps interact with agricultural drivers. Negative non-dietary aspects of agricultural productivity growth could include increased demands on women's time (Headey et al., 2012), as well as increased exposure to potentially harmful fertilizers and pesticides (Brainerd and Menon, 2014). However, observationally it appears that Bangladeshi women tend to work less in rice production and more in the homestead on rice processing and other non-rice activities. Other non-agricultural drivers of nutritional change in Bangladesh are discussed in Headey et al. (2015), and include parental education, sanitation, women's empowerment, reductions in fertility, and broader non-agricultural growth in manufacturing and services, as well as overseas remittances. In our statistical analysis we control for many of these factors, but we also assume that these factors influence nutrition independently of rice productivity growth (i.e. without interactions). This is not necessarily a plausible assumption. For example, there is evidence that women's empowerment influence the intrahousehold distribution of resources (see Malapit et al., 2015, for example), and there are clear biological links infections (which are related to WASH) and diets (Humphrey, 2009). In this paper the data are at hand are not well suited to exploring these complex interactions, but future work could relax this assumption.

3. Background on agricultural development and nutrition in Bangladesh

In this section we aim to briefly describe the important role of rice productivity growth in agricultural production in Bangladesh, and how Bangladesh's production and trade characteristics have influenced dietary patterns.

3.1. Agricultural production and trade in Bangladesh

Bangladesh is characterized by uniquely intensive agricultural production that largely takes place on very small family farms engaged in multiple cropping seasons. Most of the rural poor are landless farm or nonfarm laborers, or smallholders (Balagtas et al., 2014; Hossain, 2004). For all three groups rice is an exceptionally important crop. In 1997 – the start of our period of analysis – rice accounted for two-thirds of the value of food production, and almost 80% of the value of crop production, and around 70% of calorie intake (FAO, 2014). Rice prices have also been shown to be an important determinant of wage rates for unskilled workers in Bangladesh (Ravallion, 1990).

Traditionally, rice production utilized relatively low levels of irrigation and other modern inputs. Production was highly seasonal, with the vast majority of production taking place in the monsoonal *aman* season, with production in the dry season constrained by lack of water. But like other Asian countries, Bangladesh was to benefit substantially from the research and development of high-yielding varieties (HYVs) and the associated adoption of irrigation and other modern inputs; in short, the so called Green Revolution package (Ahmed et al., 2000; Hossain et al., 2006; Naher, 1997). Unlike most other Asian economies, however, Bangladesh's Green Revolution got off to a sluggish start. In 1967 the Bangladesh Academy of Rural Development imported the IR8 variety from The International Rice Research Institute (IRRI) in the Philippines and introduced them in the dry season, while IR20 was introduced in 1970 for the wet season. The spread of these varieties was slow in the 1970s, delayed by the war of independence and the rebuilding process, as well as the vulnerability of new varieties to pests and disease (Hossain et al., 2006). By the mid-1980s only around 27% of rice area was planted to modern varieties, and yield growth was averaging around 2.2% per annum (Fig. 2).

The 1990s saw more dramatic changes, however. First, the government progressively liberalized agricultural inputs, particularly the imports of small-scale irrigation equipment, including diesel pumps and shallow tube wells (Nazneen et al., 2007). As a result, irrigated area doubled from 1990 to 2010. The great water control afforded by the irrigated *boro* crop also increased the returns to high yielding varieties, leading to a rapid acceleration in *boro* yields. As a result, the share of the once minor *boro* crop in total production increased from around 15% in the 1970s to 58% in 2010. Moreover, while saline affected coastal areas were initially inhibited in adopting irrigation, these areas have seen

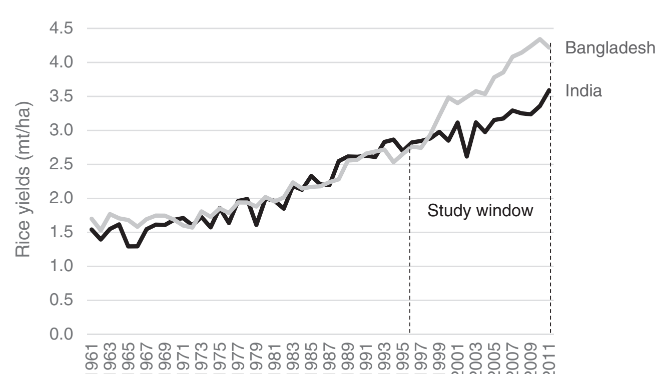

Fig. 2. Rice yields (mt/ha) in Bangladesh and India, 1961–2011. Source: FAO (2014).

some expansion in irrigation and HYV adoption since the mid 2000s, particularly with the adoption of more saline-resistant rice varieties (BR40 and BR41).

