Structural Transformation, Agriculture, Climate, and the Environment*

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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 key policy research questions concerning structural transformation and the complex feedback among agriculture, nature, and economic growth processes, especially in low-income agrarian economies.

JEL Codes: O13, Q10, Q54

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

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 labor into output. 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 and spur income growth and a steady outflow of labor from agriculture. In closed economies and in the face of income and price inelastic food demand, food supply expansion reduces relative food prices and thus relative factor returns in agriculture, inducing factor reallocation out of agriculture even as food output and agricultural income grow. Factor and/or product market imperfections boost the productivity gains from factor reallocation out of agriculture.

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[1] The intellectual origins trace back to Lewis (1954), Johnston and Mellor (1961) and Ranis and Fei (1961). See Bustos et al. (2016) for a recent illustration, and Timmer (2002) and Gollin (2014) for reviews.

One can usefully enrich these models, for example, by introducing investment in labor-augmenting human capital formation, geographic migration, trade frictions, land as a third, quasi-fixed factor of production mainly (or exclusively) used in the agricultural sector, or by endogenizing the rate and/or factor-bias of technological change. But key model predictions carry through regardless. Starting from an initial condition of a workforce concentrated in relatively low-productivity agriculture, farm productivity growth drives labor 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 sector(s).

These models all make a strong assumption: economic processes are independent of changes in the natural environment. They also yield a striking prediction: in equilibrium, capital, labor and land endowments, and the technology that boosts their productivity, are non-decreasing over time. Only the *relative* returns to a factor of production, like land, may diminish. Neither the *absolute* returns nor the stocks nor flows of the factor inputs available for future production diminish other than through 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 summarize these relationships by the equation $Y=Af(K,L,T)$, where A is the Hicks-neutral technology parameter (i.e., total factor productivity, TFP), in f(.), the production function that maps the productive capital stock, K, 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 is limited only by capital, labor and land endowments, the rates of technological change and population growth, and frictions in reallocating factors between sectors or in capital accumulation. Implicitly, nature exerts no influence over factor accumulation and productivity, even though agriculture is merely a human adaptation of nature and unavoidably dependent on natural processes.

This paper makes the case for relaxing that untenable assumption. 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, $Y=Af(K,L,T,E)$, and to endogenize A, E, L and T, not just K, as depicted by the bidirectional arrows in Figure 1. Some elements of E – e.g., atmospheric greenhouse gas (GHG) concentrations – are largely exogenous to most LMICs, but even global public bads like climate change stimulate endogenous economic responses that then impact local agroecosystems, which in turn feedback into local factor accumulation and allocation patterns.

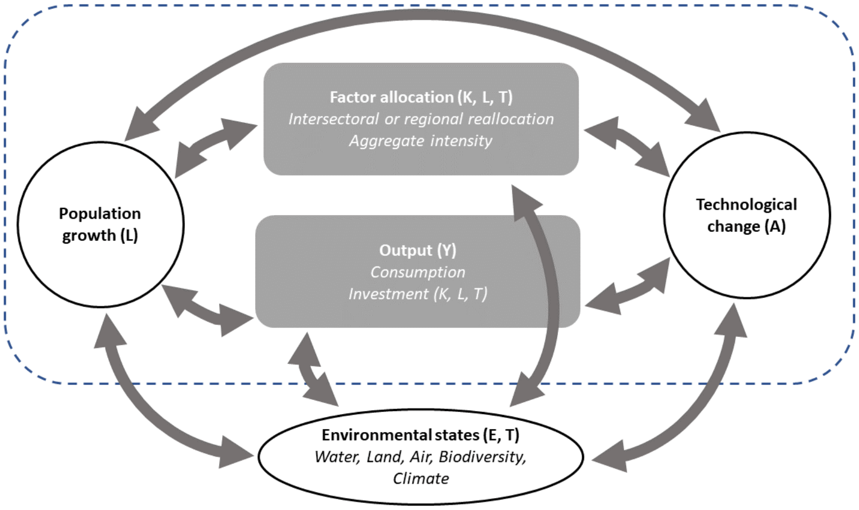

Figure 1: Conceptual summary.

