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Rapid transformation of Food Systems in Developing Regions: highlighting the role of agricultural research & innovations

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ABSTRACT. Developing regions' food system has transformed rapidly in the past several decades. The food system is the dendritic cluster of R&D value chains, and the value chains linking input suppliers to farmers, and farmers upstream to wholesalers and processors midstream, to retailers then consumers downstream. We analyze the transformation in terms of these value chains' structure and conduct, and the effects of changes in those on its performance in terms of impacts on consumers and farmers, as well as the efficiency of and waste in the overall chain. We highlight the role of, and implications for agricultural research, viewed broadly as farm technology as well as research pertaining to all aspects of input and output value chains.

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1. Introduction

The "food system" (the dendritic cluster of R&D value chains and the value chains linking input suppliers to farmers, and farmers upstream to wholesalers and processors midstream, to retailers then consumers downstream) has transformed enormously over the past 50 years. The most rapid change occurred only in the past 25 years. It shifted from being a traditional system to a mix of transitional and modern. From a historical perspective, the transformation was abrupt, not gradual. Reardon and Timmer (2014), illustrating with Asian evidence, explain the drivers as a confluence of "five interlinked transformations:" (1) Downstream demand side change "pulling" system transformation: (a) urbanization; (b) diet change; (2) Midstream/downstream change, "intermediating" system transformation: (c) change in retail, wholesale, logistics, and processing; (3) Upstream change, “feeding” system transformation: (d) intensification of farming; (e) farm input supply chain change.

Our paper extends the above work by comparing transformations, extending analysis to Africa and Latin America and updating analysis of Asia. We also extend the analysis to the role of agricultural research as a determinant of food system transformation. Here “agricultural research” includes both research on the inputs and farm segment (breeding, input design, agronomic practices, and so on) and research on the off-farm post-farm segments (on technologies and organization of processing, packaging, logistics, wholesale, retail).

We address four questions:

(1) How are food systems transforming?
(2) How have research and non-research factors (urbanization, income growth, diet change, policies) influenced food system transformation?
(3) What have been the effects of transformation on consumers and on small and medium farmers, as well as on system performance measures such as supply of affordable and safe and quality food, and efficiency and waste in the system? By chain-rule logical extension, we thus examine how research affects consumers and farmers via the “pathways” of food system transformation.
(4) What are the implications of the transformation for agricultural research strategies?

Our findings lead to the two main messages of the paper.

First, the research community, hitherto mainly focused on the farm segment of the system, needs to take into account the entire food system and its transformation in their research strategies. This will determine whether innovations in farm technology and products lead to profitable marketed output by farmers. Increasingly, the urban market, the food industry firms that mediate access to the urban market, input supply chains, and agribusiness firms that determine the development of input supply chains, set the market incentives and conditions for the affordability and profitability of new farm technologies, and thus their adoption.

Second, the research community needs to understand and act on the importance of processing and logistics and wholesale (of outputs and inputs) in the food system, and research on these off-farm components of the food system. Research on and productivity of technologies for input manufacture and output processing, packaging, logistics, and commerce have equal weight in the performance of the food system relative to the farm sector. Investment in research and development (R&D) for these off-farm segments needs a much higher profile in the context of the transformed food system where off-farm segments occupy 40-70% of value added and costs of food.

To address the research questions we face two challenges. First, unlike other pathways of the impacts of research on farmers and consumers, such as breeding research on farm yields, it is particularly complex to examine research impacts on food systems and thence on farmers and consumers. Research is just one of the conditioners of the transformation and its impacts. The emphasis must be put on discussing the transformation itself and positing impacts of research in combination with other factors (such as urbanization). Second, as food system transformation in these regions is relatively recent, and the great majority of studies have been on the farm sector, empirical evidence on the transformation of the off-farm segments of the food system is only emerging and incomplete. We do our best to survey what is available.

The paper proceeds as follows. Section 2 lays out a conceptual framework. Section 3 explores "downstream" drivers of food system transformation – urbanization, income growth, diet change, infrastructure investments, and policies. Section 4 examines trends in the transformation of the structure, and Section 5, in its conduct (including technology change). Section 6 discusses emerging evidence of the system's performance. Section 7 presents implications for agricultural R&D strategies.

2. The Food System as Dendritic

The food system can be thought of as "dendritic," linking R&D, finance, input, and output supply chains, as follows.

The first and "core" supply chain is the output value chain. An example from the rice system is an output value chain composed of rice farmers producing paddy, which is collected by rural wholesalers or transporters and taken to mills where it is de-husked and polished. The rice is taken by wholesalers to urban wholesale markets and then to retailers.

The second and upstream "feeder" supply chains are the farm input supply chains, such as seed, fertilizer, farm equipment, labor, and arable land. These in turn are fed by input supply chains further upstream, such as the supply chain from phosphate mines to phosphoric acid plants to phosphate fertilizer factories.

