Structural Transformation, Agriculture, Climate, and the Environment[*]

Christopher B. Barrett, Ariel Ortiz-Bobea, and Trinh Pham
Charles H. Dyson School of Applied Economics and Management, Cornell University

January 2021

Abstract

This paper reviews the feedbacks between structural transformation and agriculture, on the one hand, and climate and the natural environment, on the other. The longstanding, dominant economic development narrative largely ignores nature's influence on factor productivity and stocks, even as it increasingly illustrates how agricultural technological change and economic growth affect nature. We articulate some of the missing linkages and pose a range of policy research questions worth exploration concerning structural transformation and the complex feedback among agriculture, nature, and economic growth processes, especially in the low-income agrarian nations of the Global South.

JEL Codes: O13, Q10, Q54

Keywords: economic development, structural transformation, agriculture, climate, environment, feedbacks.

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1. Introduction

The standard macroeconomic model of structural transformation posits an economy with at least two sectors, each with a sector-specific production function that maps capital and labour into output. Since Lewis (1954) - and later, Johnston and Mellor (1961), Jorgenson (1961), and Ranis and Fei (1961) - the simplest 'dual economy' models have just two sectors, a 'backward' agricultural sector and a modern industrial or capital-intensive one.[1] Income growth arises from exogenous technological change and population growth, which induce endogenous capital accumulation in the non-agricultural sector, all of which spur income growth and a steady outflow of labour from agriculture. In relatively closed economies and in the face of income and price inelastic food demand, food supply expansion leads to falling relative food prices and thus falling relative returns to labour and capital in agriculture, even as food output and agricultural income grows, inducing factor reallocation out of agriculture. Factor and/or product market imperfections boost the productivity gains from factor reallocation out of agriculture.

One can usefully enrich the most parsimonious models, for example, by introducing investment in labour-augmenting human capital formation, geographic migration or trade frictions, or by endogenizing the rate and/or factor-bias of technological change. One can add land as a third, quasi-fixed factor of production mainly (or exclusively) used in the agricultural sector, with capital mainly (or exclusively) an input to the industrial sector.[2] But the key model predictions carry through regardless. Starting from an initial condition of a workforce concentrated in relatively low-productivity agriculture, farm productivity growth drives labour and investible capital to higher productivity uses in the non-farm sector, fuels farmers' demand for non-farm products, and drives down relative food prices. Thereby, stimulating capital accumulation and broader economic growth that increasingly concentrates employment and output in the non-agricultural, modern sector.

These models all make a strong assumption: these economic processes are independent of changes in the natural environment. They also yield a striking prediction: in equilibrium, capital, labour and land endowments, and the technology that augments them, are non-decreasing over time. Only the *relative* returns to a factor of production, like land, may diminish. Neither the absolute returns nor the factor inputs available for future production diminish other than through

[1] See Timmer (1988, 2002) for a more recent summary. Dercon and Gollin (2014), Bustos et al. (2016) and Gollin (2020) explain why the model fails in some places. Multi-sector models carry the same core implications (Wang and Piesse (2013); Gollin (2014)).

[2] Given a fixed stock of land, as the economy grows, capital accumulates, and labour migrates out of agriculture, capital and labour capture steadily increasing shares of income and wealth and the relative economic importance of land diminishes, as Liu et al. (2020) demonstrate empirically for Vietnam.

exogenous capital depreciation. Growth rates may diminish over time and converge across economies with different initial conditions. But they always remain non-negative.

Standard growth models summarise these relationships by the equation Y=Af(K,L,T), where A reflects the state of technology (i.e., total factor productivity, TFP), and f(.) is a production function that maps the productive capital stock, K, the workforce, L, and available land, T, into total output (and income), Y. Figure 1 presents a simple heuristic of the process if the unshaded, outer ovals representing A, L, and T remain exogenous, yielding endogenous factor allocation and output patterns reflected in the inner, shaded boxes. By assumption, productivity growth in each sector – and thus income – is limited only by capital, labour, and land endowments, the rate of technological change, and frictions in reallocating factors between sectors or in capital accumulation. The implicit claim is that nature exerts no influence over factor accumulation and productivity … even though agriculture is merely a human adaptation of nature, a sector unavoidably dependent on natural processes.

The remainder of this paper makes the case for relaxing the untenable assumption that economic processes are independent of changes in the natural environment. Climate and environmental conditions affect and are affected by absolute and relative factor productivity, the rate of technological change, and the structural transformation process. Put differently, we must augment the familiar growth model to admit environmental factors, E, as an argument in the production function, Y=A f(K,L,T, E), and to endogenize A, E, L and T, not just K, as depicted by the bidirectional arrows in Figure 1.
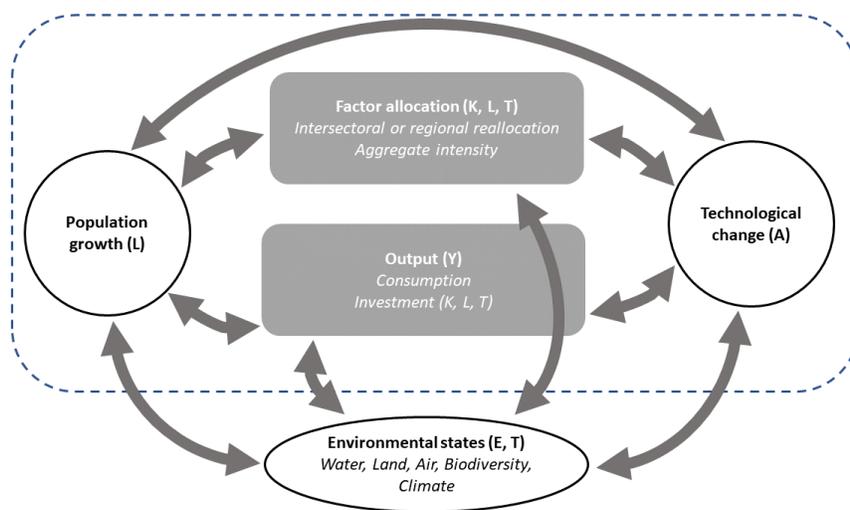

Figure 1: Conceptual summary.

In section 2, we briefly review the literature on the impacts of economic growth and structural transformation on climate and environment, for a (largely unidirectional) relationship between economic growth and the environment. Section 3 explores the implications of bidirectional feedback between economic and natural processes for structural transformation in the Global South. Section 4 flags key policy research questions raised by interconnected economic and anthropogenic natural processes in low-income agrarian nations undergoing, or poised to embark upon, structural transformation. Section 5 notes some key constraints to novel theorizing, data collection and empirical research, advocating for a more inclusive dialogue around development, agriculture, and environment.