2. The climate and environmental impacts of structural transformation

The research community has long recognized that population growth and agricultural technological change also contribute to climate change, air and water pollution, land conversion and biodiversity loss. In Figure 1, this reflects the arrows pointing towards the "Environmental states". Because these impacts are familiar, we only briefly highlight key features of that literature, mainly to underscore that direction of the feedback mechanisms that closely link the structural transformation process to climate and environmental change. In the interests of brevity, and because changing agricultural productivity and associated factor allocation are typically treated as the drivers of structural transformation (Johnston & Mellor 1961), we focus here on impacts originating from agricultural transformation, acknowledging that other pathways exist (e.g., air pollution from emergent industries, energy, and transport systems).

GHG inventories indicate emissions from 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 $GtCO_2eq/yr$ in 2010. Output has increased even more than GHG emissions, thus carbon intensity per unit of output has declined by about 40% in both crop and livestock production since the 1970s (Bennetzen et al. 2016a). While high income countries (HICs) were able to reduce GHG emissions while expanding agricultural production, low-and-middle-income countries (LMICs) expanded both emissions and production over 1970-2007 (Bennetzen et al. 2016b).

The same agricultural technological change that reduced carbon intensity has dramatically affected land use. The most compelling empirical analyses fairly consistently find that improvements in crop germplasm, in particular, slowed expansion of the agricultural frontier, thereby conserving forest and wetlands, relative to appropriate counterfactuals (Stevenson et al. 2013; Hertel et al. 2014; Abman and Carney 2020; Pelletier et al. 2020; Gollin et al. 2021). Population and income growth have nonetheless expanded the global agricultural land footprint by 10%, 1961-2006, mostly in LMICs, while cultivated and pasture lands declined 9% in HICs (Fuglie 2010). In the past decade, agricultural land has expanded roughly 3% annually in Africa, while stagnating in other LMICs (Barrett 2021). The net effect is that 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). This implies reinforcing feedback, since climate change adversely affects LMICs' agricultural land and labor productivity (see section 3) , inducing greater forest clearing and GHG emissions.

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. Water is rapidly becoming the most limiting factor in conventional agricultural production. Agriculture also pollutes, generating chemical residues and livestock waste (Paudel and Crago 2021), which especially affects fisheries productivity and human health.

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). Here too, reinforcing feedback arises as declining ecosystem services adversely affect agricultural productivity, leading to still-greater land conversion.

3. Feedback from climate and environmental change to structural transformation[2]

Climate and environmental change obviously affect the quality-adjusted stocks of and returns to land, labor 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 the social and economic impacts of climate and the environment have attracted considerable prior attention (e.g., Carleton and Hsiang 2016), the implications for the structural transformation process and associated policy (and policy research) remains unexplored. That is our focus (especially in section 4).

Once one allows for environmental feedback, then incentives to develop and adopt cleaner technologies, including renewable substitutes for non-renewable resources, could arise endogenously and affect structural transformation patterns. Moreover, policy design must then

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[2] Here we cover only the main feedback mechanisms. Barrett et al. (2020) discusses other, less well studied linkages related to violent conflict and crime, degraded interpersonal trust and exchange, gross fixed capital formation in transport and energy, and financial markets.

explicitly consider the indirect, dynamic impacts of either disrupting or reinforcing the feedback between economic and environmental processes. This is especially true for environmental changes most likely endogenous to LMICs' structural transformation patterns: local pollutants, land and water management, and biodiversity loss. 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. But LMICs' endogenous responses to climate change often cause local environmental change (e.g., shifting land and water use) that precipitates feedback within the local system.

a. Impacts on returns to land and agricultural technologies

Over the past century, global temperatures have increased by about 1°C (IPCC 2014b). Rising temperatures have substantial ecological and hydrological impacts, which disproportionately affect agriculture. For example, experts anticipate shifts in the range of pest and pathogens (Bebber 2015) and substantial crop losses related to insect pests in a warming climate (Deutsch et al. 2018). Rising temperatures also increase evapotranspiration, exacerbating salinization in coastal regions (Colombani et al. 2016), affecting agriculture in countries like Bangladesh (Dasgupta et al. 2015; Chen and Mueller 2018).