The third and downstream "feeder" supply chains are those supplying inputs to the post-farmgate segments, in a sense "laterally." An example is the truck and fuel supply chains to rice wholesalers.

The fourth "pan-system feeder" supply chain is that supplying finance into every segment of every chain in the dendritic system. This can be formal or informal credit supply chains, or the most common in developing countries, own finance from retained earnings.

The fifth "feeder" supply chain is a broad set of public assets apart from agricultural research institutions such as infrastructure, police protection, and court systems for contract enforcement.

The sixth set of "feeders" is the R&D supply chains which supply technology and product innovations. For instance, companies and the National Agricultural Research System (NARS) and the International Agricultural Research Centers (IARCs) breed new seeds which feed seed supply chains which supply paddy farms. Moreover, universities and companies form public-private partnerships that involve an emerging "educational-industrial complex" (Zilberman et al. 2012) where innovation starts at university research centers and ideas are then further developed either by applied research centers (like the CGIAR and NARS) or by private sector entities (startups, small companies, and major corporations). The innovations in agricultural technology, food processing, packaging, logistics, and so on that are supplied by R&D value chains are often powerful drivers of change in the other parts of the system.

The segments in each of the above value chains, and the six value chains themselves, are intertwined in "intersectoral (or intersegment) linkages." An increase in demand or supply from one segment "induces" investment in another segment or chain (Hirschman, 1958). The induced investment can be in physical capital or hiring labor, but it can also be in the formation of an R&D supply chain: innovators (public or private) cum entrepreneurs design and market new technologies or new products to meet demand in other value chains. For example, if supermarket chains demand shelf-stability in vegetable varieties they contract to procure, innovators can endogenously implement a vegetable breeding innovation to breed a shelf stable variety, as derived demand from farmers wishing to supply the supermarket chain.

But seen from the perspective of a given food system, there can be exogenous R&D "investment" that is not induced by factor scarcity or attribute demand in that food system. The R&D supply chain may endogenously arise in another context (another country, another product, etc.) and then present a technological innovation "exogenously" to the given food system. An example is the creation and manufacture of extruders for feed processing in the US. It might then be transferred to Bangladeshi feed mills using imported machines embodying this innovation. This would give the importer a competitive advantage and perhaps induce concentration in the feed supply chain in Bangladesh.

3. Transformation of Food Systems: downstream and context drivers

3.1. Meta conditioners: Income growth, policy liberalization, and infrastructure investment

There are three "meta conditioners" that encouraged and facilitated nearly all the transformations we discuss.

First, growth in income and population in the three regions was crucial as a pull factor. Incomes rose, especially starting in the 1980s in Latin America and Asia outside the transition countries (China, Vietnam, and India) and 1990s in Africa and the Asian transition countries. Income growth, along with increasing opportunity cost of time as women worked outside the home in urban and rural areas, led to diet and shopping changes discussed below.

Second, policy liberalization and privatization occurred during the 1980s and 1990s (from the transitions in China and Vietnam, to the de-reservations in India, to structural adjustment programs in all three regions). This led to a minimization of governments' direct role in food systems. It also increased private sector MSMEs (micro, small, and medium enterprises) that stepped into the void left by parastatals, with MSME proliferation encouraged by the expanding urban markets. The policy changes also led to entry of large-scale domestic and foreign firms such as processors and supermarket and fast food chains, as well as large input firms. The massive ingress of foreign companies was abetted by liberalization of the once-ubiquitous foreign direct investment (FDI) regulations in the 1980s-2000s.

Third, governments instituted large infrastructure programs in Asia and Latin America in the 1980s and 1990s and in some African countries (e.g. Ethiopia, Minten et al., 2014b) in the early 2000's. This reduced transaction costs and formed the foundation for food supply chain development from rural areas to the burgeoning cities and towns.

3.2. Urbanization

In a traditional situation, the urban share of the population is low. Supply chains are mainly short and local, serving villages and nearby towns. But as urbanization occurs, supply chains must stretch out from the cities and grow longer as the city needs a larger and larger catchment area to feed itself. Some fresh produce and chickens and aquaculture may be produced in peri-urban areas (rural areas near towns), but less perishable products such as grains and roots/tubers are produced far from cities and brought in. Even horticulture products and chicken and milk are increasingly produced far from cities as processing - such as vegetable freezing and ultra-high temperature milk processing - are located far from cities where production costs are lower (Reardon, 2015).

Urbanization has indeed been occurring, and quickly, in all three of the regions. Latin America's urbanization was earliest, with the urban share roughly 40% in 1950, 55% in 1970, 65% by 1990, and 75% by 2010 (UN, 2014). Asia's urban share was only 20% in 1960, rising to 45% on average by 2011, and projected to 60% by 2025 (UN, 2011). Africa had a 40% urban population share by 2011, up from 24% in 1970 and projected to average 48% by 2030 (UN, 2011). The latter figure masks heterogeneity between countries; for instance, the urban share in Nigeria is 50% by 2015 (Bloch et al., 2015).