As a result rice production grew by 80.7% over 1997–2011, or 5.8% per annum, and accounted for 61.4% of total production growth (FAO, 2014). To put things in comparative perspective, Fig. 2 shows that rice yields in Bangladesh far outstripped yield growth in India over 1997–2011, thus providing us a with a late Green Revolution experience that overlaps with regular nutritional measurement.

Over time there was also some diversification of the Bangladesh production basket out of rice, though Bangladesh still has one of the least diversified production systems in the world. Per capita production of non-rice foods is much less than neighboring India (Table 1). There are various demand and supply-side reasons to explain this lack of diversification. As is well known, dry season irrigation in Bangladesh (and other South Asian countries) has led to dramatic reduction in the area devoted to pulses. Like India, Bangladesh now primarily relies on pulse imports to meet domestic demand, with imports amounting to 70% of consumption (FAO, 2014). Another supply-side factor of some importance is the poor suitability of water-logged soils to non-rice crops (Pingali, 2007), which especially inhibits production of vegetables and many fruits. Imports of vegetables and fruits from India and China have grown rapidly in Bangladesh and now account for approximately 10% of vegetable consumption and 43% of fruit consumption (FAO, 2014). Similarly, Bangladesh's high population density also constrains livestock production because of feed constraints, and the country partly relies on milk powder imports, though milk consumption is very low by international standards. Indeed, per capita production of milk, vegetables, fruit and pulses is less than half that of India (Table 1).

Finally, fish is an important consumption item in Bangladesh, not least because of the high micronutrient and protein content of traditional fish varieties especially. Measurement of fish production in Bangladesh is difficult because so much production is not commercial, but it has been hypothesized that traditional fish harvesting declined substantially with the increased use of pesticides and fertilizers and the decline in floodwater area (Shankar et al., 2005). Indeed, from 1980 to 2003 the real price of *hilsa* fish doubled (Sen et al., 2010). In more recent years, however, commercial (specialized) fish farming has grown rapidly, leading to increase fish consumption, albeit of new varieties that tend to be less rich in micronutrients (Bogard et al., 2015).

3.2. Dietary trends in Bangladesh

How have Bangladesh's production and trade patterns translated into changes in diets? Fig. 4 uses FAO Food Balance Sheets to compare basic trends in food supply (a proxy for average diets) in Bangladesh and India. These results need to be treated with caution because there may be systematic errors in FAO Food Balance Sheets, particularly mis-reporting of production for foods that are traded little (e.g. some vegetables, fruits and animal sourced foods). Bearing that caveat in mind, Fig. 3 shows some striking differences between Bangladesh and India. Panel A in Fig. 3 shows that estimated calorie deprivation in Bangladesh declined from 42% in 1990–92 to 27% in 2010–12, a level only slightly above neighboring India. This increase in calorie availability is mechanically related to increase rice production per capita, and is a standard rationale for investments in staple foods. Panel B tells a very different story in terms of dietary diversification, as measured by the share of calorie obtained from non-starchy staples. Bangladesh has one of the least diversified diets in the world, and saw little diversification in its food supply over time, with the share of non-starch calories rising from just 15% in 1990–92 to 21% in 2010–12. This is just half the level of India.

In Table 2 we try to get a more complete and potentially more accurate picture using national level Household Income and Expenditure Survey (HIES) data to separate dietary trends across expenditure quintiles in both rural and urban areas. Although the HIES data show a somewhat faster diversification of diets than the FAO, they confirm that dietary diversification is very low in Bangladesh, especially in rural areas and especially among poorer quintiles. Indeed, in 2011 the share of calories from non-starchy staples in rural diets was less than 30% in all but the richest quintile.

While national and household level indicators are useful for understanding broad patterns of dietary change, for these changes to influence young children one must observe improvements in their diets, or in the diets of their mothers (which affects growth in utero, and potentially also the quality of breastmilk). For maternal diets, we lack data on trends over time, although the Demographic Health Surveys can be used to estimate changes in mothers' body mass index (BMI) over time in rural Bangladesh. We find that BMI increased among both pregnant (by 7.8% over 1997–2011) and non-pregnant mothers (by 9.2% over 1997–2011). While even adult BMI can be influenced by infection, these large increases likely reflect increased calorie consumption among Bangladeshi women.

For postnatal growth, however, child level feeding practices will have a more direct impact on linear growth and weight gain. Poor feeding practices are regarded by nutritionists as a critical constraint in South Asia (Senarath et al., 2012; Kabir et al., 2012; Menon, 2012). In addition to inappropriate breastfeeding practices (which are unlikely to be directly influenced by agricultural production), there are significant problems with *when* solid and semi-solid foods are introduced, and with limited diversity in those foods. Table 3 reports various indicators of the timing and diversity of solid foods (we note that these indicators should be interpreted cautiously because food categories in the DHS change somewhat over time). The WHO recommends that solid/semi-solid foods should be introduced at 6 months, but Table 3 shows that

Table 1
Trends in per capita production (kg) of various food groups, Bangladesh and India, 1996–2011.
Source: FAO (2014).