2. The climate and environmental impacts of structural transformation

The research community has long recognised economic growth affects climate change, air and water pollution, land conversion and biodiversity loss. In the language of Figure 1, such research concerns the arrows pointing toward the "Environmental states".

a. Impacts on greenhouse gas emissions and climate change

Greenhouse gas (GHG) inventories indicate emissions from the agriculture, forestry and other land uses (AFOLU) are responsible for about 24% of global GHG emissions, of which agricultural production alone is responsible for more than half (IPCC 2014b). Direct agricultural emissions stem primarily from livestock, soil, and nutrient management. While overall direct emissions from AFOLU have stagnated across most of the world over the past 50 years, they have substantially increased in Asia, rising from 2.6 in 1970 to 4.3 GtCO$_2$eq/yr in 2010.

Output has increased even more than GHG emissions, suggesting that the carbon intensity of agricultural production has declined over time. GHG emissions per unit of output have declined by about 40% in both crop and livestock production since the 1970s (Bennetzen et al., 2016a). While emission intensities have decreased across the board, the trends differ across regions. High-income countries (HICs) were able to reduce GHG emissions while expanding agricultural production; whereas low- and middle-income countries (LMICs) have expanded both emissions and production during 1970-2007, with Sub-Saharan Africa experiencing the lowest reduction in emission intensities (Bennetzen et al., 2016b).

b. Impacts on land, water, and biodiversity

Agricultural technological change is central to the structural transformation narrative. However, the impacts of technological change on land use fundamentally remain an empirical question

4

(Angelsen 1999, 2010; Angelsen and Kaimowitz 2001). The land-sparing (Borlaug) hypothesis holds that increases in agricultural productivity in closed economies reduce crop prices and farmers' incentives to bring more land into cultivation. The competing hypothesis, known as Jevons Paradox, holds that technological advances that boost agricultural profitability incentivise expanding the agricultural frontier. The most compelling empirical analyses fairly consistently find that improvements in crop germplasm, in particular, slowed expansion of the agricultural frontier, relative to appropriate counterfactuals (Stevenson et al. 2013; Hertel et al. 2014; Gollin et al. 2018; Abman and Carney 2020; Pelletier et al. 2020).

Population and income growth have nonetheless expanded the global agricultural land footprint by 10% between 1961-2006, mostly in LMICs, while cultivated and pasture lands in HICs declined 9% over that period (Fuglie 2010). In the past decade, agricultural land has expanded roughly 3% annually in Africa, while stagnating in other LMICs (Barrett 2021).

Agricultural extensification appears the main driver of deforestation globally, responsible for 83% of forest cover loss across the tropics between 1980 and 2000 (Gibbs et al. 2010) and 51% from 2001 to 2015, over which time 92% of Africa's forest cover loss was attributable to smallholder agricultural extensification (Curtis et al. 2018).

Agricultural land conversion is also the primary driver of biodiversity loss , especially in LMICs (IPBES 2019). Moreover, the most extinction-vulnerable species contribute the most to pest control, pollination, and seed dispersal services on which agriculture heavily depends (IPBES 2019; Hendershot et al. 2020).

Agricultural production requires water even more than it does land. Today, agriculture accounts for roughly 70% of aggregate water withdrawals, often exceeding 80% in Africa and Asia. Especially in the face of climate change, water is rapidly becoming the most limiting factor in conventional agricultural production.

Finally, agriculture also pollutes. Chemical fertiliser use and livestock waste (Paudel and Crago, in press) especially affect the fisheries productivity and human health.

c. The Environmental Kuznets Curve and its shortcomings

Improvements in HIC environmental quality over the past 50 years motivated a large literature on the so-called Environmental Kuznets Curve (EKC) hypothesis, which posits an inverted-U-shaped relationship between pollution and income per capita (Dinda 2004). A vast literature explores this relationship empirically, mostly for air pollutants associated with industrial

production and transportation (Shafik and Bandyopadhyay 2002; Selden and Song 1994; Grossman and Krueger 2001), while other studies explore trade and the resulting delocalisation of dirty industries to poorer countries in a "race to the bottom" that leads to "pollution havens" in poorer countries (Stern et al. 1996; Suri and Chapman 1998; Cole 2004; Copeland and Taylor 2004). A parallel literature investigates the theoretical foundations of the EKC (Arrow et al. 1995; Jones and Manuelli 1995; Andreoni and Levinson 2001).

Many shortcomings plague the EKC literature, ranging from restrictive functional forms to high sensitivity to the inclusion of various covariates (Harbaugh et al. 2002). More broadly, Stern (2004) dismisses the basis for the EKC relationship, observing that developing countries have often tackled environmental issues much earlier than today's HICs. Dasgupta et al. (2002) point out that clean technologies' diffusion to developing countries has both flattened and shifted the EKC to the left. More broadly, the EKC has (ironically) ignored feedbacks between environmental quality and economic growth (Arrow 1995).

3. Feedback from climate and environmental change to structural transformation

Climate and environmental change obviously affect the quality-adjusted stocks of and returns to land, labour, and capital, and may endogenously influence technological change. In this section we briefly survey the mounting evidence on these channels, as reflected in the arrows pointing from the "Environmental states" to economic phenomena in Figure 1. Although growth theory models have rarely focused on environmental feedback,[3] one can easily envision how incentives for developing and adopting cleaner technologies, including renewable substitutes for non-renewable resources, could arise endogenously and affect structural transformation patterns.

We also note that while environmental feedbacks are important, some remain mostly exogenous to many LMICs. Most notably, just six major countries or groups (China, US, EU-28, India, Russia, and Japan) account for 70% of global CO_2 emissions (IPCC, 2014a), rendering climate change largely exogenous for most LMICs. The environmental changes that most likely exert endogenous effects on structural transformation patterns concern local pollutants and land and water management.

a. Impacts on returns to land and agricultural technologies

Over the past century, global temperatures over land and ocean have increased by about 1°C with almost the entire world warming. Global average precipitation also increased but with less clear regional trends, particularly in places with shorter instrumental records (IPCC, 2014b). Rising

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[3] Exceptions include Lopez (1994) and Bovenberg & Smulders (1995).

temperatures have substantial ecological and hydrological impacts, which disproportionately affect agriculture. For example, experts anticipate shifts in the range of pests and pathogens (Bebber 2015) and studies project substantial crop losses related to insect pests in a warming climate (Deutsch et al. 2018). Rising temperatures also increase evapotranspiration, exacerbating processes like salinisation in coastal regions (Colombani et al. 2016), which affects agriculture in countries like Bangladesh (Dasgupta et al. 2015; Chen and Mueller 2018).

Climate impacts on agriculture: The literature analysing climate change impacts on agriculture has focused primarily on a few staple crops (Hertel and de Lima 2020) and on the relatively distant future. However, a growing literature documents how (largely anthropogenic) historical temperature and precipitation changes have affected agricultural production. Lobell and Field (2007) and Lobell et al. (2011) estimate a series of crop statistical models which they combine with recent growing season temperature and precipitation changes. They find that climate change has slowed yield growth in major crops, mostly due to recent warming trends, with a few regional exceptions. Anthropogenic climate change may have reduced global agricultural TFP by about 20% from 1961-2020 (Ortiz-Bobea et al. 2020). The estimated impacts are even larger in warmer regions such as sub-Saharan Africa, which experienced stagnating agricultural productivity over this period. It remains unclear how to most effectively adapt agricultural research and development (R&D) investments and technological diffusion strategies to offset these substantial – and ongoing – impacts.