Moreover, the urban food market is in fact the majority food market on average in the three regions. This is because urban areas have higher incomes than rural areas (e.g., in ESA, Eastern and Southern Africa not including South Africa, urban income per capita is double that of rural; Tschirley et al., 2015), enough so to overwhelm the negative relation of income and overall food budget share noted by Engel's Law. In an Asian study of Bangladesh, Nepal, Indonesia, and Vietnam, Reardon et al. (2014b) show that while 38% of the population is urban, 53% of food consumption is urban. Even in the poorest region, ESA, 26% of the population is urban but cities consume 48% of food produced and sold (Dolislager et al., 2015).

To feed the cities, rural-urban supply chains have grown rapidly. Haggblade (2011) estimates this growth at 600-800% over three decades for Africa; Reardon and Timmer (2014) have it at roughly 1000% in Southeast Asia in the same period.

3.3. Diet change

3.3.1. Rise in the share of non-cereals

As incomes rise, "Bennett's Law" (Bennett, 1954) predicts a shift toward a higher proportion of non-staples in the diet. At a system level, this means that with development (which we roughly proxy by GDP per capita), one expects disproportionate growth of the supply chains of non-staples such as vegetables and fruit, meat and fish, dairy, and edible oils. Table 1 shows this with macro data from FAOSTAT for 1970 to 2013 with shares of tons of consumption-by-disappearance.

For Africa, the share of cereals inched down from 28% to 26%, roots/tubers stayed stable at around 20%, and non-staples rose from 50 to 55%. There was however some composition change in cereals consumption especially in West Africa toward rice, discussed below.

For Asia, the non-staples rise was more dramatic: cereals were 40% in 1970, inched down to 37% by 1990, and then dropped to only 24% by 2013. Timmer et al. (2010) use macro data on rice to show that in most Asian countries there has been a stagnant trend in rice consumption per capita, and even in some cases a gradual decline. Roots/tubers moved from 15% to only 3% over the period. By contrast, the striking winner in the diet was non-staples, soaring from 46% to 74%.

Latin American diet composition changed less during the period compared to the other two regions. This could be because a considerable part of Latin America's rapid development occurred in the 1960s-1970s, two decades earlier than most of Africa and Asia. Even by 1970 staples were only 30% of Latin American consumption, and that share had only dropped to 24% by 2013, and non-staples to 76%, like Asia.

Recent micro level survey data on household food expenditures corroborate the above macro figures.

For Asia, Reardon et al. (2014b) analyzed household survey data (LSMS) from 2010 and found that that for South Asia (Nepal and Bangladesh) and Southeast Asia (Indonesia and Vietnam), the share of cereals (mainly rice) in the food budget in value terms was about 26% for urban and 37% for rural households on average. Interestingly, the poorest tercile was only a little higher: 37% for urban and 47% for rural areas. Despite average income differences between the South Asian sample and the Southeast Asian sample, they found the shares of cereals in urban food budgets were similar (29% in South Asia and 23% in Southeast Asia). Meat and fish averaged 30% of the urban budget – itself equal to the grain share. Horticulture products averaged 15%. Together meat/fish and horticulture average 45%, more than grains all together. Another study showed similar results for India: Indiastat (2010) showed that the share of cereal in the urban diet (in value terms) dropped from 36% in 1972 to 23% in 2006, and in the rural diet, from 56% to 32%.

It may come as a surprise that African findings from LSMS analysis do not differ sharply from Asia's. For ESA urban and rural areas, Dolislager et al. (2015) found for Malawi, Tanzania, Uganda, and Zambia, that the share of grains (mainly maize) in urban food expenditure (in value terms) was 34%, and rural, 39%. The share of non-grains in urban food expenditure was 66%, and rural, 61%. As in Asia, they found the patterns for the poor stratum were not that different from the other strata.

For West Africa urban areas, Hollinger and Staatz (2015) analyzed data from urban food expenditure studies. Where the main staples are grains alone (Burkina Faso, Mali, and Senegal), they found that the share of grains in diets in value terms increased some over several decades:

from 33 to 38%, and 62% of expenditure is on non-grains. Animal products and fish are the foremost items in this set: in the 2000s they formed a quarter of the total. Fruits/vegetables average another 12% (compare that with 16% in Asia and the US). Meat plus horticulture products equal grain expenditure in the urban Sahel. They found that for the countries where grains plus roots/tubers are the staples (Cote d'Ivoire, Ghana, and Nigeria), the share of grains dropped from 27 to 23% and tubers/roots rose from 14 to 17% over the 1990s to the 2000s. The share of non-staples (neither grains nor roots/tubers) was about 60%. Again meat/fish was found to be 21% of expenditure, and horticulture products, 17%: together (38%) they have nearly the share of staples (grains and roots/tubers), 40%.