The literature analyzing 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. Climate change has slowed yield growth in major crops, mostly due to recent warming trends, with a few regional exceptions (Lobell and Field 2007, Lobell et al. 2011). Anthropogenic climate change may have reduced global agricultural TFP by about 20% over 1961-2020, with even larger impacts in warmer regions such as sub-Saharan Africa (Ortiz-Bobea et al. 2021). 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.

Changes in industrial and urban pollution may also 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 (Boone et al. 2019).

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's risk profile. First, without access to actuarily fair insurance markets, any increase in rainfall and/or temperature variability should induce risk averse households to reallocate labor and capital out of agriculture towards non-farm livelihoods less subject to climate risk, including via migration to urban areas (Barrett et al. 2001; Macours 2013). Second, exogenous productivity shocks can either generate windfall gains – directly, or via a temporary stimulus to local demand for non-farm nontradables – that rural households invest in non-farm enterprises (Foster and Rosenzweig 2007; Emerick 2018), or cause shortfalls that households cover through increased non-farm labor effort (Jayachandran 2006, Blakeslee et al. 2020; Colmer 2021).

Another mechanism affecting the returns to land arises from the emergence of alternative rural land uses to agriculture. First, in peri-urban areas, residential and industrial expansion fueled by structural transformation drives up land values and induces land reallocation out of agriculture. Second, 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 stimulate land use 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. Third, rural lands are attractive sites for the provision of environmental services, as we discuss below. Greater, but as-yet-largely-unrealized, 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 important spillover effects (Faber and Gaubert 2019).

Sea-level rise (SLR) and increased flooding are anticipated consequences of climate change that interact dangerously with natural subsidence, i.e., land sinking largely due to other anthropogenic processes such as groundwater withdrawal (McGranahan et al. 2016; Nicholls et al. 2011; Herrera-Garcia et al. 2021; Tellman 2021). With more frequent extreme climate events expected under both business-as-usual and moderate emission-mitigation-policy scenarios, by 2050 most of the tropics are projected to experience *annual* exposure to the present-day 100-year extreme SLR (Vousdoukas et al. 2018). This will significantly increase salinization, 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. 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). This will not only force mass labor migration but also result in massive stranded assets in fixed capital and absorb considerable capital to finance coastal regions' evacuation.

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; Vousdoukas et al. 2020). 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.

The economic feedback effects of anthropogenic climate and environmental change on land disproportionately impact agriculture, especially in rainfed 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 labor to non-farm sectors, generates surpluses to invest off farm, and stimulates domestic demand for non-farm nontradables.

b. Impacts on human capital formation and allocation

A growing literature likewise causally links climate and environment to human capital formation and allocation, from health to education performance and adult cognitive and physical outcomes and migration.

The most studied mechanism concerns temperature. High temperatures generally worsen human capital outcomes, including increased risk of infant mortality, low birth weight and preterm delivery (Deschênes et al. 2009; Banerjee and Maharaj 2020; Barreca and Schaller 2020) and of child stunting (Blom et al. 2019), which in turn predicts worse health and cognitive outcomes in adulthood (Almond et al. 2018), and even adult mortality rates (Burgess et al. 2017; Deschênes and Greenstone 2011). High temperature negatively affects cognition and educational outcomes (Seppänen et al. 2006; Cho 2017; Graff Zivin et al. 2018; Fishman et al. 2019; Park et al. 2020; Garg et al. 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. The impacts of long-run variation in temperature on human performance remain understudied, however, with the few results available (e.g., Graff Zivin et al. 2018) suggesting caution in projecting long-run climate impacts based on estimates from short-run weather shocks.

