From Blessing To Burden: Long-Run Health Effects of India's Green Revolution

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1. Introduction

Between 1965 and 1990, India witnessed a dramatic shift in its agricultural landscape, driven by the widespread adoption of high-yielding variety (HYV) of wheat and rice, along with extensive usage of agrochemicals– a hallmark of the Green Revolution. This transformative period, fueled by innovations in agricultural research in wheat and rice, led to remarkable gains in crop productivity, making India a global agricultural leader and improving food security [Evenson and Gollin, 2003, Pingali, 2012]. However, while much of the scientific discourse has centered on calorie security through investments in these grains, the impacts on non-staple crops, and their role in providing essential proteins and micronutrients, remain less understood. Potential health concerns have arisen, likely linked to nutritional shifts resulting from reliance on wheat and rice, while the heavy usage on agrochemicals has also raised alarms about exposure to environmental toxins and their long-term health consequences. [Shiva, 1991, Pingali et al., 2019].

This study explores the long-run health effects of the Green Revolution in India by addressing three main questions. First, I examine how the adoption of Green Revolution technologies affected crop diversity and which crops experienced a decline in area and production. Second, I look at how these shifts influenced per-calorie production of key macro- and micronutrients. Finally, I investigate long-run health outcomes, focusing on the effects of in-utero nutritional changes and exposure to agrochemicals resulting from the adoption of these technologies.

In my empirical strategy, I use a difference-in-differences (DiD) framework to evaluate the effects of Green Revolution technologies, leveraging two key variations: the timing of their introduction in 1966 and cross-district differences in "potential productivity gains" of wheat and rice based on climatic and ecological conditions. For the potential productivity gains, I use potential yield (kg per hectares) models provided by the Food and Agriculture Organization (FAO). These models estimate maximum potential crop yields of wheat and rice at a high resolution grid cell level, considering climatic and ecological suitability. They provide two yield estimates for each crop per grid cell: one with traditional practices and another with modern technologies (HYVs). I aggregate these to the district level to create a district-specific measure of potential productivity gains for wheat and rice. Regions with larger potential gains are those with the biggest difference between traditional and modern varieties, driven by time-invariant characteristics.

I start by providing motivating evidence on potential occurrence of nutritional shifts. My analysis proceeds in four steps. First, I test the hypothesis that districts with higher potential productivity gains from wheat and rice would have higher HYV adoption rates.[1] To do this, I use a longitudinal dataset with annual district-level data on HYV wheat and rice areas, total cropped area, and production for 21 crops across 266 districts from 1957 to 2007. I find that potential productivity gains are a strong predictor of the HYV adoption rate of wheat and rice.[2] Second, I assess the effect on crop diversity and find significant declines in districts with higher potential productivity gains from the Green Revolution.[3] In districts with the highest potential productivity gains, the findings indicate that crop diversity decreases from an average of 5 crops to 2.5 crops. Event study analysis confirms that these changes are attributable to HYV adoption, not pre-existing trends, and results are robust across different measures of crop diversity. After analyzing the overall decline in crop diversity, I identify which specific crops have been reduced. The analysis reveals a significant drop in the cultivated area for barley, pearl millet, chickpea, minor pulses, and groundnut.[4] I then assess changes in crop production to understand the effect on diverse food availability. This shows a notable increase in wheat and rice production, while pearl millet, chickpea, minor pulses, pigeonpea, and groundnut have seen substantial declines.

What is the impact of these production changes on availability of macro and micro-nutrients? The decline in lentils and millet, rich in protein and essential micronutrients like iron and zinc, is concerning for food supply. Reduced cultivation of diverse crops could decrease nutrient availability.[5] Lastly, I translate crop production data into caloric and nutrient equivalents to evaluate the effects on total calorie production and nutrient supply per calorie.[6] The results indicate an average 20% increase in calorie production,

[1] HYV adoption rate is defined as the share of land under HYV wheat and rice in total cropped area.

[2] I control for district, time fixed effects and district-time varying factors: precipitation and temperature, and baseline district characteristics, including crop areas, yields of wheat and rice, and socio-economic variables, interacted with year fixed effects

[3] Crop diversity is defined using Shannon Diversity Index. For more details, see Section **??**

[4] I observe similar patterns for both the extensive and intensive margins.