Climate change impact studies on agriculture typically rely on panel data linking agricultural outcomes with presumably random temperature and other weather anomalies (Blanc and Schlenker 2017; Kolstad and Moore 2017). Some efforts have attempted to capture long-run adaptation based on recent trends or by exploring how much climate explains heterogeneity in the sensitivity to weather variables (Butler and Huybers 2013; Burke and Emerick 2016; Moore and Lobell 2014; Mérel and Gammans 2020).

There is also some evidence that changes in industrial and urban pollution can directly affect agricultural production via atmospheric deposition. Unlike stratospheric ozone, atmospheric ozone is hazardous to human, animal, and plant health (Reich and Amundson 1985) and thus to agriculture (Ashmore and Marshall 1998; Agrawal et al. 2003). But regional confounders make it difficult to unpack ozone's effects on agricultural production in non-controlled environments (Boone et al. 2019). Perhaps surprisingly, certain pollutants damaging to human health have proved beneficial to agricultural production. For example, implementation of the US' Acid Rain Program reduced emissions of sulfur dioxide, which inadvertently reduced crop output in much of the US Midwest (Sanders and Barreca 2015).

Beyond direct changes in land productivity due to climate and environmental change, the relative returns to land-based livelihoods, like agriculture, can shift because of changes in agriculture' risk profile due to at least two distinct mechanisms. First, without access to actuarily fair insurance markets, any increase in rainfall and/or temperature variability should induce risk averse households to reallocate labour and capital out of agriculture towards non-farm livelihoods less subject to climate risk, including via migration to urban areas. A growing literature consistently finds empirical support for that claim (Barrett et al. 2001; Macours 2013). Second, an ex-post effect can arise from exogenous productivity shocks that either generate windfall gains – directly, or via a temporary stimulus to local demand for non-farm nontradables – that rural households use to invest in non-farm enterprises (Foster and Rosenzweig 2004, 2007; Emerick 2018), or cause shortfalls that households cover through increased non-farm labour effort (Kochar 1999; Jayachandran 2006).

Another mechanism affecting the returns to land arises from the emergence of alternative rural land uses to agriculture.[4] At least two distinct mechanisms exist that merit attention.

First, greater demand for electricity, increased awareness of the climate externalities associated with burning fossil fuels, and falling unit costs of production due to technological advances in (especially off-grid) renewable wind, solar, and geothermal power generation open up opportunities to use land to produce energy rather than agriculture. Rural lands' low opportunity cost makes them increasingly attractive sites, especially when proximate enough to urban centers that the transmission costs remain low.

Second, rural lands are increasingly attractive sites for the provision of environmental services. In some cases, this involves direct payments for ecosystem services (PES), now widespread in LMICs, with over 550 active programs and an estimated $40 billion or so in annual transactions (Salzman et al. 2018). A much larger, but as-yet-largely-unrealised, potential exists in markets for GHG sequestration in trees, soils, and cover crops. Some environmental services can also be monetized through tourism or eco-tourism, which have been shown to have important spillover effects (Faber and Gaubert, 2019).

A special threat to coastal lands arises from sea-level rise (SLR), a catastrophic anticipated consequence of climate change that interacts dangerously with natural subsidence, i.e., land sinking largely due other anthropogenic processes such as groundwater withdrawal (McGranahan et al. 2016; Nicholls et al. 2011; Herrera-Garcia et al. 2021). Although scientific

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[4] In peri-urban areas, residential and industrial expansion can drive up land values and induce land reallocation out of agriculture. Here we abstract from those mechanisms.

uncertainties remain regarding SLR and subsidence, the relevant economic literature is strikingly thin. With more frequent extreme climate events expected under both business-as-usual and moderate emission-mitigation-policy scenarios, beginning in 2050 most of the tropics are projected to experience *annual* exposure to the present-day 100-year extreme SLR (Vousdoukas et al. 2018).

SLR will significantly increase salinisation, soil erosion, and coastal flooding along low-lying coastal areas by the end of this century (Oppenheimer et al. 2019). This not only directly affects agricultural returns to land but also imperils non-agricultural rural livelihoods, especially tourism. Vousdoukas et al. (2020) estimate that by the end of this century, 52-63% of low-elevation coastal zones will experience critical erosion. The estimated impact is especially great in LMICs such as Comoros, the Democratic Republic of the Congo, Gambia, Guinea-Bissau, Pakistan, and Suriname, which are expected to suffer over-100-meter beach losses on up to 70-80% of sandy beach coastlines by 2100.

Without significant adaptation, substantial lands will be permanently lost to SLR by 2100. Up to 8% of the global population will face annual floods under 25–150 cm of global mean SLR (Hinkel et al. 2014; IPCC 2019; Kulp and Strauss 2019). Indonesia's recent decision to move its capital from a swelling and sinking coastal city, Jakarta, to eastern Borneo is partly linked to SLR (Firman et al 2011; Simarmata et al 2019). Such displacements not only reflect declining returns to coastal lands but imply massive stranded assets in fixed capital and tie up considerable capital in the costs of evacuating coastal regions.

SLR effects are spatially concentrated. Eight Asian countries – Bangladesh, China, India, Indonesia, Japan, Thailand, the Philippines, and Vietnam – are home to more than 70% of the world population now occupying land vulnerable to SLR (Kulp and Strauss 2019). Bangladesh and Vietnam are especially vulnerable, as roughly one-third of each country's population will permanently fall below high tide lines by 2100, even with a significant reduction in emissions. The most catastrophic cases will be low-lying small island states, whose very existence SLR imperils.

Overall, the economic feedback effects from climate and environmental change, although geographically varied, seem to disproportionately impact agriculture, especially in rainfed systems and in warmer tropical agroecosystems more vulnerable to rising temperatures, SLR and shifting animal and plant pest and pathogen ranges. This may slow structural transformation for lower-income, agrarian countries by retarding the rate at which agricultural productivity growth releases labour to non-farm sectors, generates surpluses to invest off farm, and stimulates domestic demand for non-farm nontradables. Conversely, in economies further along the

transformation pathway, the seemingly differential effect of natural feedback on the returns to agricultural land may accelerate factor reallocation out of agriculture. We could see considerable divergence among LMICs in the coming years based on physical geography and the current state of agricultural productivity.

b. Impacts on human capital formation

A growing literature likewise causally links climate and environment to human capital formation and accumulation, from health to education performance and adult cognitive and physical outcomes. Most studies focus on HICs, but the LMIC evidence builds steadily.

The most studied mechanism concerns temperature. In general, high temperature worsens human capital outcomes, including increased risk of infant mortality, low birth weight, preterm delivery (Deschênes et al. 2009; Basu et al. 2010; Banerjee and Maharaj 2020; Barreca and Schaller 2020; Bekkar et al. 2020) and of child stunting (Blom et al. 2019), which in turn predicts worse health and cognitive outcomes in adulthood (Almond and Currie 2011; Almond et al. 2018). The effects could be direct via physiological mechanisms or indirect, through economic mechanisms such as adverse shocks to agricultural production and labour markets, or through infectious disease mechanisms such as diarrhoea (Banerjee and Maharaj 2020; Bekkar et al. 2020). Extremely high temperatures are also associated with higher mortality rates (Burgess et al. 2017; Deschênes and Greenstone 2011).