Precipitation's impacts on human capital outcomes differ by contexts and time scale. Early-life rainfall in 29 tropical countries correlates positively with children's education attainment in Africa and Asia but the relationship is reversed in Central America and the Caribbean (Randell and Gray 2019). 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 has ambiguous effects on human capital, depending on whether substitution or income effects dominate. Similarly, while minor to severe droughts lead to worse child nutrition, these effects can be mitigated by factors affecting both the adaptive capacity and sensitivity of local food systems such as nutritional diversity, irrigation, governance, and political stability (Cooper et al. 2019). 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 2022). The apparent mechanisms mostly concern income effects in the face of liquidity constraints that lead to reduce inputs important to child development.

Air pollution has sizable negative effects on fetal, infant and child mortality (Jayachandran 2009, Arceo et al. 2016, Heft-Neal et al. 2018, Deryugina et al. 2019. Bombardini and Li 2020). 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 those geographic differences. Ebenstein et al (2016) 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 diarrhea-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, not only through increased air pollution due to smoke and suspended particulates from burning forest to clear land for cultivation, but also through induced local climate change and disease ecology. Most extreme warming occurs in large patches of deforested lands, which poses a challenge to the 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).

Chemical control of insects and other disease vectors have largely eradicated tropical infectious diseases – cholera, dengue, malaria, etc. – from HICs. But as much as 75% of LMIC deaths remain attributable to infectious diseases (Lozano et al. 2012). Indeed, infectious disease ecology illustrates nicely the feedback between human and natural systems. Tropical deforestation due to agricultural expansion has been repeatedly linked to increased vector-borne and zoonotic disease (Tucker Lima et al. 2017; Brock et al. 2019). Agricultural drivers – primarily land conversion – are associated with more than 25% of all new infectious diseases in humans since 1940, including more than 50% of zoonoses (Rohr et al. 2019). Among many mechanisms, vector species – e.g., bats, primates, rodents – routinely outcompete non-host species in agricultural lands converted from forest or wetlands, thereby increasing human zoonoses exposure (Gibb et al. 2020). Anthropogenic land conversion similarly aggravates transmission of infectious diseases like malaria or dengue fever. For example, primary deforestation increased the incidence of malaria in Indonesia while logging of secondary forests designated for that purpose did not affect malaria prevalence (Garg 2019).

The estimated net impact of climate and environmental change on human health capital is perhaps best captured by the estimated disability adjusted life years (DALYs) lost. Poor air and water quality contributed 22% of the DALYs lost globally in 2010 (Lim et al. 2012). Moreover, because human, domestic animal, and zoonotic infectious pathogens are climate sensitive, they will likely worsen with climate change to account for perhaps 40% of total DALYs (McIntyre et al. 2017).

The evidence on labor productivity impacts of climate and environmental change remains scant, especially in developing countries. High temperature adversely affects labor productivity, even for indoor manufacturing activity in India (Somanathan et al. 2021; Adhvaryu et al. 2020). And the effects are likely greater in outdoor manual labor, like most primary agricultural activities, than in manufacturing and services. Air quality can also directly affect labor productivity independent of human capital formation (Hanna and Oliva 2015) for both outdoor (Graff Zivin and Neidell 2012) and indoor activities (Adhvaryu et al. 2022; Chang et al. 2016, 2019), including by seemingly affecting cognitive performance and decision making. But little compelling evidence exists on differential intersectoral effects, especially from LMICs.[3] If true, then climate change may magnify pre-existing intersectoral labor productivity differences that help drive structural transformation.

Climate and environmental change will affect not only human capital accumulation and labor productivity, but also the spatial distribution and thus intersectoral allocation of labor. Climate change has been accelerating urbanization (Castells-Quintana et al. 2021). Clement et al. (2021) predict 216 million internal climate migrants by 2050, and their estimates neglect induced international migration. Climate change and environmental stress migrants appear most likely to move to cities with jobs and social services, which may accelerate the intersectoral flow of labor out of agriculture but at the same time may create burden and slow economic growth in the ill-prepared receiving areas (Clement et al. 2021).