[5] India's food supply is predominantly plant-based, with plant foods contributing around 94% of total food energy, micronutrients and 85% of total protein [Hopper, 1999]

[6] National Food Composition Table (2017), India, is used to convert crop production into caloric and nutrient units.

accompanied by a 0.6% increase in carbohydrate supply per calorie. However, I find 3% decline in protein supply per calorie. Additionally, there are statistically significant reductions in micronutrient production per calorie, with declines of 2% in iron, 9% in folate, and 2% in zinc, while calcium production remains unchanged.[7]

This could affect nutritional intake, particularly in India, where limited market integration and high price dispersion persist. First, increased wheat and rice production may have lowered prices for these staples in some districts compared to others, leading to greater consumption of these grains. Moreover, even with increased incomes and a demand for dietary diversity, the supply of diverse crops may not be keeping up, as their overall production continues to decline.[8,9]

Having established the changes in caloric and nutrient availability, I now address the central question regarding the health outcomes associated with these nutritional shifts. For this analysis, I draw on the medical literature related to the Barker hypothesis [Barker, 1994], which underscores the role of maternal nutrition in "fetal programming" and its potential epigenetic effects on long-term growth and disease risk. The key factor here is the maternal diet's balance of macronutrients and micronutrients.[10] Diets high in calories and carbohydrates but low in protein and micronutrients may not cause overt deficiencies; however, multiple mild deficiencies combined with excess energy can disrupt cellular metabolism. These interactions are particularly significant during pregnancy, influencing fetal development and increasing the risk of non-communicable diseases [Christian and Stewart, 2010, Zou et al., 2021, Rees, 2019]. Research shows that inadequate protein or micronutrient intake during pregnancy and early childhood can lead to reduced linear growth, greater susceptibility to metabolic disorders, and impaired cognitive and motor development [Stocker et al., 2005, Hoppe et al., 2004, Mehta et al., 2002, Stein et al., 2003].

Building on this, I examine whether in-utero exposure to nutritional shifts from the Green Revolution affected long-run health outcomes. To conduct this analysis, I use individual-level data from the 2017 Longitudinal Aging Study in India (LASI), which includes health information for over 42,000 individuals born between 1945-1985. The dataset, sampled from 2,440 villages and towns across 13 states, records the district of birth, enabling me to link health outcomes to birth locations rather than current residences,

[7] The event study analysis shows no significant pre-trend differences in caloric or per-calorie nutrient availability.

[8] Pingali et al. [2019], Pingali [2012] highlights that while the Green Revolution effectively solved calorie sufficiency, it led to reduced dietary diversity and failed to address micronutrient deficiencies, "hidden hunger," and dietary quality.

[9] Although pre-Green Revolution consumption data is not available, I analyze consumption data from National Sample Survey, Household Consumption Expenditure Survey (1999) to support the relationship between district-level food crop production per capita and consumption per capita. This period, following economic liberalization, suggests improved market integration; even with this integration, local production remains a strong predictor of local consumption. See Table **??**.

[10] One theory suggests that undernutrition in utero can lead to a "thrifty phenotype," which helps the fetus optimize calorie use but increases the risk of metabolic syndrome later on, particularly in calorie surplus environments later in life. While this adaptation is linked to nutritionally scarce environments during fetal development, it may not explain the health outcomes of those born after the Green Revolution, when caloric supply improved but the quality of nutrition may have been diminshed [Sekhri and Shastry, 2024].

thereby controlling for non-random migration patterns.

Using a similar empirical approach, I employ a difference-in-differences strategy at the individual level. I compares individuals from the same district, who experienced different potential productivity gains based on their birth year. By controlling for district and year fixed effects, individual demographics, and time-varying district characteristics[11], I isolate the effects of potential productivity gains on health outcomes while accounting for unobserved health shocks that may vary by birth year. I estimate the effects on adult height, metabolic syndrome, cognitive decline, and motor skill deficits.[12] Given the multiple outcome variables, I adopt the approach of Kling et al. [2007] and Hoynes et al. [2016] by estimating summary standardized indices, which consolidate information across various outcomes and improve statistical power.