	Rice		Milk		Vegetables	
	Bangladesh	India	Bangladesh	India	Bangladesh	India
1996	152.9	74.7	29.5	117.7	11.5	54.6
2011	172.6	70.8	41.9	168.4	26.0	80.5
	Meat		Fruit		Pulses	
	Bangladesh	India	Bangladesh	India	Bangladesh	India
1996	4.0	6.1	11.1	36.0	4.3	11.8
2011	5.0	7.4	24.4	52.9	3.9	14.2

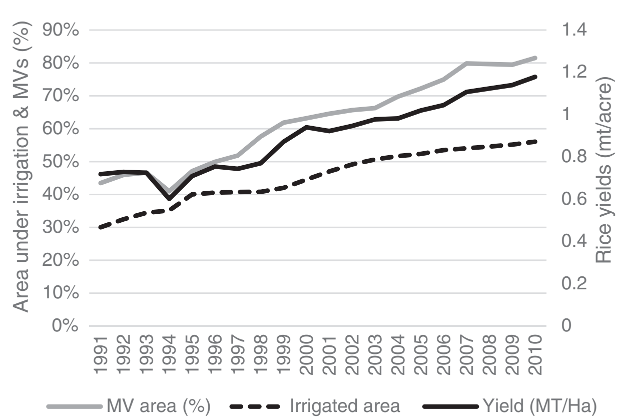

Fig. 3. Trends in irrigation, modern variety (MV) uptake and rice yields.
Source: Data are from the Bangladesh Bureau of Statistics, various years.

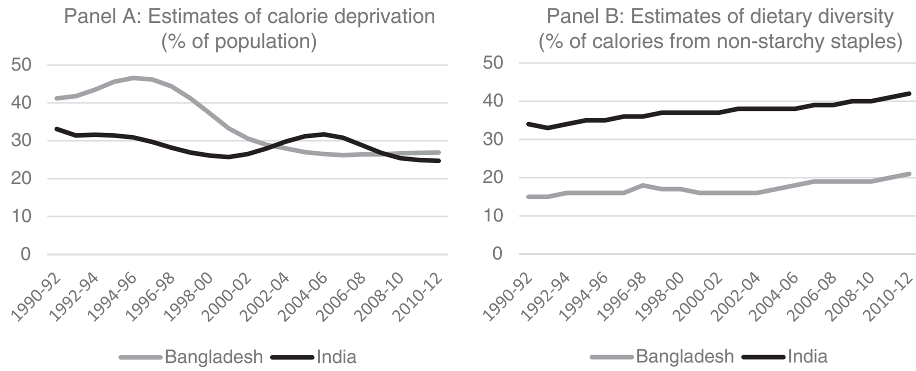

Fig. 4. FAO estimates of calorie deprivation and dietary diversity in Bangladesh and India, 1990–2012.
Source: FAO (2014).

in 2000 only half of children aged 6–8 months were given solid foods yesterday. By 2011 this had risen substantially to around 60%. Mean dietary diversity appears to have stayed the same or declined, with the average child aged 6–24 months given only 2.11 food groups in 2011. Likewise only a few children were given at least 4 food groups yesterday (the WHO recommendation for minimum dietary diversity). Finally, consumption of dairy products – which has previously been shown to be a strong predictor of child growth outcomes in a number of studies (Hoddinott et al., 2015; Hoppe et al., 2006; Iannotti et al., 2013; de Beer, 2012) – was unchanged over 2000–2011. Overall, then, there are some signs of improvements in maternal BMI and in the timely introduction of solid foods – both of which likely reflect increased calorie consumption by mothers and young children - but little indication that children's diets have diversified.

4. Construction and analysis of a district level agriculture-nutrition panel

More formal empirical tests of agriculture-nutrition linkages is greatly constrained by lack of data, with nutritional surveillance rarely collecting agricultural data, and long running household economic surveys rarely collecting anthropometric or dietary data for young children. For these reasons we create a synthetic panel by merging together five rounds of data on rural households and children from the nationally representative Bangladesh Demographic Health Surveys (DHS) collected in the years 1996/97, 2000, 2004, 2007 and 2011, with district level agricultural data (BBS, 2014). We focus on rural areas only. While rice productivity growth might benefit urban areas through lower rice prices, high levels of market integration across urban areas would presumably result in very little spatial variation in rice prices. Moreover, the urban sample in the DHS is relatively small, leaving some districts with very few urban observations.