Yet the complex relationship between climate and environmental change and migration appears highly contextual and no unified theory has yet emerged that satisfactorily reconciles key empirical observations (Cattaneo et al. 2019; Kaczan and Orgill-Meyer 2019; Hauer et al. 2020). Increasing farmer access to shock-coping strategies (e.g., off-farm employment, remittances, credit, insurance), decline in the potential displacement effects of climate shocks and climate change adaptation within agriculture offer an alternative response.[4] The climate change-migration relationship and its consequence remain unknown and difficult to predict.

It is difficult, however, to generalize human capital and reallocation impacts over both sexes. Income shocks induced by climate anomalies may interact with pre-existing gender bias in intrahousehold resource allocation to result in disproportionate effects on girls (Maccini and

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[3] The temperature effect in the US appears more acute for highly exposed industries (e.g., agriculture, construction, mining, transportation, and utilities) than for non-exposed industries such as retail, education, and health (Park 2016).

[4] Farmers adjust agricultural inputs and crop varieties, shift sowing and harvesting dates, and reallocate labor among sub-sectors to mitigate the negative agroecological effects of changing rainfall and temperature patterns (Emerick et al. 2016; Chen and Mueller 2018; Fiorella et al. 2020; Jagnani et al. 2021; Cui and Xie 2021).

Yang 2009, Björkman-Nyqvist 2013). In places where child marriage is prevalent, poor households cope with weather shocks by having girls marry much earlier (Corno et al. 2020). Climate-induced migration can help women enjoy more empowerment and opportunities in the origin communities (Rigaud et al. 2018) but climate risks can make it difficult for women to migrate and pose risks that result in unfavorable outcomes in the receiving communities (Clement et al. 2021). That climate and environmental change may magnify the gender gap in human capital and labor outcomes has important implications for structural transformation process, given the unique role of women, who constitute more than half of the population of LMICs, in, for example, the rise of service sectors (Buera et al. 2019).

4. Major policy research questions

Once one recognizes the bidirectional feedback between agriculture-led structural transformation and natural phenomena, a host of questions arise about prospective alternatives to familiar development strategies. Thinking back to Figure 1, how can policies disrupt damaging reinforcing feedback, such as that between climate change, deforestation, and the loss of ecosystem services that both cause and result from agricultural extensification? Where and how can policies induce balancing feedback instead, permitting recovery of ecosystems that can facilitate inclusive and orderly structural transformation? Should governments and donors still emphasize agricultural technological change among smallholder farmers, and factor and product market integration so as to drive intersectoral factor reallocation into higher return uses and spark capital accumulation and factor productivity growth? The impacts of anthropogenic climate and environmental change on factor stocks and productivity necessitate rethinking familiar prescriptions and reassessing priorities in light of the building evidence on feedback between the economic development process and climate and environmental change. In this section we briefly consider some key policy issues that merit more in-depth research.

a. Agricultural research and extension

There remains a central role for agri-food R&D and extension in LMICs. Rising food demand must be met through agri-food system TFP growth to avoid increased food prices, poverty and food insecurity. The familiar logic of structural transformation still holds at least in part in some more landlocked settings. Local R&D investments were the main driver of lower food prices in Africa, 1991-2011, not trade nor the diffusion of technologies developed on other continents (Hertel et al. 2020). Advances in genomics and synthetic biology can accelerate and broaden the scope of genetic advances and in fine tuning varietal characteristics to local needs (Barrett 2021).

But the familiar Green Revolution-era mix of improved crop and livestock genetics, chemical fertilizers, irrigation and machinery will no longer suffice. Increasingly we need to focus on interventions that dampen or break the reinforcing feedback – or even introduce balancing feedback – between nature and agriculture, and to look beyond conventional agricultural production to alternative, land-and-water-saving methods of satisfying growing food demand.

Adaptive research is especially needed for climate change, increased risk of drought and flooding (especially with sea water), and to pathogens and pests whose ranges are shifting. Productivity-boosting and risk-mitigating technologies can dampen the reinforcing feedback between environmental conditions and farmer investment and factor allocation patterns. Even in temperate zones where warmer temperatures should physiologically boost crop growth, warming-induced changes in pathogen and pest pressures increasingly compel defensive (e.g., pesticide, weeding labor) investments to protect crops, generating costly tradeoffs with productivity-enhancing inputs such as inorganic fertilizer or improved seeds among liquidity constrained small farmers (Jagnani et al. 2021). Initial results with flood tolerant rice have proved very promising (Emerick et al. 2016). But uptake of a range of climate-smart agricultural innovations has generally proved sluggish in recent years, obstructed by a range of institutional and market failures (Westermann et al. 2018).