I find that in-utero exposure to potential productivity gains from wheat and rice significantly reduces height and increases the incidence of metabolic syndrome (a cluster of conditions including obesity, hypertension, heart disease, and diabetes). Specifically, a one standard deviation increase in productivity gains leads to a 0.2 cm decrease in height and a 0.014 standard deviation increase in metabolic syndrome, driven by a 2 percentage point rise in hypertension and a 0.8 percentage point increase in diabetes. While I also observe a rise in cognitive imbalance and motor function deficits, these effects are not statistically significant. Gender-based heterogeneity analysis shows stronger effects for males. Using a cohort event study design, I confirm no significant pre-trends, [13] reinforcing the causal interpretation of the results.

A potential challenge to my identification strategy is the correlation between recent trends—such as increased consumption of processed foods, more sedentary lifestyles, and varying access to healthcare—and potential productivity gains from wheat and rice, which could obscure the true effects. To mitigate this, I control for baseline characteristics, including urbanization, literacy, employment in the service sector, and access to healthcare, each interacted with a time trend. Despite these adjustments, I still observe a significant reduction in height and an increase in hypertension. While there are positive effects on metabolic syndrome, cognitive imbalance, and motor deficits, these findings are not statistically significant.

Another concern is that the Green Revolution may have impacted long-term health through non-nutrition-related factors, such as increased exposure to pesticides and fertilizers. While I account for fertilizer exposure at birth, in utero pesticide exposure could still influence health outcomes. To address this concern, I explore heterogeneous effects by rural versus urban birth. Interestingly, I find that the reduction

[11]Individual demographics include caste, religion, gender, and rural or urban birthplace. Time varying district controls include precipitation, temperature and fertilizer exposure at the year of birth

[12]Metabolic syndrome include BMI obesity (BMI $>$30), waist-hip ratio (WHR) obesity (WHR $>$0.9 for men and $>$0.85 for women), hypertension, diabetes, chronic heart disease, and high cholesterol. Cognitive decline refers to neurological disorders and lower cognitive scores, while motor skill deficits include grip strength deficit and balance impairment. See Section **??** for detailed variable construction.

[13]I do find pre-trends in hypertension, although all the significant estiimates have negative sign.

in height is smaller in rural areas, where pesticide exposure is presumably higher. This suggests that pesticide exposure may not be the driving factor. While both dietary changes and pesticide exposure in rural areas should theoretically lead to greater height declines, a possible explanation is that initial calorie deficiency was more pronounced in rural areas. The Green Revolution's increase in calorie availability may have offset the negative effects of lower protein and micronutrient intake, leading to a smaller net height reduction compared to urban areas. I also do not find statistically significant difference in the incidence of metabolic syndrome, cognitive imbalance and motor deficits between individuals born in rural and urban areas. Remaining threats to identification are challenging to identify, as they would need to create differences in health outcomes across districts with different potential productivity gains for those born immediately after 1966, but not for those born before. Nonetheless, I perform a robustness check by including district-specific trends to account for any such factors. This adjustment keeps the magnitude of the height effect consistent but reduces its significance, likely due to lower statistical power. The effects for other health outcomes are statistically insignificant.

As mentioned earlier, the Green Revolution significantly increased the use of agrochemicals, the Green Revolution led to a significant rise in agrochemical use, which may influence various health outcomes beyond those associated with nutritional changes. Prenatal exposure to environmental chemicals can trigger developmental adaptations in the lungs and airways, resulting in narrower airways. This alteration may lead to decreased expiratory flows, as indicated by lower lung function values, ultimately heightening the risk of adverse respiratory outcomes [Miller and Marty, 2010]. To assess the effects of agrochemical exposure, I investigate effects on chronic respiratory disorders, uro-genital issues, and cancer. These risks are typically elevated in rural areas due to closer proximity to agricultural activities, although urban resident could also be affected for instance, through aerial transfer. My findings indicate a statistically significant effect on chronic respiratory disorder, particularly in rural populations.

To address potential confounding from pesticide-intensive crops like cotton and sugarcane, I control for the baseline area under these crops and interact it with a time trend, and the results remain robust. Furthermore, I account for lung disease risks associated with crop residue burning, which became more prevalent in India during the mid-to-late 1980s. Analyzing individuals who migrated to different states—where exposure to residue burning is reduced— reveals significant associations with chronic lung disorders among those born in rural areas exposed to higher potential productivity gains.