High temperature negatively affects cognition and educational outcomes, both in the short and long term (Seppänen et al. 2006; Cho 2017; Graff Zivin et al. 2018; Park 2020; Garg et al. forthcoming). Estimated effect sizes appear larger in India (Garg et al. forthcoming) than in higher-income contexts such as Korea and the US (Graff Zivin et al. 2018; Park 2020). A range of mechanisms could explain the estimated temperature-performance relationship, including direct mechanisms such as heat-induced fatigue, food poisoning, or poor sleep, as well as indirect ones related to, for example, lost earnings or increased risk of violence. Few studies convincingly pinpoint a mechanism, and thus prospective remedies (Park et al. 2020).

In contrast to the well-studied impacts of short-run variation in temperature on human performance, the impacts of long-run variation remain understudied. Graff Zivin et al. (2018) find no significant evidence of average weather exposure between tests, as well as climate exposure from birth until test taking, on human capital accumulation for students in the US. This suggests caution in projecting long-run climate impacts based on estimates arising from short-run weather shocks.

The impacts of precipitation on human capital outcomes differ by contexts between short and long run. Analysing census data from 29 tropical countries, Randell and Gray (2019) document that early-life rainfall is positively correlated with education attainment of children aged 12-16 in Africa and Asia, but the relationship is reversed in Central America and the Caribbean. While higher-than-average rainfall during early life improves school enrollment, grade progression, and test scores of children in India, positive rainfall has contemporaneous negative effects on their school attendance, enrollment status, and education performance, which could be explained by the increasing opportunity cost of schooling associated with higher wages (Shah and Steinberg 2017). The evidence suggests that positive rainfall can have ambiguous effects on human capital, depending on whether substitution or income effects dominate.

In a sample of children from 53 countries, Cooper et al. (2019) find that minor to severe droughts lead to worse child nutrition, and these effects could be mitigated by factors that affect both the adaptive capacity and sensitivity of local food systems such as nutritional diversity of agricultural systems, irrigation, governance, and political stability. Other studies document adverse effects of in utero and early-life exposure to El Niño-associated extreme rainfall and floods on short- and medium-run nutrition, health, or educational outcomes in Ecuador (Rosales-Rueda 2018), or Mexico (Aguilar and Vicarelli 2018). The apparent mechanisms vary, but most seem to trace back to income effects in the face of liquidity constraints that lead to reduce inputs important to child development.

Air pollution has been shown to have sizable negative effect on fetal, infant, and child mortality in China (Bombardini and Li 2020), Indonesia (Jayachandran 2009), Mexico (Arceo et al. 2016), and African countries (Adhvaryu, Bharadwaj et al. 2019; Heft-Neal et al. 2018); on birth outcomes and mortality in the US (Bekkar et al. 2020; Deryugina et al. 2019); and on mental health in China (Zhang et al. 2017). In utero and early-childhood exposure to pollution can have lasting effects on various later-life outcomes, including school exams, adult labor force participation, adult earnings, and IQ test scores (Bharadwaj et al. 2017; Black et al. 2019; Isen et al. 2017; Sanders 2012). One would expect these effects to concentrate mainly in urban areas, although the burning of crop residues and forests can reduce or eliminate those geographic differences. Ebenstein et al (2016) also find that even transitory changes in air pollution can have long term consequences on educational attainment and earnings.

The impacts of water quality on human capital in LMICs has been less well studied. Garg et al. (2018) find that upstream use of rivers for bathing and other sanitary practices explains as much as 7.5% of diarrhoea-related deaths annually in Indonesia. These effects fall disproportionately on rural and poorer households with less access to piped, potable water and indoor plumbing.

Deforestation affects human capital accumulation, and not only through infectious disease ecology or increased air pollution due to smoke and suspended particulates from burning forest to clear land for cultivation, as discussed above. A second mechanism is induced local climate change. Most extreme warming is found in large patches of deforested lands, which in combination with climate change poses a greater challenge to the public health and livelihoods of tropical populations (Vargas Zeppetello et al. 2020). Moreover, deforestation has spatial spillover effects, affecting surface temperature not only locally but also in neighboring and even more remote regions that are not deforested (i.e. nonlocal effects), with globally averaged nonlocal effects dominating the local effects (Winckler et al. 2019).

A third mechanism operates through disease ecology. Chemical control of insects and other disease vectors have largely eradicated many tropical infectious diseases – cholera, dengue, malaria, etc. – from HICs. But as much as 75% of deaths in LMICs remain attributable to infectious diseases (Lozano et al. 2012), which may create disease-poverty traps (Bonds et al. 2010; Ngonghala et al. 2014).

Indeed, infectious disease ecology illustrates nicely the feedback between the human and natural systems. Tropical deforestation due to agricultural expansion has been repeatedly linked to increased vector-borne and zoonotic disease (Walsh 1993; Wolfe et al. 2005; Morris et al. 2016; Tucker Lima et al. 2017; Burkett-Cadena and Vittor 2018; Brock et al. 2019). Agricultural drivers – primarily due to land conversion – have been associated with more than 25% of all new infectious diseases in humans since 1940, including more than 50% of zoonoses - e.g. COVID-19, ebola, MERS, SARS (Rohr et al. 2019). While the exact mechanisms remain the subject of much current research, one cause is that vector species – e.g. bats, mosquitoes, primates, and rodents – routinely outcompete non-host species in agricultural lands converted from forest or wetlands, thereby increasing human zoonoses exposure (Gibb et al. 2020). As a result, anthropogenic land conversion can aggravate the transmission of longstanding infectious diseases like malaria or dengue fever. For example, primary deforestation has been shown to have increased the incidence of malaria in Indonesia while logging of secondary forests designated for that purpose did not affect the malaria prevalence (Garg 2019).

The net impact of climate and environmental change on human health capital is perhaps best captured by the estimated disability adjusted life years (DALYs)[5] lost. Risk drivers such as poor water quality and air pollution contributed 22% of the DALYs lost globally in 2010 (Lim et al. 2012). An estimated 63% of European human and domestic animal infectious pathogens are

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[5] DALYs represent the Years of Life Lost due to premature mortality in the population plus the Years Lost due to Disability for people living with the health condition or its consequences (WHO 2020).

sensitive to climate and 82% of them to primary factors such as precipitation and temperature (McIntyre et al. 2017). Compared to human-only or animal-only pathogens, zoonotic pathogens are more climate sensitive; human infectious diseases that have primary climate drivers - thus will likely worsen with climate change - account for 37% of total DALYs (McIntyre et al. 2017).

c. Impacts on labour productivity

Compared to the impacts of short-run environmental variation on human capital accumulation, there is little evidence on labour productivity impacts, especially in developing countries. High temperature adversely affects labour productivity, even for indoor manufacturing activity in India (Somanathan et al. 2018; Adhvaryu et al. forthcoming). The effects are likely greater in outdoor manual labour, like most primary agricultural activities, than in manufacturing and services. But little compelling evidence exists on differential intersectoral effects, especially from LMICs.[6] If this hypothesis proves true, then climate change may magnify pre-existing intersectoral labour productivity differences that help drive structural transformation.