Each observation in our rural panel is a year-district mean. There are 23 rural districts and five observations per district, but because we are missing data for several districts in several rounds, our sample has 109 district-year observations in total. When constructing this sample, we were concerned that we had a sufficient number of children in each district. In our main sample the median number of children per district-year is 352, though there are a handful of districts where much fewer children were measured (the minimum being 17 children), mostly in the Chittagong Hill districts. We test the robustness of our results to the exclusion of such districts.

Our outcome variables reflect two dimensions of undernutrition in children: acute undernutrition (weight for height); and chronic undernutrition (height for age). We also apply cut-offs to create indicators of undernutrition prevalence at the district level. For weight-for-height z-scores we use a threshold of −1 standard deviations to identify "mild wasting" prevalence, and −2 to identify "moderate wasting". For height for age z-scores we use −2 standard deviations for moderate stunting and −3 for severe stunting. We focus on weight gain and linear growth in the first 24 months, largely because anthropometric processes tend to stabilize beyond 24 months (Victora et al., 2009) but also because we lack the aforementioned dietary indicators for children older than 24 months.

We also test whether rice productivity growth explains changes in some basic DHS indicators of child feeding practices among children aged 4–18 months.[1] The first such indicator is the timely introduction of complementary foods, which refers to the proportion consuming any solid or semi-solid foods. A second child feeding indicator is minimum dietary diversity (as defined by the World Health Organization), which is the percentage of children consuming four or more food groups out of a maximum of seven. Dietary diversity indicators have previously been shown to be a robust predictor of linear growth in children.

In terms of rice productivity, we focus on rice yields in the 12 months just prior to the start date of each DHS round. Yields are likely the best summary indicator of productivity in rice production, reflecting the benefits of both high-yielding varieties, irrigation, and other modern inputs such as fertilizers, pesticides and herbicides. But because our weight-based indicators of nutrition outcomes are potentially quite sensitive to short term fluctuations, we pay particular attention to the timing of measurement. We measure yields in the 12 months prior to each survey since current household rice stocks and local rice prices

Table 2
Changes in dietary diversification (share of calories from non-starchy staples) across rural and urban income quintiles.
Source: Author's estimates from the Household income and expenditure surveys (HIES), BBS (2014).

	Q1	Q2	Q3	Q4	Q5
Rural income quintiles					
1995	15.0	17.3	19.0	21.2	25.3
2010	20.2	23.1	25.6	28.9	33.6
Urban income quintiles					
1995	16.7	18.4	19.5	21.8	32.1
2010	21.7	24.9	29.0	33.0	41.0

[1] The timely introduction of complementary foods is normally measured in the 6–8 month window as per WHO guidelines. However, restricting the sample to 6–8 months would not provide us with enough children at the district level to ensure sufficiently minimal measurement error. Moreover, earlier rounds of the Bangladesh DHS suggest that reasonably large numbers of children were not even given solid or semi-solid foods in late infancy (12–18 months). In the past, some nutritionists have also advocated earlier introduction of solid or semi-solid foods (4–5 months) in conjunction with continued breastfeeding. Hence, our window of measurement for this indicator is somewhat unconventionally large. In any event our results are qualitatively robust to marginally reducing this window, although they are inevitably somewhat less precise.

Table 3
Trends in selected child feeding indicators in rural Bangladesh, 2000–2011.
Source: Author's estimates from the 2000 and 2011 rounds of the Demographic Health Surveys.

	Child given any solid or semi-solid food yesterday (children 6–9 months)	Mean dietary diversity yesterday (7 food groups; children 6–24 months)	Minimum dietary diversity yesterday (children 6–24 months given 4-plus food groups)	Child given any dairy yesterday (children 6–24 months)
2000	46.7%	2.25	22.2%	25.1%
2011	58.9%	2.11	13.8%	27.7%

largely depend on production in recent seasons rather than the still-ongoing current season.[2] Given Bangladesh's multiple seasons, rice yields are the sum of production in different seasons divided by the total crop area harvested in those seasons. This indicator is only available at the district level, and is based on agricultural surveys carried out by the Bangladesh Bureau of Statistics (Bangladesh Statistical Yearbook, various years). Table 4 shows descriptive statistics for our key agricultural and nutrition indicators for the 109 district-years in our sample.