Finally, I provide suggestive evidence on consumption patterns. Since no panel data is available covering the pre-Green Revolution period, I rely on cross-sectional data from National Sample Survey: Household Consumption Expenditure Survey (1999). The analysis reveals that regions with higher HYV adoption of wheat and rice have greater calorie and carbohydrate intake but lower consumption of iron, zinc, folate, vitamins, and calcium, compared to recommended dietary standards.[14]

[14] However, I do not find similar effects when using potential productivity gains.

The results of my paper improve our understanding of the long-run unanticipated health affects of the Green Revolution in India. This research is highly relevant to ongoing policy debates about agricultural practices, agrochemical use, and nutrition in both developing and developed nations. While the Green Revolution increased food productivity, it did not adequately address persistent malnutrition and health issues associated with the over-reliance on high-yield varieties and agrochemicals. Agricultural and food policies have often overlooked the critical role of crop diversity in tackling micronutrient deficiencies and ensuring food security. this study underscores the need for policies that prioritize food quality and sustainability, promoting practices that enhance biodiversity, reduce agrochemical reliance, and ultimately improve nutritional outcomes and health resilience.

My identification strategy draws from an expanding literature in economic development and economic history that leverages variations in ecological anf geographic characteristics as exogenous factors influencing technology adoption [Nunn and Qian, 2011, Bustos et al., 2016, Bartik et al., 2019, Moscona, 2023]

My findings complement recent scholarship examining the effects of Green Revolution. Previous studies [Gollin et al., 2021, Moscona, 2023, Foster and Rosenzweig, 1996] emphasize the Green Revolution's significant role in economic development, which likely enhanced overall well-being. However, it also led to unforeseen negative consequences. Although Bharadwaj et al. [2020] and Von Der Goltz et al. [2020] show a decline in infant mortality rates, Brainerd and Menon [2014] finds a positive relationship between heightened infant and neo-natal mortality and increased seasonal fertilizer usage. In another correlational study in Bangladesh, Headey and Hoddinott [2016] observed that while child weight-for-height improved with Green Revolution, height-for-age did not, suggesting a complex interplay between agricultural practices and nutrition. Most closely related to my research, Sekhri and Shastry [2024]investigate the long-run impact of Green Revolution exposure on diabetes in India, employing the historical presence of aquifers as an exogenous source of variation for HYV adoption. Their findings indicate that cohorts born after the Green Revolution show a greater susceptibility to diabetes, particularly in regions with higher aquifer availability. This study builds on existing research by demonstrating that the health impacts of the Green Revolution extend into later life outcomes. My central contribution lies in careful examination of the long-term effects on nutrient availability and providing evidence of health repercussions that transcend nutritional factors, including the effects of agrochemical exposure.

This study is also connected to the extensive body of research examining the health impacts of different types of environmental contamination [Chay and Greenstone, 2005, Currie and Neidell, 2005, Dias et al., 2023]. This paper also contributes to the broader literature on economic and nutritional resources in utero and during childhood to economic and health outcomes in adulthood (For comprehensive reviews, see [Currie and Vogl, 2013, Almond and Currie, 2011, Almond et al., 2018]). A substantial body of literature highlights the long-term benefits of enhanced early childhood nutrition in developing nations [Adhvaryu et al., 2019, 2020, Field et al., 2009, Clay et al., 2019]

References

Achyuta Adhvaryu, James Fenske, and Anant Nyshadham. Early life circumstance and adult mental health. *Journal of Political Economy*, 127(4):1516–1549, 2019.

Achyuta Adhvaryu, Steven Bednar, Teresa Molina, Quynh Nguyen, and Anant Nyshadham. When it rains it pours: The long-run economic impacts of salt iodization in the united states. *Review of Economics and Statistics*, 102(2):395–407, 2020.

Douglas Almond and Janet Currie. Killing me softly: The fetal origins hypothesis. *Journal of economic perspectives*, 25(3):153–172, 2011.