3.3.2. Shift of the diet toward (purchased) processed products

Research in the 1980s-1990s examined the incipience of processed food purchase in developing regions, driven by a new era of income increases and emerging urbanization and the rise of rural nonfarm employment. Processed food began to be sought as a time-saver for women whose opportunity cost of time increased as they entered the labor force outside the home in urban and rural areas, in Latin America (e.g., Amat y Leon and Curonisy, 1981, Peru); Asia (e.g., Senauer et al., 1986, Sri Lanka); and Africa (e.g., Bricas and Muchnik, 1985 for West Africa; Kennedy and Reardon, 1994 for East Africa).

There has been a revival of interest in processed foods in developing regions in the 2000s. This occurred with the confluence of (1) urbanization and increased incomes; (2) easing of import of processed foods; (3) FDI and domestic investment in processing following liberalization and privatization.

In Africa, processed foods have penetrated both rural and urban markets. In the ESA study of Tschirley et al. (2015), 56% of urban household, and 29% of rural household food expenditures (in value terms) went to processed foods. Some half to two-thirds of processed foods are low-processed, like packaged flour or noodles and bread. These are usually domestic products and time-savers for women. More processed packaged foods are usually a mix of domestic products and imports. For Nigeria, Liverpool-Tasie et al. (2017) found that while imported processed goods dominate in numbers of types of products, they are a minority in retail volume terms. Of course, a number of these products depend at least partially on imported raw materials such as flavorings, wheat, and milk powder.

In Asia, Pingali (2006) noted a "Westernization" of diets with packaged convenience foods emerging. Reardon et al. (2014b) (for the Asian countries noted op cit.) found that urban households dedicate 73% of food expenditures to processed foods, and rural households, 60%.

Surprisingly, the penetration of processed food did not differ much over income terciles in the African and Asian consumption analyses. Women in poorer and richer households are pressed for time working out of the home in rural nonfarm employment and urban jobs, and the quest for convenience in processed foods instead of laborious home processing characterizes both.

3.3.3. Shift of the Product Composition among grains

First, the surge in demand for livestock products has translated into the precipitous rise of demand for maize as a feed grain. A striking example is in China: maize (mainly for feed) had been half of the tonnage of rice in 1993 but by 2013 overtook rice (Zheng, 2013). In Bangladesh, aquaculture grew 25-fold in three decades (nearly all for the domestic market), spurring a massive rise in the feed industry and demand for maize and other feed grains (Hernández et al., 2017). Liverpool-Tasie et al. (2016) found in Nigeria that the maize-based feed industry grew 600% in the past decades as derived demand from the booming aquaculture and chicken sectors.

Second, the rise of demand for convenience foods by consumers has as a derived demand a rapid rise in wheat and rice. In Asian areas where rice traditionally reigned, wheat has made inroads in the form of noodles and bread (Senauer et al. 1986, for Sri Lanka; Pingali, 2006, for Asia overall). Timmer (2015) shows for Southeast Asia that wheat imports rose from 1 million tons in 1961 to 13 million by 2010, and wheat consumption from 2.8% to 11.5% that of rice.

In West Africa where millet and sorghum and tubers are the traditional staples, rice and wheat have rapidly increased with the drivers noted above (Reardon, 1993). While rice doubled in tons of domestic production in ECOWAS over 1987 to 2009, domestic rice output stayed at about 55-60% of self-sufficiency, and imports of cereals (mainly rice) soared from 1 billion to 5 billion dollars in those two decades (Hollinger and Staatz, 2015). There has been a recent surge in commercialization of prepared and packaged millet dishes in rural areas so coarse grains may be making a significant convenience riposte.

In East Africa, the rise of wheat consumption has also been driven by convenience food demand (Kennedy and Reardon, 1994). Wheat consumption in West Africa has also started to rise not just via the half century old luxury of bread for the middle class, but now as cheap fast noodles and bread and bean sandwiches for the poor. An example is the rapid spread of the Indonesian multinational Indofood's "indomie", a packaged (wheat) ramen noodle, produced by Indofood FDI in Nigeria (cooked often with egg, and thus a fillip to egg consumption) (Liverpool-Tasie et al., 2016b).

Third, in a number of countries there is a shift toward higher quality grains, such as finer rice in Bangladesh. In Ethiopia, there is a shift away from the cheap red teff to the more expensive and preferred white teff. This increasing shift in intra-cereal demand drives changes in the portfolio of farmers as well as changes in the milling sector (Minten et al., 2013, 2016).

4. Transformation of food systems – focus on structure

4.1. Stages of structural change

There has been a lot of variation in the timing of take-off and speed of transformation of food systems across products, regions, countries within regions, and zones within countries. In general the transformation is over three stages of structure and conduct change.

(a) The least advanced stage is the "traditional" system. This tends to be spatially short ("local") and fragmented in structure, using technologies with little capital and much labor, with no contracts or formal standards, and spot markets linking all segments.

(b) The next stage is the “transitional.” It is spatially long (as cities grow and their catchment area is larger and larger) but still fragmented. Chain actors use a mix of labor-intensive and capital-intensive technologies. There are emerging public standards of quality. But still spot market relations dominate.