We model the relationship between nutrition outcomes and yields as:

$$N_{i,t} = \alpha + \beta.y_{i,t} + \theta.R_{i,t} + \boldsymbol{\gamma D}_{i,t} + \boldsymbol{\delta X}_{i,t} + \boldsymbol{T}_t + \boldsymbol{\mu}_i + \varepsilon_{i,t} \quad (1)$$

where N refers to child nutrition outcomes for district i and time t, y to rice yields, β to the impact of yields on nutrition, R to district level rainfall, D to child age and its square, X to various other determinants of nutrition outcomes such as education, health, sanitation and demographic variables, T to time dummies for each survey round, $\boldsymbol{\mu}$ to district fixed effects, and ε to an error term. As such, we control for time-invariant factors that could be correlated with both yields and nutritional quality (e.g. water availability, soil quality, climate, cultural practices), aggregate temporal effects that might simultaneously influence agricultural productivity and nutrition (for example, changes in international food prices) and a number of nutrition-relevant control variables that could also potentially be correlated with rice productivity/technology growth.

While the Eq. (1) controls for a wide range of observable factors, we acknowledge that empirical estimates of the effects of yields on nutrition could still be biased by unobservable factors that simultaneously influence rice yields and nutrition. Our assumption is that growth in district level rice yields largely reflects local suitability to improved technologies, particularly irrigation and HYVs. Dry season (*boro*) irrigation – the major driver of yield growth over 1997–2011 – was substantially constrained in coastal saline-affected districts and in the higher altitude Chittagong hill tracts. This assumption is contestable because it is possible that other endogenous factors may have substantially influenced yield growth (such as rising demand from growing urban centers) and simultaneously affected nutrition through other pathways (such as increased non-farm income). This means that we must treat the results below as suggestive rather than definitive evidence on the linkages between rice productivity growth and changes in child nutrition outcomes.

5. Empirical tests of the links between yield growth and changes in nutrition outcomes and feed practices across Bangladeshi districts

In this section we use the district level panel to test whether growth in rice yields explains changes in nutrition outcomes over 1997–2011, before then testing whether yields explain changes in child feeding practices. Finally, we describe the results of various empirical extensions to our main results, including several robustness tests.

5.1. Child nutrition outcomes

Table 5 reports the results of regressing the various chronic and acute child nutrition outcomes against rice yields in models that control for fixed effects and time period effects, as well as child age and its square. In regressions 1, 2 and 3 we find that rice yields have no significant effect on the three indicators of height gain (HAZ, HAZ < −2 and HAZ < −3). One explanation may be that current stunting rates are in fact related to cumulative nutrition processes, and hence to several years of lagged rice productivity outcomes. Another explanation may be that linear growth benefits more from dietary diversification than calorie availability. We explore these explanations below.

Unlike height gain, rice yields have a large and well-measured association with weight gain. The effects of yields on the WHZ score is significant at the 5% level and is meaningful in magnitude. The 0.5 metric ton (mt) increase in yields per acre over 1997–2011 predicts a 0.4 standard deviation improvement in WHZ scores. The same increase in yields predicts a 12 percentage point decline in mild wasting (WHZ < −1). But in regression 6 we see no significant association between yield growth and moderate wasting (WHZ < −2).

These results could be confounded by district time-varying characteristics. The focus of our study is on policy-driven changes in rice yields, but rainfall also influences yields, and can influence nutrition independently of yields via infection. Headey et al. (2015) also find evidence that many other socio-economic factors may have driven nutritional change over time, and some of these factors may be correlated with yield growth at the district level. We follow Headey et al. (2015) in extracting a wide array of relevant indicators, such as parental education, toilet use, access to antenatal care, fertility rates, a proxy for

Table 4
Descriptive statistics for the district level panel.

	Number of district-year observations	Mean	Standard Deviation
Rice productivity			
Yields (mt/acre)	109	0.93	0.21
Child nutrition[a]			
HAZ score	109	−1.56	0.33
Moderate stunting, HAZ < −2 (0–1)	109	0.39	0.11
Severe stunting, HAZ < −3 (0–1)	109	0.16	0.08
WHZ score	109	−1.02	0.29
Mild wasting, WHZ < −1 (0–1)	109	0.51	0.10
Severe wasting, WHZ < −2 (0–1)	109	0.19	0.08
Child feeding[b]			
Complementary feeding, 6–9 months (0–1)	109	0.68	0.18
Minimum dietary diversity, 6–24 months (0–1)	89	2.17	0.78
Dairy consumption, 6–24 months (0–1)	109	0.31	0.15

[a] Child nutrition indicators are measured for children aged 0–24 months.
[b] Child feeding indicators are measured for children aged 4–18 months. Note that the dietary diversity indicator is not available for 1 the 1996/97 round.

[2] The availability of seasonal production data at the district level allows us to adjust our agricultural measurement dates to the DHS survey timing. For example, in the 1996/1997 DHS rounds the survey dates ranged from October 1996 to April 1997. Thus we measured yields in the 12 months from July 1995 to June 1996, which includes the 1995 *aman* yield (harvested mostly in November and December 1995) and the *boro* and *aus* yields from April to June 1996. In another round (2004) the DHS began in January and finished in May, so we measured yields in the previous calendar year (2003).