Douglas Almond, Janet Currie, and Valentina Duque. Childhood circumstances and adult outcomes: Act ii. *Journal of Economic Literature*, 56(4):1360–1446, 2018.

David James Purslove Barker. *Mothers, babies, and disease in later life*. BMJ publishing group London, 1994.

Alexander W. Bartik, Janet Currie, Michael Greenstone, and Christopher R. Knittel. The Local Economic and Welfare Consequences of Hydraulic Fracturing. 11(4):105–155, 2019. ISSN 1945-7782. URL https://www.jstor.org/stable/26794323.

Prashant Bharadwaj, James Fenske, Namrata Kala, and Rinchan Ali Mirza. The Green revolution and infant mortality in India. 71:102314, 2020. ISSN 01676296. doi: 10.1016/j.jhealeco.2020.102314. URL https://linkinghub.elsevier.com/retrieve/pii/S0167629618307574.

Elizabeth Brainerd and Nidhiya Menon. Seasonal effects of water quality: The hidden costs of the Green Revolution to infant and child health in India. 107:49–64, 2014. ISSN 03043878. doi: 10.1016/j.jdeveco.2013.11.004. URL https://linkinghub.elsevier.com/retrieve/pii/S0304387813001661.

Paula Bustos, Bruno Caprettini, and Jacopo Ponticelli. Agricultural Productivity and Structural Transformation: Evidence from Brazil. 106(6):1320–1365, 2016. ISSN 0002-8282. doi: 10.1257/aer.20131061. URL https://pubs.aeaweb.org/doi/10.1257/aer.20131061.

Kenneth Y Chay and Michael Greenstone. Does air quality matter? evidence from the housing market. *Journal of political Economy*, 113(2):376–424, 2005.

Parul Christian and Christine P Stewart. Maternal micronutrient deficiency, fetal development, and the risk of chronic disease. *The Journal of nutrition*, 140(3):437–445, 2010.

Karen Clay, Ethan Schmick, and Werner Troesken. The rise and fall of pellagra in the american south. *The Journal of Economic History*, 79(1):32–62, 2019.

Janet Currie and Matthew Neidell. Air pollution and infant health: what can we learn from california's recent experience? *The quarterly journal of economics*, 120(3):1003–1030, 2005.

Janet Currie and Tom Vogl. Early-life health and adult circumstance in developing countries. *Annu. Rev. Econ.*, 5(1):1–36, 2013.

Mateus Dias, Rudi Rocha, and Rodrigo R Soares. Down the river: glyphosate use in agriculture and birth outcomes of surrounding populations. *Review of Economic Studies*, 90(6):2943–2981, 2023.

R. E. Evenson and D. Gollin, editors. *Crop Variety Improvement and Its Effect on Productivity: The Impact of International Agricultural Research*. CABI Publishing, 1 edition, 2003. ISBN 978-0-85199-549-6 978-0-85199-853-4. doi: 10.1079/9780851995496.0000. URL http://www.cabidigitallibrary.org/doi/book/10.1079/9780851995496.0000.

Erica Field, Omar Robles, and Maximo Torero. Iodine deficiency and schooling attainment in tanzania. *American Economic Journal: Applied Economics*, 1(4):140–169, 2009.

Andrew D Foster and Mark R Rosenzweig. Technical change and human-capital returns and investments: evidence from the green revolution. *The American economic review*, pages 931–953, 1996.

Douglas Gollin, Casper Worm Hansen, and Asger Mose Wingender. Two blades of grass: The impact of the green revolution. *Journal of Political Economy*, 129(8):2344–2384, 2021. doi: 10.1086/714444. URL https://doi.org/10.1086/714444.

Derek D. Headey and John Hoddinott. Agriculture, nutrition and the green revolution in Bangladesh. 149:122–131, 2016. ISSN 0308521X. doi: 10.1016/j.agsy.2016.09.001. URL https://linkinghub.elsevier.com/retrieve/pii/S0308521X16304723.

Camilla Hoppe, Tina Rovenna Udam, Lotte Lauritzen, Christian Mølgaard, Anders Juul, and Kim Fleischer Michaelsen. Animal protein intake, serum insulin-like growth factor i, and growth in healthy 2.5-y-old danish children. *The American journal of clinical nutrition*, 80(2):447–452, 2004.