(c) The most advanced stage is “modern.” It is usually spatially long. But it is consolidating in various segments (such as in retail, the rise of supermarkets). There is also some “dis-intermediation” such as supermarkets buying directly from processors, or urban wholesalers directly from farmers. Private standards are emerging, and some use of contracts. Capital intensification is common as the modern stage tends to coincide with higher wages in the economy. More quality and safety control are demanded by the food industry.

There have been waves of diffusion of food system transformation over space and products in the developing regions.

The spatial waves are as follows (Reardon and Timmer, 2012).

(a) The first wave included East Asia outside China (such as South Korea) and South America such as Brazil, with transformation taking off in the 1980s.

(b) The second wave was in Mexico and Central America and in parts of South America (such as Colombia, Chile), Southeast Asia outside “transition” countries, and South Africa (with the take-off starting in the 1990s).

(c) The third wave, taking off mainly in the 2000s, includes the “transition” countries, China, Vietnam, and India, and South American countries “catching up” such as Peru and Bolivia.

(e) The fourth wave, in the 2000s, includes parts of Africa especially in southern (Zambia) and eastern Africa (Kenya) and emerging in West Africa such as in Nigeria, Ghana, and Senegal.

The product waves are as follows. The grain value chains transform earliest, animal products next, and fresh fruits and vegetables last. (These waves are similar to the pattern of diffusion of change in Europe and US food systems earlier.)

4.2. **Dimensions of structural change**

4.2.1. Expansion

Food volumes grew a lot from 1970 to now with the steepest increase from 1990 to 2013 (the latest year in FAOSTAT). This pattern roughly tracks the path of “economic development” or average income growth. Table 1 shows “food supply quantities” from FAO food balance sheets for 1970, 1990, and 2013. These are measures of “domestic consumption by disappearance” per capita, calculated starting with aggregate production, adding imports, and deducting disposal of the output (exports, waste, storage for the next year, and use as seed). We then use their population data to derive aggregate consumption by disappearance per region. This is a rough measure as it is only in physical terms, not value or nutrition terms. A physical measure probably underestimates growth in value terms as non-staples and processed foods, which grew the fastest, have higher prices on average than grains or roots/tubers. But our goal here is not fine precision but orders of magnitude and key trends. Several points emerge.

First, in 43 years, the total “food system” in these three regions grew from 1.3 to 5 billion tons, 4-fold, faster than population grew (from 2.6 to 6.5 billion, 2.5 fold). Interestingly, the trends did not differ much over the three regions. Africa’s food volume expanded 1.8 times in the first two decades and then 2.1 times in the following 25 years, hence 3.8 times over 43 years. Asia’s total food supply rose 1.8 times in the first 20 years and then 2.1 times in the next 25 years, for overall growth of 3.8 times. Latin America’s rose 1.7 times in the first 20 years and then 1.7 times in the next 25 years, for overall growth of 2.8 times.

Mirroring demand changes, output per category grew overall, but with relative gains for non-staples over the four decades – in Africa, 340% in cereals volume, 400% in non-staples; in Asia, 220% in cereals, 590% in non-staples; in Latin America, 230% in cereals, and 300% in non-staples.

Second, imports as a share of food supply (net of exports) have risen, but are still minor. In Africa, tons of imports rose 11 times over the 43 years – from 7% to 15% to 21% of consumption by disappearance. In Asia, they rose 7 times and went from 9% to 13% to 18% of total consumed tons. In Latin America, they rose 7 times, and went from 3% to 6% to 9% of consumption. Import growth occurred steadily over the whole half century; it was in the policy debate in Africa in the 1980s/1990s (see Reardon, 1993) and has continued in the debate in the 2000s (African Development Bank, 2016).

Third, agricultural exports, while often important in policy debates, are small compared with the domestic food system. In Africa, these reached 7% of the level of domestic consumption; in Asia, 10%; in Latin America, 22%. It was especially in Latin America that exports rose in the well-known story of its agricultural export success in the globalization period.

4.2.2. Elongation

(a) Growth of rural to urban food supply chains

When the urban share was low, supply chains were short, with farmers feeding themselves and local villages and towns. As the urban share rose, and the cities grew, supply chains stretched further and further to fulfill the enormous needs of the cities. As domestic supply chains surge to feed cities, several points stand out.

First, seen from the countryside, most food goes to cities. As noted above, roughly 50-75% of domestic food supply now goes to cities; in the 1970s it was but 20-30% depending on the region. Even in the least urbanized and poorest region, ESA, 46% of cereal consumption (home-consumed by farmers and purchased by rural and urban households) is consumed in urban areas; 61% of purchases of cereal, 52% of fruit and vegetables, 58% of meat and fish, and 63% of edible oils are consumed in urban areas (Reardon et al., 2014d).