Agricultural R&D has historically generated very high returns, accruing mainly to poor food consumers, following the standard structural transformation logic (Alston & Pardey 2021). But agricultural R&D has increasingly shifted to the private sector, even in LMICs (Chai et al. 2019). Given that many promising agricultural innovations will depend on digital and genetic innovations reliant on private finance, this raises important issues surrounding intellectual property and market concentration and the legal and economic institutions needed to support diffusion. Previously most agricultural R&D was publicly or philanthropically funded, generating public goods that rendered technological change quasi-exogenous. But as agricultural R&D increasingly privatizes, how will it affect the climate and environmental impacts of agricultural technological change, as well as the distributional impacts of R&D? Can new technologies (e.g., gene editing) reduce the barriers to entry for smaller innovators in underserved regions and product niches? And how will Europe-US conflict around the regulation of biotechnologies like transgenic or gene edited crops 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 privatized agricultural R&D and input distribution systems and increasingly sophisticated digital and genetic technologies protected by intellectual property?

b. Facilitating de-agrarianization

The other reason we must not rely solely (even mainly) on familiar Green Revolution-style interventions is that it is infeasible to expand land and water use proportionately to meet looming food demand growth in response to income and population growth, as well as urbanization, in LMICs. Policy tools can (indeed, must) loosen food production's ties to the land. This will likely have significant implications for the structural transformation process.

Governments and donors have long promoted agricultural mechanization to facilitate the substitution of capital for labor in agriculture and accelerate workers' migration to non-farm sectors where their average annual earnings are appreciably greater (Gollin et al. 2014; McCullough 2017). As alternative uses of land in renewable energy and environmental services provision rise, there is merit to analogous 'de-agrarianization' strategies to promote the substitution of capital for land (Barrett 2021). Because non-agricultural land uses are even less labor-intensive than farming, de-agrarianization will release labor while expanding the supply of intermediate inputs (e.g., electricity) for secondary and tertiary production – including food manufacturing and processing – especially in rural towns proximate to new renewable energy sources. But will the fixed capital formation and non-farm job creation effects be as large as under agriculture-led rural development? Much will depend on whether manufacturing absorbs labor at the rates one would expect in LMICs, which is not uniformly happening now under the standard structural transformation process (Diao et al. 2021).

De-agrarianization may enable some technological leapfrogging in parts of Africa and Asia, satisfying rapidly growing demand for animal-sourced foods (ASFs) without requiring dramatic expansion of land and water devoted to feed crops. This might not be as far-fetched an idea as it may seem. HIC consumers are flocking to plant-based and cellular substitutes for traditional ASFs. Analogous changes are already occurring in horticultural production as controlled environment agriculture – ‘indoor’ or ‘vertical’ farming – has exploded in Asia, providing urban middle- and upper-class consumers with pan-seasonal, localized supply chains delivering consistent quality, high-value, short cycle leafy greens and fast-growing fruits (Pinstrup-Andersen 2018; WWF 2020). Will LIC consumers follow a similar pattern for ASFs as income growth, urbanization, 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 – transform agri-food value chains in Africa, Asia and Latin America (Barrett et al. forthcoming)? The underlying technologies are accessible, growing 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 –fermentation-based businesses already widespread in LICs. ASF substitute production costs are falling fast and seem to scale easily, offering countries facing huge future growth in ASF demand food production alternatives that could free land for energy and environmental services (Buckler and Rooney 2019; Tubb and Seba 2019). Shifts in the direction of de-agrarianized food production may accelerate as technological change in renewable energy drives down electricity costs and as increased water scarcity proves more easily managed in compact spaces than in large, open fields.