Gordon R Hopper. Changing food production and quality of diet in india, 1947–98. *Population and Development Review*, 25(3):443–477, 1999.

Hilary Hoynes, Diane Whitmore Schanzenbach, and Douglas Almond. Long-run impacts of childhood access to the safety net. *American Economic Review*, 106(4):903–934, 2016.

Jeffrey R Kling, Jeffrey B Liebman, and Lawrence F Katz. Experimental analysis of neighborhood effects. *Econometrica*, 75(1):83–119, 2007.

G Mehta, HI Roach, S Langley-Evans, P Taylor, I Reading, ROC Oreffo, A Aihie-Sayer, NMP Clarke, and C Cooper. Intrauterine exposure to a maternal low protein diet reduces adult bone mass and alters growth plate morphology in rats. *Calcified tissue international*, 71:493–498, 2002.

Mark D Miller and Melanie A Marty. Impact of environmental chemicals on lung development. *Environmental health perspectives*, 118(8):1155–1164, 2010.

Jacob Moscona. Agricultural Development and Structural Change, Within and Across Countries, 2023.

N. Nunn and N. Qian. The Potato's Contribution to Population and Urbanization: Evidence From A Historical Experiment. 126(2):593–650, 2011. ISSN 0033-5533, 1531-4650. doi: 10.1093/qje/qjr009. URL https://academic.oup.com/qje/article-lookup/doi/10.1093/qje/qjr009.

Prabhu Pingali. Green Revolution: Impacts, limits, and the path ahead. 109(31), 2012. doi: 10.1073/pnas.0912953109. URL https://www.pnas.org/doi/epdf/10.1073/pnas.0912953109.

Prabhu Pingali, Bhaskar Mittra, and Andaleeb Rahman. The bumpy road from food to nutrition security – Slow evolution of India's food policy. 15:77–84. ISSN 22119124. doi: 10.1016/j.gfs.2017.05.002. URL https://linkinghub.elsevier.com/retrieve/pii/S2211912416301407.

Prabhu Pingali, Anaka Aiyar, Mathew Abraham, and Andaleeb Rahman. *Transforming Food Systems for a Rising India*. Palgrave Studies in Agricultural Economics and Food Policy. Springer International Publishing, 2019. ISBN 978-3-030-14408-1 978-3-030-14409-8. doi: 10.1007/978-3-030-14409-8. URL http://link.springer.com/10.1007/978-3-030-14409-8.

William D Rees. Interactions between nutrients in the maternal diet and the implications for the long-term health of the offspring. *Proceedings of the Nutrition Society*, 78(1):88–96, 2019.

Sheetal Sekhri and Gauri Kartini Shastry. The Curse of Plenty: The Green Revolution and the Rise in Chronic Disease. *American Economic Journal: Applied Economics (Forthcoming)*, 2024.

Vandana Shiva. *The violence of the green revolution: third world agriculture, ecology and politics*. Zed Books, 1991.

Aryeh D Stein, Huiman X Barnhart, Morgen Hickey, Usha Ramakrishnan, Dirk G Schroeder, and Reynaldo Martorell. Prospective study of protein-energy supplementation early in life and of growth in the subsequent generation in guatemala. *The American journal of clinical nutrition*, 78(1):162–167, 2003.

Claire J Stocker, Jonathan RS Arch, and Michael A Cawthorne. Fetal origins of insulin resistance and obesity. *Proceedings of the Nutrition Society*, 64(2):143–151, 2005.

Jan Von Der Goltz, Aaditya Dar, Ram Fishman, Nathaniel D. Mueller, Prabhat Barnwal, and Gordon C. McCord. Health Impacts of the Green Revolution: Evidence from 600,000 births across the Developing World. 74:102373, 2020. ISSN 01676296. doi: 10.1016/j.jhealeco.2020.102373. URL https://linkinghub.elsevier.com/retrieve/pii/S0167629619311282.

Runyu Zou, Hanan El Marroun, Charlotte Cecil, Vincent WV Jaddoe, Manon Hillegers, Henning Tiemeier, and Tonya White. Maternal folate levels during pregnancy and offspring brain development in late childhood. *Clinical Nutrition*, 40(5):3391–3400, 2021.