Second, the product categories output growth plus the rise in the share of urban consumption in total national consumption both noted above together yield the result that one can double or triple the product category volume growth rates to get a rough idea of how much the volume of rural-to-urban supply chains increased over 45 years. For instance, for Africa, this means that non-staple rural-urban supply chains increased about 800 to 1000% (depending on the sub region). That figure is about 1800% for non-staples in Asia. These enormous climbs represent a major investment by actors along the supply chain from farmers to urban retailers and wholesalers.

(b) Growth of Rural-to-rural and urban-to-rural supply chains

Even rural consumer markets are developing fast.

First, in Africa over three decades, rural population grew from 0.37 billion in 1970 to 1.05 billion in 2011 (UN, 2011); in Asia, from 2.1 billion in 1970 to 4.2 billion in 2011. The increase in the rural market in value terms is greater than population growth shows, for in many areas rural incomes have grown over several decades, albeit with regional variation. Even in the poorest regions, a rural middle class has emerged; Tschirley et al. (2015) demonstrate that 55% of the middle class in the ESA is in rural areas.

Second, rural purchases of food are now substantial. The traditional situation was one of farm households being either self-sufficient or buying a little of their food. While Mellor (1976) in India and Reardon et al. (1988) in Africa pointed out that many rural households, even farmers, were net buyers of grains, the share of total consumption from purchases was on average traditionally low. This of course differed by semi-arid versus more humid areas, such as in Senegal, where purchases of food were important for the drought prone areas and much less important in the relatively lush areas (Kelly et al., 1993).

But recent data show high shares of purchased food in rural diets in Africa and Asia. In ESA, Dolislager et al. (2015) show rural households bought 44% (in value terms) of food they consume; Liverpool-Tasie et al. (2016b) show 70% in Nigeria. Sibhatu and Qaim (2017) show that 42% of calories consumed of rural Ethiopian households are from purchased foods. In the Reardon et al. (2014b) Asian study, rural households purchase share averaged 73%. Third, recent evidence shows these purchases are mainly financed by rural nonfarm employment (RNFE) as well as by agricultural product sales. Very little is purchased on credit, whether from informal or formal sources (Adjognon et al., 2017, for Africa). RNFE is roughly 40% of rural household incomes in Africa and Asia, and a much higher share of total cash available, and far higher than migration income or credit flows (Haggblade et al., 2007).

(c) Challenges to farmers from longer supply chains

There are challenges for farmers of longer supply chains, with urban markets becoming the main markets faced by farmers.

First, in longer supply chains, small farmers face more competition. Urban traders seek a diverse set of zones to reduce seasonality and supply risk. They have the logistics and purchasing power to require that different regions compete for their procurement. This means that farmers from a given zone no longer have a "protected" (by transaction cost barriers) local market but are competing with farmers large and small from other zones for the urban market.

Local farmers also vie with imports for city markets. But local farmers and rural processing enterprises have even to vie with cheap packaged processed foods from urban areas coming into rural areas, often via the conduit of secondary city/rural town markets (Reardon et al., 2007b). An example is Indofoods' packaged noodles and drinks into rural towns in Indonesia and Nigeria (Liverpool-Tasie et al., 2017), or Maseca's ready-made tortillas or mix coming into rural towns in Mexico (Rello, 1996).

Second, as urban markets modernize with the rise of supermarkets (discussed below), the competition by a region for supplying to urban supermarket procurement centers heightens, and becomes more challenging yet with the imposition of private grades and standards. Reardon et al. (2007) and Berdegue et al. (2005) illustrate this for the cases of Mexico and Central America. Large processing firms and supermarkets based in towns also tend to prefer supply regions with low transaction costs, and eschew contracting with farmers in hinterland zones (Barrett et al., 2012).

Third, longer supply chains mean heightened vulnerability to shocks that beset long exposed chains – shocks of climate change (Reardon and Zilberman, 2017), energy cost spikes, disease outbreaks, food safety crises, and sociopolitical strife. A case in point is the vulnerability to all these represented by the south-north and north-south maize and egg supply chains in Nigeria (Liverpool-Tasie et al., 2016).

4.2.3. Change in "industrial organization" structure of the system

a) Increase in the "post-farmgate" segments

In a local traditional short supply chain, very little of the value added of the chain is due to off-farm components of the supply chain – the midstream (wholesalers, logistics agents, processors) and downstream (retailers). The farmer sells the grain or milk to neighbors and transports it herself. The consumer buys the raw product and processes it herself.

As the chain grows longer, the market volume grows large enough, and economies of specialization emerge in the midstream and downstream segments, the off-farm components' shares rise compared with traditional chains. Typically the farmer's share in the total value added of the supply chain drops as the counterpart to post-farmgate segments' development. Reardon (2015) reviewed evidence and produced a rough estimate for Asia and Africa food supply chains of about 40% of value added from farms, 40% from midstream (what he calls the "hidden middle" as this segment is usually ignored in both policy debates and research) and 20% from the downstream. This share varies over products and regions.

b) Emergence of a "Quiet Revolution" of small off-farm food system enterprises

As supply chains develop to cities, and gradually consumers purchase processed products, there is a proliferation of midstream MSMEs in wholesale and processing, as well as upstream in input supply. This is part of the "transitional stage" and is the dominant situation now in Africa and South Asia. Recent studies in South Asia, China, Vietnam, and Africa have termed this a "Quiet Revolution" wherein tens of thousands of MSMEs emerge (Minten et al., 2010; Reardon et al., 2012b, 2014c). Four examples intrigue.