Table 5
Fixed effect estimates of the impact of rice yields on chronic and acute child nutrition indicators.

	1	2	3	4	5	6
	HAZ score	Moderate stunting (HAZ < −2)	Severe stunting (HAZ < −3)	WHZ score	Mild wasting (WHZ < −1)	Moderate wasting (WHZ < −2)
Rice yields	−0.14	0.18	−0.05	0.79**	−0.23*	−0.15
	(0.34)	(0.16)	(0.10)	(0.30)	(0.12)	(0.14)
Age control	Yes	Yes	Yes	Yes	Yes	Yes
Time effects	Yes	Yes	Yes	Yes	Yes	Yes
Fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.42	0.35	0.41	0.28	0.33	0.41
Sample size	109	109	109	109	109	109

Notes: *, **, and *** indicate significance at the 10%, 5% and 1% significance levels respectively. Robust standard errors are included in parenthesis. All indicators are measured for children 0-24 months of age.

women's empowerment (her self-reported ability to go to a health clinic alone), membership of BRAC (a large Bangladeshi NGO that provides agricultural and non-agricultural services), and a household asset score (scaled to vary between 0 and 10). This last indicator provides excessive control because we expect yields to chiefly influence nutrition via household economic status, either through increased food production, higher wages or lower food prices, or some combination of all three. Hence we specify multivariate regressions with and without the asset index to check whether rice productivity does indeed operate via economic status.

Table 6 shows that adding time-varying control variables (excluding assets) to the bivariate models from Table 5 reduces the effects of yield growth on the weight-for-height indicators only very slightly. In the case of WHZ scores the coefficient drops from 0.79 to 0.66, while in the case of mild wasting it remains unchanged but more imprecisely estimated and is now marginally insignificant at the 10% level. We also note that adding these controls substantially increased the coefficients of determination of these models, and that significant coefficients are observed on rainfall, toilet use and prenatal care.

Table 6
Adding control variables to the WHZ and mild wasting fixed effects models.

	1	2	3	4
	WHZ		Mild wasting (WHZ < −1)	
	Excluding assets	Including assets	Excluding assets	Including assets
Rice yields	0.66**	0.19	−0.23	−0.11
	(0.25)	(0.31)	(0.15)	(0.15)
Log of rainfall	0.38	0.47*	−0.19*	−0.21*
	(0.26)	(0.25)	(0.11)	(0.11)
Maternal education (years)	0.14	0.09	−0.02	−0.01
	(0.09)	(0.08)	(0.03)	(0.02)
Paternal education (years)	0.01	−0.04	0.01	0.03
	(0.06)	(0.05)	(0.02)	(0.02)
Households with toilets (%)	0.67*	0.66**	−0.18	−0.18*
	(0.35)	(0.31)	(0.11)	(0.10)
Prenatal care (%)	0.28	0.09	−0.26*	−0.21**
	(0.40)	(0.27)	(0.13)	(0.10)
Fertility rates	0.19	0.12	−0.05	−0.03
	(0.12)	(0.09)	(0.05)	(0.04)
Women can visit clinics (%)	−0.11	0.38	0.07	−0.06
	(0.32)	(0.31)	(0.11)	(0.11)
NGO members (%)	0.42	0.51	−0.17	−0.19
	(0.67)	(0.66)	(0.20)	(0.21)
Household asset score (1−10)		0.25***		−0.07***
		(0.05)		(0.02)
Age controls	Yes	Yes	Yes	Yes
Time effects	Yes	Yes	Yes	Yes
Fixed effects	Yes	Yes	Yes	Yes
R-squared	0.40	0.53	0.39	0.47
Sample size	109	109	109	109

Notes: *, **, and *** indicate significance at the 10%, 5% and 1% significance levels respectively. Robust standard errors are included in parenthesis. All indicators are measured for children 0-24 months of age.

Quantitatively, the results from Table 5 therefore appear quite robust to incorporating some of the alternative explanations of nutritional change in Bangladeshi districts. However, the coefficients on yield growth drop significantly in magnitude and lose significance when the mean household asset score is added to these models. This result lends some uncertainty to the relationships between yield growth and changes in weight gain. One interpretation is that yield growth drives income growth and asset accumulation (i.e. assets are a mediating factor between yield growth and weight gain in young children. But this result is also consistent with the possibility that independent economic factors – such as rising demand for rice from non-farm economic growth – are simultaneously increasing household assets in rural areas and driving yield growth. We examine this issue in robustness tests and extensions reported below.