Air quality can also directly affect labour productivity independent of human capital formation (Hanna and Oliva 2015) for both outdoor (Graff Zivin and Neidell 2012) and indoor activities (Adhvaryu, Kala et al. 2019; Chang et al. 2016). A few studies establish a negative relationship between air pollution and productivity in semi-skilled occupation (Chang et al. 2019) and high-skilled, quality-focused occupation (Archsmith et al. 2018), suggesting that air quality can directly affect cognitive performance and decision making.

d. Impacts on migration

People relocate in response to climate and environmental change, potentially influencing structural transformation in low-income agrarian economies. Agriculture is widely considered the most climate-and-environment vulnerable sector, with climate and conflict shocks producing 'climate refugees' likely to move to towns and cities with jobs and social services to support them (Burke et al. 2015; Cai et al. 2016). Climate and environmental change may thereby accelerate the intersectoral flow of labour out of agriculture and geographic migration from rural to urban areas. Furthermore, the prospect of mass climate migration seems plausible, especially given widespread predictions of more frequent extreme weather events due to climate change (Diffenbaugh et al. 2018) and of SLR. Rigaud et al. (2018), for example, predict 143 million internal climate migrants by 2050, and their estimates neglect induced international migration.

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[6] Park (2016) finds that the temperature effect in the US (measured as annual payroll per capita) is more acute for highly exposed industries (e.g., agriculture, construction, mining, transportation and utilities). No significant effect was detected for non-exposed industries such as retail, education, and health.

Yet the complex relationship between climate and environmental change and migration appears highly contextual. No unified theory has yet emerged that satisfactorily reconciles key empirical observations, including the nonmonotonic relationship between household poverty and propensity to migrate in response to changing climate conditions, seemingly greater migration response to slow-onset changes such as droughts as compared to rapid-onset ones like floods or tropical storms, and the tendency for climate migration to be both domestic and long distance, rather than international or short distance (Cattaneo et al. 2019; Kaczan and Orgill-Meyer 2019).

One popular framework holds that adverse climate conditions increase vulnerability (i.e. exposure and sensitivity to climate shocks), manifest as the risk of falling (deeper) into poverty, while decreasing capability (i.e. ability and capacity to choose) to migrate in response to shocks, leading to ambiguous migration effects depending on which mechanism dominates (Kaczan and Orgill-Meyer 2019). It might be that, in some contexts, rather than accelerating intersectoral and geographic labour movement, adverse climate conditions reduce human mobility, consistent with severe liquidity constraints and high relocation costs ensnaring poor populations in geographic poverty traps (Bryan and Morten 2019; Cattaneo and Peri 2016; Kraay and McKenzie 2014; Wesselbaum and Aburn 2019). Indeed, climate and environmental migration projections typically work from relatively simplistic models of subpopulations likely to face a worsening climate, without regard to the economic constraints and incentives to migrate (Cattaneo et al. 2019). And we know relatively little about the evolution of the climate-migration relationship over time, largely due to limited long-term longitudinal data and significant attrition bias problems in the data that do exist.[7] Furthermore, if slow-onset change exerts more influence on migration than do sudden shocks, then that significantly complicates causal identification. For example, migration due to SLR appears inevitable. But disentangling natural drivers from people's endogenous expectations and resulting market and policy responses (e.g. in real estate valuation, in public infrastructure investments) remains a major empirical obstacle (Hauer 2017; Hauer et al. 2020).

Mass migration could signal a partial decoupling of intersectoral factor reallocation from technological change, with unknown impacts for allocative efficiency and TFP growth. But increasing farmer access to shock-coping strategies (e.g. off-farm employment, remittances, credit, insurance), decline in the potential displacement effects of climate shocks - as has been observed in Bangladesh (Call et al. 2017) and China (Gray et al. 2020) - and climate change

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[7] The China Health and Nutrition Survey, Indonesian Family Life Survey, and Kagera Health and Development Survey (Tanzania) appear to be some of the few LMIC data sets that have the spatial and temporal breadth and sufficiently high rates of tracking to permit study of the longer-term migration impacts of climate and environmental change (Gray et al. 2020; Hirvonen 2016; Thiede & Gray 2017).

adaptation within agriculture offer an alternative response.[8] The net effects remain unknown and difficult to predict. Furthermore, if one interprets the climate-migration relationship as labour reallocation in response to climatic conditions (Carleton and Hsiang 2016), then given the increasing prevalence of urban poverty (Ravallion et al. 2007; Lucci et al. 2018), accelerated reallocation could result in overadjustment, aggravating urban poverty rather than relieving both rural and urban poverty.

e. Impacts on conflict and inter-group trust

As economies develop and increasingly rely on commercial exchange, interpersonal trust becomes more important, whether enforced endogenously through sociocultural norms or exogenously through laws and the police and judicial powers of states (Barrett 1997, 2005; Platteau 2000). Indeed, the emergence of institutions that promote the rule of law and trust appear key drivers of macroeconomic growth, in large part by facilitating the sorts of exchange and investment patterns that describe structural transformation (Acemoglu et al. 2002).

Environmental and climate change can affect inter-group trust by fomenting conflict. Warmer temperatures appear to increase the incidence of violence and large-scale conflicts in many settings (Burke et al. 2009, 2015; Hsiang et al. 2013) along with political instability manifest in irregular leader transition in LICs (Dell et al. 2012). Precipitation is also associated with conflict, mostly through economic channels, such as land invasions in Brazil (Hidalgo et al. 2010), ethnic riots in India (Sarsons 2015), and civil war in Sub-Saharan Africa (Miguel et al. 2004). Extreme weather events likewise affect inter-group trust and cooperation. Droughts have been found to increase civil conflict in Africa (Harari and Ferrara 2018), crime in India (Blakeslee and Fishman 2018), peasant rebellion in historical China (Jia 2014), organized crime in Italy (Acemoglu et al. 2019), and to significantly amplify the impacts of disease exposure on civil conflict globally (Cervellati et al. 2017). Global-scale ocean-atmosphere climate interactions such as El Niño-Southern Oscillation are also positively associated with increased probability of conflicts (Hsiang et al. 2011). Although a growing literature strongly suggests that climate increases violence and conflict within countries, identifiable causal mechanisms and their relative importance remain elusive (Mach et al. 2020). But the net effect must be to slow investment and increase market frictions, thereby retarding the structural transformation process. It remains quite unclear, however, whether the net effects of these varied impacts differ across sectors or geographies such

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[8] We see, for example, farmers adjusting agricultural inputs to mitigate the negative agroecological effects of warmer temperatures in Kenya (Jagnani et al. forthcoming), shifting sowing and harvesting dates for wheat and maize in response to changing rainfall and temperature patterns in China (Wang et al. 2012), adopting new crop varieties expressly to mitigate downside risk (Emerick et al. 2016), adjusting freshwater fishing effort in Cambodian rice fields (Fiorella et al. 2020), and diversifying into pan-seasonal aquaculture production in Bangladesh (Chen and Mueller 2018).

that it might influence intersectoral labour productivity differentials and the pace of factor reallocation in developing economies.

f. Impacts on gross fixed capital formation and the returns to capital

Although climate and environmental change likely impact the stock and productivity of land and labour more than those of physical capital, one might reasonably expect some feedback on capital stocks and their productivity as well. The most obvious impacts relate to physical infrastructure, such as roads, ports, bridges, etc. that are vulnerable to extreme weather events (e.g. tropical cyclones), associated damage (e.g. due to erosion or mudslides), and to SLR. There may also be somewhat less obvious impacts on energy systems, and even on financial markets. Each of these may impact the relative returns to investment in and the intersectoral allocation of factors of production. This section briefly flags these issues.