First, there has been a rapid emergence of MSME potato cold storages in Bihar (Minten et al., 2014) and Western Uttar Pradesh near Delhi (Das Gupta et al., 2010). The storages diffused due to a confluence of trends – the rise of nearby cities, the improvement of road links and electricity grids, the introduction of a disease-resistant and long-shelf-life potato varieties by the NARS, and a flood of private investments by local small/medium entrepreneurs.

Second, there has been a proliferation of SME "outsourced agricultural services". Examples include SME providing mobile combine services for small rice farmers in China (Zhang et al., 2017) and Myanmar (Belton 2017). There has also been a diffusion of "sprayer trader" services in mango areas of Indonesia and the Philippines: teams of skilled laborers equipped with sprayers and vehicles and ladders go from farm to farm and prune, spray, harvest, sort, and market mangoes for small and medium farmers targeting demanding urban and export markets (dela Cruz et al., 2010; Qanti et al., 2017).

Third, Minten et al. (2016) show that the value chain of teff (the leading cereal in Ethiopia) has developed rapidly over the past decade. There has been a proliferation of MSME mills-cum-retailers, wholesale, and logistics firms spurred by Addis's development and road improvements. The development of the teff value chain is in turn correlated with increasing adoption of modern inputs by farmers, and shift from cheap red varieties to the more expensive, higher quality white teff varieties and uptake of improved varieties of the latter.

Fourth, in Senegal in the past decade, the millet supply chain has rapidly transformed with the emergence of processed and prepared millet products. Badiane (2016) shows that this transformation has featured the development by small female-headed enterprises of branded packaged millet and millet-cum-dairy products for the Dakar market.

c) *Concentration and dis-intermediation*

As markets expand with longer supply chains, and especially where there are economies of scale or economies of scope, such as in processing or retail procurement and storage, and large-scale firms are more efficient than small firms, segment concentration tends to occur. Some segments of a chain may concentrate while others stay fragmented for some time. For example, in the dairy sector in Zambia, some small farms sell to large processors who sell some of their output to supermarkets (Neven et al., 2016). In the Bangladesh rice sector, town-based larger wholesalers have competed out of the market many small rural brokers, but the wholesalers sell on to many small urban millers and small retailers (Minten et al., 2013).

Reardon (2015) conceives of the evolution of concentration as a "J curve" with three stages.

The first stage in many developing countries has been the establishment of government grain retail and wholesale parastatals to serve emerging urban markets, building economies of scale as a counter to the traditional fragmented supply chain, and to obviate what governments perceived as "exploitative traders." This is the leftmost part of the J of concentration over time.

The second stage occurs after market liberalization and the privatization of the parastatals. The vacuum thus left attracts investments at least initially by many MSMEs. This is the bottom of the J curve; it can be broad or narrow depending on how long the MSMEs can hold out against competition or acquisition by large private firms.

The third stage is the steep rightmost part of the J, and is the re-concentration that occurs after competition thins the ranks of MSMEs and large firms emerge to outcompete or buy the small firms. The emergence is usually spurred by FDI liberalization as seen in Latin America in the 1980s/1990s and domestic investment regulation relaxation (such as "de-reservation" in India in the late 1990s. The large firms arise at first in the midstream and downstream (processing, wholesale/logistics, retail, and fast-food) and later in upstream (seed, chemical, and machine agribusiness firms) (Reardon et al. 2003 for supermarkets; Reardon and Timmer, 2012 for processing and wholesale; Popkin and Reardon, 2017 for fast food). Supermarkets in Central America have shifted to buying directly from agribusiness firms for crops in which the latter are engaged (e.g., pineapples, bananas) (Berdegué et al., 2005).

Also, large scale firms in different segments facilitate each other's growth through "coevolution." To reduce transaction costs and make sure private standards are met, supermarket chains tend to source from large processors. An example of this is supermarket chains in China sourcing mainly from large rice mills (Reardon et al., 2014c). Large processors target product differentiation to the requests of supermarkets, such as for milk and juice products by Nestle in Brazil (Farina et al., 2005). Large logistic and wholesale multinationals as well as processors "follow" supermarket chains into new countries, in "follow sourcing", as with Baakavor following Tesco into China (Reardon et al., 2007b).

Furthermore, large firms have a tendency to try to "cut out the intermediaries" and sell or buy directly – "disintermediation." This is done mainly to cut costs, as well as control quality or assure traceability. For example, larger wholesalers based in towns and cities have in India gone well along the path of eliminating use of traditional village brokers in order to buy directly from rice and potato farmers (Reardon et al., 2012b).