5.2. Associations between yield growth and changes in child feeding indicators

Yield-induced improvements in child weight gain suggest that children are either given more food, or possibly also better food (since micronutrients can also build up immunity to diseases, which can affect weight gain). In Table 7 we therefore explore associations between the three child feeding indicators introduced in Section 3: the introduction of solid foods among children 6–9 months, minimum diet diversity among children 6–24 months, and dairy consumption among children 6–24 months. Consistent with expectations we observe a large and significant effect of rice yields on consumption of solid foods among children 6–8 months, suggesting that poor rural Bangladeshi households may delay the introduction of complementary foods by extending their reliance of breastfeeding as the principal source of nutrition for young children. Consistent with this rationing hypothesis we also find that rainfall is positively associated with the introduction of complementary foods. As expected, we observe no significant associations between rice yields and minimum dietary diversity or milk consumption.

Finally, Table 8 reports associations between regressions of mild wasting and moderate stunting rates against the three indicators of feeding practices. Regression 1 shows that the introduction of complementary foods is strongly associated with child weight outcomes, with a coefficient of −0.19. Minimum dietary diversity and milk consumption have insignificant coefficients in the wasting model (regressions 2 and 3 respectively). In regression 4 we observe no significant association between complementary feeding and stunting, consistent with the lack of a significant impact of yields on stunting. However, minimum dietary diversity and dairy consumption are strongly and negatively associated with stunting rates, with comparable point estimates (−0.29).

Together, the results above suggest that rice productivity growth has significantly influenced child weight gain through the earlier introduction of complementary foods, and perhaps also greater quantities of these foods. However, the insignificant effects of yield gains on linear

Table 7
Fixed effects estimates of the impact of yield growth on child feeding indicators.

	1	2	3
	Complementary foods, 6–9 months	Minimum dietary diversity, 6–24 months	Dairy consumption, 6–24 months
Rice yields	0.47*	−0.04	−0.17
	(0.25)	(0.13)	(0.17)
Child age controls	Yes	Yes	Yes
Additional time varying controls	Yes	Yes	Yes
Time effects	Yes	Yes	Yes
Fixed effects	Yes	Yes	Yes
R-squared	0.87	0.88	0.44
Sample size	100	89	109

Notes: *, **, and *** indicate significance at the 10%, 5% and 1% significance levels respectively. Robust standard errors are included in parenthesis. Additional time varying controls include those used in Table 6, excluding assets.

growth in children seems related to the limited impacts of these gains on dietary diversification.

5.3. Extensions and robustness tests

In addition to the results above we conducted a number of extensions and robustness tests. For the sake of brevity, these results are summarized here in the text only; the full set of results is available upon request.

In terms of basic robustness tests, we tested robustness to the exclusion of the Chittagong Hill districts (which have smaller DHS samples and somewhat less dependence on rice production), and to the inclusion of additional control variables (such as alternative indicators of access to health services). The core results remain robust to these additional tests.

Another concern with these results rests with our assumption that yield growth was largely an exogenous supply-side technology-driven process. Economists might argue that rice yields might be driven more by demand-side than supply-side factors, and that these demand-side factors have other links to nutrition. For example, remittances from overseas workers have grown rapidly in Bangladesh (with spatial variation), as has the manufacturing sector (again with spatial variation). These other sources of income growth could raise demand for rice, but also influence nutrition via household income/assets. However, there are three predictions of our technology-led assumption that are testable: (1) that yield growth over 1997–2011 was overwhelmingly driven by the package of irrigation and HYVs; (2) that child wasting is higher in coastal areas where irrigation adoption was exogenously constrained by salinity problems; and (3) that the more rapid increases in irrigation in non-coastal areas was associated with more rapid asset accumulation in those areas.

All three predictions are supported by the data. With respect to prediction (1) we use the district level agricultural sample survey data to test how much of the growth in yields is explained solely by changes in irrigation and HYV adoption; the answer is a high 80%. Second, we run least squares regressions of nutrition indicators against a dummy variable for coastal districts, and the set of time-varying control variables used above (excluding assets, and excluding the three hill districts that are agroecologically different, but also culturally very different). The results suggest that, controlling for differences in other nutritional determinants, mild and moderate wasting rates are significant higher in coastal areas compared to non-coastal areas, by 5 and 6 percentage points respectively.[3] Consistent with the results in sub-section 5.1, we find no stunting/HAZ differences between coastal and non-coastal districts. Finally, we look at trends in the asset index (which varies between 0 and 10) across coastal and non-coastal districts (again, excluding the three hill districts). In 1997 the data suggest that coastal districts were significantly richer than inland non-hill districts at the 10% level, by about 0.60 points. This is a reasonably large difference of about two-thirds of a standard deviation. However, by 2011 the non-coastal districts had slightly higher asset scores than the coastal districts (though not significantly so); in other words, asset accumulation was more rapid over 1997–2011 in those districts with greater suitability for irrigation.