Changing patterns of precipitation and temperature extremes, or of storm tracks, frequencies, and intensities, as well as SLR and associated storm surges and coastal flooding, may disrupt infrastructure services such as water supply, energy production, and transportation (Wilbanks and Fernandez 2013). These problems can cascade when disruptions in one infrastructure system in an area cause interruptions in other systems or areas, as when electricity outages disrupt water pumps or rolling blackouts that impact more distant locations. Furthermore, the quality and reliability of infrastructure and services affects the returns to private fixed capital – machines, vehicles, etc. So feedback from anthropogenic climate and environmental change may have impacts beyond the more obvious ones on land and labour.

Transport infrastructure vulnerabilities, in particular, directly influence the costs of commerce and thus the returns to trade and to specialisation.[9] Most empirical studies on the impacts of physical, especially transport, infrastructure focus on construction, not degradation or destruction.[10] But the available evidence across multiple countries and eras strongly suggests that roads, railways, etc. have enabled increased intra- and inter-national specialisation according to comparative advantage, facilitating the rise of cities, commercialisation of farming, increased trade across space, and reduced spatial and inter-sectoral price differentials, signaling increased allocative efficiency and welfare (Jedwab and Moradi 2016; Burgess and Donaldson 2017; Jedwab et al. 2017; Donaldson 2018; Zant 2019). The potential for climate and environmental change to

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[9] Seaports around the globe, however, are under prepared to cope with SLRt challenges (Asariotis et al. 2018). Port disruptions risk increasing market frictions that affect the relative returns to exportables, importables and nontradables, thereby influencing the structural transformation process.

[10] One exception is Zant (2018), which uses the collapse of a railway bridge in Malawi due to a tropical storm as a natural experiment, concluding that railway transport services had reduced inter-market agricultural commodity price dispersion by 14 to 17%.

degrade or destroy physical infrastructure that facilitates trade risks slowing low-income agrarian economies' structural transformation.

As the world becomes more attuned to the damages wrought by fossil fuels, and ongoing R&D investments drive down the cost of biomass, geothermal, solar, wind, and other sources of renewable energy – as sources of electricity, heat, and liquid fuels for combustion engines – the promise of technological leapfrogging in energy looms ever larger in low-income rural areas. Cleaner, off-grid, distributed, renewable energy production can provide some insurance against shocks to centralized power generation systems. They may also offer some of the same impactful opportunities that LMICs have enjoyed from mobile communications and associated mobile services (e.g. banking) that have stimulated non-farm investment and enterprise creation in rural areas, human capital formation, and improved extension services and market performance (Jensen 2007; Aker and Mbiti 2010; Suri and Jack 2016). Insofar as climate and environmental change accelerates the arrival of such technologies – if only through policy and behavioural adjustments – it may impact the path of structural transformation.

There is, however, no consensus on how renewable energy technologies might impact behaviours and welfare in currently-off-grid rural areas. For example, studies in Bangladesh (Kudo et al. 2019), Rwanda (Grimm et al. 2017), Uganda (Furukawa 2014), and Zambia (Stojanovski et al. 2018) find uneven impacts of solar lighting on children's education and academic performance. And there is suggestive evidence of heterogeneous treatment effects even within local areas. The gains from grid connection are higher for households willing to connect at a high price than for those willing to connect when it is effectively free (Lee et al. 2020b). It seems unlikely that improved household-level access to electricity alone will prove sufficient to generate substantial improvements in economic outcomes for the world's poor (Lee et al. 2020a). And scant evidence exists on how the arrival of electricity affects household productive investment, production, and technology adoption patterns. So quite apart from the thus-far-ambiguous effects of electricity access on human capital accumulation, it remains unclear how shifting energy generation and distribution might influence the direction and pace of structural transformation. Likewise, the appropriate strategy for expanding energy access remains unclear, although off-grid renewable technologies may be preferred for rural mass electrification, whereas in regions with potentially high business growth, grid infrastructure should be focused (Grimm et al. 2020).

Anthropogenic climate and environmental change is increasingly believed to affect financial markets, as an emerging subfield of climate finance reveals (Hong et al. 2020). One obvious mechanism is that adverse weather and other events can cause financial losses. These can be direct, arising perhaps from destruction of a firm's physical assets, or due to disruption of firms' operations or of whole supply chains, or because of shock-induced reduced demand for firms'

products. Or expected transition costs may rise as expectations shift around likely future changes in policies (e.g. carbon taxes) and technologies (e.g. viable hydrogen fuel cells), leading companies to announce previously-unexpected costs (Campiglio et al. 2019).

But perhaps the biggest financial market effects surround changes in investors' expectations, which adjust in response to shifting climate or environmental risk assessments. Shocks like droughts, floods, or storms lead investors to revalue firms' cash flow forecasts, the likelihood of stranded assets, and broader forecast model parameters, thereby impacting returns on equity and borrowing costs (Campiglio et al. 2019; Elliott et al. 2019; Hong et al. 2019; Choi et al. 2020). These effects can vary across sectors and firms within sectors, altering the relative returns to moving capital out of agriculture and into manufacturing and services or across regions or countries (Bansal et al. 2019; Griffin et al. 2019; Hugon and Law 2019; Krueger et al. 2020). Such effects may be more pronounced in LMICs where firms have been less able to invest in adaptive mechanisms for dealing with climate and environmental shocks (Addoum et al. 2020).

4. Major policy research questions

Once one recognises the bidirectional feedback between agriculture-led structural transformation and natural phenomena, a host of questions arise about prospective alternatives to familiar development strategies. Should governments and donors emphasise agricultural technological change among smallholder farmers – e.g. through agricultural R&D and extension investments – and factor and product market integration – e.g. through communications, transportation, or institutional infrastructure investments – so as to drive intersectoral factor reallocation into higher return uses and spark capital accumulation? The impacts of anthropogenic climate and environmental change on the stocks and productivity of factors of production necessitate rethinking of familiar prescriptions and reassessing priorities. In this section we briefly consider some key policy issues that merit more in-depth research.

a. Agricultural research and extension. Is there still a major role for agricultural R&D and extension in LMICs? The answer is almost certainly 'yes!'. Rising food demand must be met through agricultural TFP growth in order to avoid increased food prices, poverty, and food insecurity. Moreover, the familiar logic of structural transformation still holds at least in part in some more landlocked settings.