De-agrarianization requires alternative, non-agricultural income streams for rural landowners (Barrett 2021). At least three options exist. The first is renewable energy production. Technological advances are rapidly driving down geothermal, solar and wind production costs and off-grid alternatives grow increasingly viable. In HICs, lease royalties from energy companies and power utilities generate attractive non-agricultural income supplements to rural communities. Further, there may be reinforcing feedback between renewable energy production and de-agrarianized food production methods because cost-reducing technological change in each sector lowers costs in the other. But the possibility of expanded rural power generation raises a host of underexplored regulatory and infrastructure questions.

A second option arises through carbon markets to monetize sequestration in trees, soils, and cover crops. Payments for reducing emissions from deforestation and forest degradation (REDD) represent one candidate instrument (Angelsen et al. 2009; Venter et al. 2009), although careful evaluation of REDD's impacts on rural livelihoods remain scarce. Sequestration is an internationally tradable service, driven largely by HIC carbon taxes and emissions trading systems (ETS), along with digital technologies that enable low-cost, reliable verification of GHG fluxes on distant lands. Currently, global average carbon prices remain far below the US$40–80/t$CO_2$ range necessary to cost-effectively reduce emissions in line with the Paris Agreement (World Bank 2019, 2020). But climate smart agriculture appears to offer viable means of GHG sequestration 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 supplement) for rural landowners in Africa and Asia. Working out the necessary institutional and technological details, the distributional and local general equilibrium effects - especially 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 over 550 active programs and an estimated $40 billion annually worldwide (Salzman et al. 2018). PES have had favorable environmental impacts when well designed to induce desired behavioral change, although a range of design flaws continue to impede broader economic gains to rural communities (Jack et al. 2008; Jayachandran et al. 2017; Jack and Jayachandran 2019). But PES schemes are no panacea as they likely 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 labor to convert, maintain and cultivate the land – even to improve lands through on-field investments in trees, irrigation, etc. If land increasingly generates income by remaining idle, or by simply hosting others' renewable energy generation structures, it might increase contestation over land and boost the value of cadastral surveys to establish clearly who owns which rights in what lands. 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 have long been key investments for such places, partly by stimulating agricultural productivity growth, but perhaps even more by facilitating non-farm labor markets and enterprises (Fan and Chan-Kang 2005; Asher and Novosad 2020). Infrastructural improvements boost incomes and the absolute returns to capital, labor and land in rural areas. But the relative returns across factors and among sectors remains seriously under-explored, as does 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 that distorts the returns to factors of production in different sectors, albeit with a lag. Road building appears highly correlated with deforestation and habitat fragmentation (Chomitz and Gray 1996; Pfaff 1999; Mertens and Lambin 2000; Cropper et al. 2001), although there has been mixed evidence on the effects of road improvements (Busch and Ferretti-Gallon 2017). Road expansion in regions with 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 (Weinhold and Reis 2008; Balmford et al. 2016). 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, which is especially necessary in Africa where less than half of households have access and population growth has outpaced electrification (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 behavior plays in climate and environmental change must now stimulate efforts to explicitly incorporate intro research on structural transformation the bidirectional feedback from nature back on the land, labor and physical capital stocks and factor productivity, as well as TFP growth.

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, non-trivial measurement errors can bias causal inference (Fowlie et al. 2019; Jain 2020). Furthermore, detailed, georeferenced farm- or household-level datasets too often remain inaccessible to researchers outside of government agencies. Remotely sensed data increasingly create exciting new measurement and near-real-time monitoring and evaluation opportunities (Lobell et al. 2020), but still require traditional survey or census datasets for ground truthing. New data collection methods, such as crowdsourcing environmental data, could help fill gaps that remote sensing cannot address using small and cheap sensors. But decentralized data collection raises important sampling error questions along with 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 endogenizes both the structural transformation process and its climate and environment correlates necessarily poses methodological challenges, especially for causal inference. The relatively slow emergence of climate change and other changes, for example, allows for adaptation, which makes estimation of causal 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. The needed 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) and can inform policy. But to craft effective structural transformation policies and investment strategies, we must take seriously bidirectional linkages with the natural environment in today's low-income agrarian economies.

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