We also explored whether the lack of an association between yields and HAZ/stunting stems from the fact that yields from the most recent season might be less important than yields from earlier seasons, including those preceding a child's birth (i.e. in utero). Consistent with this possibility, Headey et al. (2015) show that much of the improvement in child HAZ scores in Bangladesh seems to stem from improvements in birth size. We therefore estimated regressions of HAZ again yields in the year of a child's birth, but found no significant results. We also estimated mean maternal BMI scores (and maternal underweight prevalence) against yields, but again found no significant results (despite maternal BMI being strongly associated with asset scores). Of course, it may be that there really are significant linkages between yields and linear growth in children, but that they are simply to dynamically complex to untangle with the data at hand. Or it may be that rice yields genuinely have little influence on linear growth, perhaps precisely because of the limited impacts of Bangladesh's Green Revolution on dietary diversity.

Table 8
Fixed effects estimates of the associations between child feeding indicators and child nutrition outcomes.

	1	2	3	4	5	6
	Mild wasting (WHZ < −1)			Moderate stunting (HAZ < −2)		
Complementary feeding (%)	−0.24**			0.08		
	(0.09)			(0.14)		
Minimum diet diversity (%)		0.06			−0.29*	
		(0.11)			(0.15)	
Dairy consumption (%)			0.07			−0.29**
			(0.09)			(0.14)
Age controls	Yes	Yes	Yes	Yes	Yes	Yes
Time effects	Yes	Yes	Yes	Yes	Yes	Yes
Fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.32	0.27	0.26	0.31	0.24	0.36
Sample size	100	88	107	109	89	109

Notes: *, **, and *** indicate significance at the 10%, 5% and 1% significance levels respectively. Robust standard errors are included in parenthesis.

6. Conclusions

In this paper we explored the links between rapid productivity growth in rice production, dietary diversification and changes in the

[3] WHZ scores were also lower in coastal areas by about 0.12 standard deviations, though this coefficient is only significant at the 11% level.

nutritional status and feeding patterns of young children during Bangladesh's impressive late Green Revolution period. We first show that diets in Bangladesh are remarkably undiversified, and have only diversified slowly during this period of rapid rice intensification. We also find that increases in rice yields have large and statistically significant associations with child weight gain, which appears to be at least partially explained by increased food consumption for young children, particularly the timelier introduction of complementary foods in the critical early window of child development. This potential impact of yields on child weight gain is important – Bangladesh still has one of the highest rates of child wasting in the world – but it is also somewhat disappointing that we were unable to detect any benefit from increasing rice yields on child growth outcom03 empirical tests may not be granular enough to unravel the complex dynamic linkages between yields and linear growth in young children, both our descriptive and econometric evidence does suggest that this may be explained by the very limited dietary diversification in Bangladesh.

These results point towards several potentially important policy implications, though further evidence is still needed to corroborate the linkages hypothesized in this paper.

First, we provide strong evidence that delays in the introduction of complementary foods – and most likely, in adequate calorie intake of children - are related to low levels of agricultural productivity and household economic status (assets). Hence, public investments in staple food production would appear to be an important tool for overcoming those constraints, in addition to safety net programs for poor households, as well as the kinds of behavioral change communications programs typically favored by nutritionists for the improvement of complementary feeding (Dewey and Adu-Afarwuah, 2008).[4]

Second, it is clear from different types of data that diets have diversified very little over a period of rapid productivity growth in the main food staple. A major challenge in Bangladesh is to understand the constraints to dietary diversification, and policy options for accelerating diversification. Examples of potential policy levers include a reorientation of Bangladesh's agricultural R&D portfolio towards more micronutrient-rich crops and livestock products, an increased focus on diversifying production via agricultural extension programs, behavioral change and communication interventions to nudge parents into healthier feeding practices, nutrition-sensitive social safety nets to improve the purchasing power of the poorest households (perhaps conditional upon participation in nutritional programs), and interventions to alleviate the many marketing bottlenecks that inhibit both domestic production and domestic and international trade of perishable nutrient-rich foods in particular (e.g. lack of cold storage, inadequate infrastructure, regulatory burdens to trade).

Assessing the effectiveness of these types of policies and programs in accelerating diversification towards healthier and more nutrient-rich diets would seem to be an important area for future research.

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[4] Indeed, the importance of household economic status and food security for complementary feeding may explain why purely behavioral interventions to improve child feeding practices have had variable and often rather modest effects (Dewey and Adu-Afarwuah, 2008).

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