Underspending on agricultural R&D is reflected in average internal rates of return from 1975-2014, of 35-42 and 38-62 percent in Sub-Saharan Africa and the rest of the world, respectively (Pardey, Andrade et al. 2016). Local R&D investments were the main driver of lower food prices in Africa from 1991-2011, not trade nor the diffusion of technologies developed via R&D on other

continents (Hertel et al. 2020). Advances in genomics and synthetic biology can accelerate and broaden the scope of genetic advances in crops and livestock and in fine tuning varietal characteristics to local needs.

Adaptation research is required not only for climate change, but equally to increased risk of drought, flooding (especially with sea water), and to pathogens and pests whose ranges are shifting. Even in temperate zones where warmer temperatures should physiologically stimulate more rapid crop growth, warming-induced changes in pathogen and pest pressures increasingly compels defensive (e.g. pesticide, weeding labour) investments to protect crops, generating costly tradeoffs with productivity-enhancing inputs such as inorganic fertiliser or improved seeds among liquidity constrained small farmers (Jagnani et al. forthcoming). Initial results with flood tolerant rice have proved very promising (Emerick et al. 2016). But what effect does shifting the orientation of crop and livestock research have on the returns to agricultural R&D? Do particular subpopulations disproportionately benefit from those investments? We know little about these important questions.

Agricultural R&D has also increasingly shifted to the private sector, even in LMICs (Chai et al. 2019; Pardey, Chan-Kang et al. 2016). Given that many of the most promising agricultural innovations will depend on digital and genetic innovations that rely overwhelmingly on private finance, this raises important issues surrounding intellectual property, market concentration and the critical legal and economic infrastructure needed to support diffusion. In prior generations, agricultural R&D was publicly or philanthropically funded, generating public goods that rendered technological change quasi-exogenous. But as agricultural R&D increasingly privatises in response to market incentives, how will the climate and environmental impacts of agricultural technological change, as well as the distributional impacts of R&D? Can new technologies (e.g. CRISPR) reduce the barriers to entry for smaller innovators in underserved regions and product niches? And how does Europe-US conflict around the regulation of biotechnologies like transgenic plant and animal varieties or gene editing affect the political economy of agricultural R&D in LMICs?

Furthermore, what is the role of conventional agricultural extension in promoting technology diffusion given increasingly privatised agricultural R&D and input distribution systems? The evidence on the returns to agricultural extension have always been thin, and too often discouraging (Anderson and Feder 2007; Fu and Akter 2016; Ogutu et al. 2020; Vandercasteelen et al. 2020). How must agricultural extension systems adapt to increasingly sophisticated digital and genetic technologies protected by intellectual property?

b. Facilitate de-agrarianisation? Although it is hard to imagine meeting increased domestic food

demand in the coming decades without continued agricultural technological change, might the familiar strategies be usefully supplemented by increasingly decoupling food production from the land? There is merit to the idea, especially given the many, largely adverse feedback effects from agricultural land conversion through GHG emissions, infectious disease ecology, loss of biodiversity, and associated ecosystem services, etc.

Governments and donors have long promoted agricultural mechanisation so as to facilitate the substitution of capital for labour in agriculture and accelerate workers' migration to non-farm sectors where their average annual earnings are appreciably greater (Gollin et al. 2014), if perhaps only because of less underemployment (McCullough 2017). As alternative uses of land in renewable energy and environmental services production rise, might there be merit to considering analogous strategies to promote the substitution of capital for land, i.e. de-agrarianisation that (partly) decouples food production from the land (Barrett 2021)? Does the familiar structural transformation logic, by which exogenous income gains accruing to rural land owners stimulate nontradables demand and employment through local general equilibrium effects, apply as well to shocks originating in the emergence of viable carbon markets, payments for ecosystem services schemes, and renewable energy generation? Do energy and environmental services innovations similarly release labour from primary production in rural areas and expand the supply of intermediate inputs into town-based secondary and tertiary sector production, just as under old-fashioned dual economy models? Might these enable some technological leapfrogging in parts of Africa and Asia?

This might not be as far-fetched an idea as it initially seems. HIC consumers are flocking to plant-based and cellular substitutes for traditional animal-sources foods (ASFs). Will LIC consumers follow a similar pattern as income growth, urbanisation and post-pandemic interest in shorter food supply chains – reinforced by growing middle-class consumer concerns about nutrition, food safety, animal welfare, and the environmental impacts of conventional farming methods – build momentum for technological leapfrogging in the food systems of Africa and Asia? The underlying technologies are accessible. The necessary adjustments are made increasingly simple by advances in synthetic biology that enable a company to design microbes (e.g. bacteria, yeast) to turn inexpensive feedstock (e.g. distillers' grain) into more complex proteins than beer or cheese – the viable fermentation-based businesses that LICs all have. The costs of production in these systems are falling fast and seem to scale easily, offering countries staring at huge future growth in demand for ASF with land-saving alternative food production systems that could free land for energy and environmental services (Buckler and Rooney 2019; Tubb and Seba 2019). And LMIC agri-food value chains are rapidly evolving to capture rising credence good valuation by urban middle- and upper-class food purchasers, generating an vastly accelerated pace of change in the post-harvest components of value chains as compared to prior transitions in the high

income world (Barrett et al. forthcoming). Indeed, we already see signs of analogous changes in horticultural production as controlled environment agriculture (CEA) – so-called 'indoor' or 'vertical' farming based on aero-, aqua- or hydro-ponic methods – has been exploding in Asia, providing urban middle- and upper-class consumers with pan-seasonal, localised supply chains delivering consistent quality, high-value, short cycle leafy greens and fast-growing fruits (Pinstrup-Andersen 2018; WWF 2020; Barrett 2021). Shifts in the direction of de-agrarianised food production may well accelerate as technological change in the renewable energy sector drives down (especially off-grid solar) electricity costs and as increased water scarcity proves more easily managed in compact spaces than in large, open fields.

Deagrarianisation requires alternative, non-agricultural income streams become viable for rural landowners (Barrett 2021). At least three options exist. The first is renewable energy production, demand for which is growing rapidly globally, especially as technological advances rapidly drive down geothermal, solar, and wind production costs and as off-grid alternatives have become increasingly viable. In HICs, lease royalties from energy companies and power utilities have opened up attractive non-agricultural income supplements to rural communities. Further, there may be reinforcing feedback between renewable energy production and novel, non-farm food production methods because cost-reducing technological change in each sector helps lower costs in the other. But the possibility of rural power generation, including in local grids, raises a host of underexplored regulatory and infrastructure questions.

A second option arises through carbon markets to monetise sequestration in trees, soils, and cover crops. Payments for reducing emissions from deforestation and forest degradation (REDD) mechanism represents one such instrument (Angelsen et al. 2009; Venter et al. 2009), although careful evaluation of REDD's impacts, especially on rural livelihoods, remain scarce.

Sequestration is an internationally tradable service, driven largely by carbon taxes and emissions trading systems (ETS) in HICs, along with the digital technologies necessary for low-cost, reliable verification of GHG fluxes on distant lands. This is not viable currently, as the global average carbon price remains far below the US$40–80/tCO2 range necessary to cost-effectively reduce emissions in line with the Paris Agreement (World Bank 2019, 2020). But a burgeoning literature on climate smart agriculture clearly establishes the viability of GHG sequestration via regenerative agriculture using sustainable farming practices in low-income communities (Lal 2015; Mbow et al. 2014; Sa et al. 2017). There may be a tipping point where the monitoring technologies, ETS mechanisms, and HIC regulatory and tax policy suddenly make GHG sequestration a viable income source (or at least supplement) for rural landowners in Africa and Asia. Working out the necessarily institutional and technological details, the distributional and local general equilibrium effects if windfalls accrue mainly to (wealthier) landowners, and the

balance of payments implications remain underexplored research topics.

A third option is payments for ecosystem services (PES), which have grown to an estimated $40 billion annually worldwide (Salzman et al. 2018). PES have clearly demonstrated favourable environmental impacts when well designed to induce desired behavioural change, although a range of design flaws continue to impede broad inclusion and broader economic gains to rural communities (Jack et al. 2008; Jayachandran et al. 2017; Jack and Jayachandran 2019). But these are no panacea as they are likely to work more effectively in a limited number of contexts where gains from trade are large and transaction costs are low (e.g. involving few and large beneficiaries of the environmental services, such as hydroelectric companies or municipalities).

If LMICs are to establish viable non-agricultural revenue streams for rural lands, land tenure issues become especially salient. Customary land tenure usually involves a land claimant applying labour to convert, maintain, and cultivate the land – even improve it through on-field investments in trees, irrigation, etc. If land increasingly generates income by remaining idle, or by simply hosting renewable energy generation structures, increased contestation for lands might ensue. This might increase the value of clear cadastral surveys to establish clearly who owns which rights in what lands, as compared to the returns to such surveys in agriculture-driven rural systems now. A new chapter of research on land tenure may be dawning.

c. Rural infrastructure. Low population densities and long distances to major markets limit non-agricultural options for low-income rural areas. Rural communications, electricity, and road infrastructure has long been thought a key investment for such places, partly by stimulating agricultural productivity growth, but perhaps even more by facilitating non-farm labour markets and enterprises (Fan and Chan-Kang 2005; Khandker et al. 2009; Asher and Novosad 2020). Infrastructural improvements clearly boost incomes and the absolute returns to capital, labour, and land in rural areas. But the relative returns across factors and among sectors remains seriously under-explored, and with it the answer to the question of whether rural infrastructure improvements really accelerate structural transformation out of agriculture.

Moreover, rural roads are widely believed to accelerate deforestation, thereby inducing anthropogenic climate and environmental change of the sort that seems to distort the returns to factors of production in different sectors, albeit with a lag. Road building and deforestation appear to be highly correlated in Brazil (Pfaff 1999), Cameroon (Mertens and Lambin 2000), or Thailand (Cropper et al. 1999, 2001). In areas with agriculturally poor soils and low population densities, road building may be no-win, causing habitat fragmentation and providing low economic returns (Chomitz and Gray 1996). Although there seems a consensus that newly built roads in remote forested areas cause deforestation, there has been mixed evidence on the effects

of road improvements (Busch and Ferretti-Gallon 2017). Road expansion in regions that have substantial prior clearing may attract development away from areas that are extensively forested and thus could help reduce deforestation, safeguard ecosystem services and biological diversity (Balmford et al. 2016; Deng et al. 2011; Pfaff et al. 2007; Weinhold and Reis 2008). The expansion of road networks, therefore, must be considered cautiously or even reduced if to remote forested areas (Busch and Ferretti-Gallon 2017). Recent evidence from India, however, finds that new rural roads have precisely zero effect on local deforestation, while highway upgrades lead to substantial forest loss due to increased timber demand along the transportation corridors (Asher et al. 2020).

Expanding access to broadband internet service will be especially important in low-income rural areas in order to facilitate orderly migration out of geographic poverty traps (Kraay & McKenzie 2014; Barrett et al. 2019) and to enable rural lands' remunerative use in non-agricultural production of energy or environmental services. This links to expanding electrification, if only through local, unconnected grids and off-grid power generation. This is especially necessary in Africa where less than half of households have access and population growth has outpaced electrification in recent decades (Blimpo and Cosgrove-Davies 2019).

5. Conclusions

Contemporary development policy for low-income agrarian nations still rests heavily on old structural transformation models that abstract from the central role nature plays in agriculture and other sectors. Broad acceptance of the prominent role human behaviour plays in climate and environmental change should now stimulate efforts to expressly incorporate bidirectional feedback from nature back on the land, labour, and physical capital stocks, as well as TFP growth into theories of – and empirical research on – structural transformation.

Several challenges lie ahead in this research agenda. First, high-quality, linkable data for rigorous empirical work remain scarce in LMICs, especially longitudinal health, socioeconomic, and weather data. While satellite-based weather and environmental data are now available over extended periods at reasonably high spatial resolution, there is growing recognition that measurement errors and biases could bias causal inference (Fowlie et al. 2019; Jain 2020). The detailed, georeferenced farm- or household-level datasets too often remain inaccessible to researchers outside of government agencies. Remotely sensed data increasingly open up exciting new measurement and near-real-time monitoring and evaluation opportunities (Lobell et al. 2020), but still require traditional datasets for ground truthing. New data collection methods, such as crowdsourcing of environmental datasets, could help fill gaps that remote sensing cannot address using small and cheap sensors. But decentralised data collection raises important issues

of property rights in data and privacy protections within data sharing agreements. This will also require greater attention to data interoperability to link socioeconomic survey and census data with earth observations, especially because the relevant sampling units – e.g. human population or land area – do not always correspond, with important implications for inference (Pelletier et al. 2020).

Second, research that endogenises both the structural transformation process and its climate and environment correlates necessarily poses methodological challenges, especially for causal inference. The slow occurrence of climate change and other changes, for example, allows for adaptation, which makes estimation of impacts even more uncertain (Pindyck 2020).

Third, advances in economic theory are necessary to develop testable hypotheses around mechanisms through which anthropogenic climate or environmental changes affect the returns to and intersectoral allocation of factors of production. Abstraction from the bidirectional feedback between nature and the economy has burdened the empirical structural transformation literature with pervasive omitted variables problems. Such theory advances require enhanced understanding of the underlying mechanisms that link climate, environment, and weather variables to socioeconomic outcomes. This requires the support of deeper cross-disciplinary collaborations with natural science subject experts.

The potential for 'green rural transformation' seems real (Barbier 2020). But to craft effective policies and investment strategies to foster structural transformation, we must take seriously bidirectional linkages with the natural environment in today's low-income agrarian economies.

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