Finally, supermarkets and processing companies also have a tendency for "re-intermediation" - to shift from procurement on the traditional fragmented spot market to use, as much as possible, specialized, dedicated wholesalers to procure and market (Reardon and Berdegué, 2002). They are charged with applying quality and safety standards of the chains or processor, selecting regular suppliers such as farmers or supplier villages or coops who can meet the standards, and collecting or marketing exclusively for the chain or processor. An example is large rice millers in China relying on specialized agents to wholesale their branded packaged rice (Reardon et al., 2012b), and supermarkets in Latin America and Africa and China using dedicated wholesalers to source produce according to the private quality standards of the chains (Reardon and Berdegué, 2002 for Latin America, Weatherspoon and Reardon, 2003 for Africa, and Hu et al., 2004 and Michelson et al., 2017 for China).

5. Transformation of Food systems: focus on conduct

5.1. Endogenous transfer, co-evolution, and innovators' strategic system design

Many basic industrial and agricultural innovations were generated in the past 200 years since the British industrial revolution (itself partly based on the earlier Chinese innovation of horizontal loom, Braudel, 1979), and the subsequent agriculture technology and food system revolutions in the US and Western Europe. In particular in the past 100 years food system technology innovations emerged (often the fruit of machine engineering and chemistry linked to the industrial revolution) in the US and Western Europe. These were two way drivers in the food system transformation in these two regions. These technology innovations were in agriculture (such as chemical fertilizer, hybrid maize, tractors, pesticides, genetic modification, and so on), in processing and wholesale and transport (motorized mills, trucks, refrigeration, freeze drying, and so on), and in market organization and communication (chain stores, self-service retail, supermarkets, private standards, ICT).

Many of the food system innovations from the US and Western Europe were then transferred and adapted in developing Asia, Africa, and Latin America in the past 50 years in the system transformation waves as demand side and policy conditions grew receptive and propitious for their transfer. The channels of transfer included: (1) massive waves of foreign direct investment (FDI) by agribusiness, processors, logistics and wholesale, and retailers; (2) investments by local entrepreneurs and public sector in innovations from the US or Western Europe they observed in FDI activities or on a business trip or university education, or read about on the internet.

The local private entrepreneurs and public sector in developing countries as well as innovating "Western" companies diffused those initial innovations, adapting and modifying them to local conditions. Just as in the "West" the initial innovations had developed as packages of inter-dependent innovations (such as the example of Tyson with genetic variation, contracting, private standards, piecing and cooling or freezing, long distance transport, and marketing in supermarkets), the transfer of one or more innovations, in technology or organization, brought with it the cluster of other related innovations both in technology and products, and in market organization.

Of course, not all of the basic innovations during the past 50 years were transferred initially from the "West." There was a wave of technology innovations, some basic and new and others applications and adaptations of prior innovations generated in international research institutes based in developing countries (such as IRRI's developed of modern varieties of rice in the 1960s in the Philippines, David and Otsuka, 1994) and in the large NARS in the developing regions. Examples include the foundational work in rice varieties in Taiwan and Japan in the 1920s-1930s and China and India in the 1950s-1970s (Barker and Herdt with Rose, 1985) and Argentina and Brazil (for no-till cropping technology innovation in the 1960s-1970s, see Trigo et al., 2009). In other NARS, there was significant adaptation work done that amounted to innovation in application, such as the Zaria maize work cited below.

Technology and product innovations are not "neutral" in their impact on the structure and conduct of food systems. The impact itself is often endogenous to the deliberate system designs of the innovator, as argued by Zilberman et al. (2017). They examine the proactive links between innovators' innovations and their "implementation," to generate and protect an initial advantage and profit arising from the innovation's superiority (in cost or quality or safety) to the technology or product it supplants. They depict as endogenous the structure and the conduct of the supply chain based on that innovation.

In that sense then, the food system changes we observe, especially in the modern phase, are emanations of the strategies of innovating companies. These strategies are sets of technologies and institutions and organizations chosen to implement the innovations. But they also "induce" innovation in other companies to "co-evolve" and help (symbiotically) the initial innovators implement the innovation. An example of this is given below of co-evolution of Nestle and Tetrapak investments in the Brazilian dairy industry.

Understanding both the role of public research and private innovators, and the linkages between technological, organizational, and institutional innovations in developing food systems, is central to our analysis. Below we explore in more detail these innovations.

5.2. Organizational and institutional change

First, organizational and institutional change occurs at different rates over products. Thus, in Mexico, for grains and meat one can find fully coordinated supply chains from farmers to supermarkets, with (1) branding and packaging; (2) direct purchase from suppliers or special agents, (3) distribution centers, (4) public and private standards, and (5) some contracts. But for fresh produce, one finds supermarkets relying on a mix of: (1) spot market relations in wholesale markets, (2) off-market specialized wholesalers such as Pedraza, and (3) direct contracts with large agribusinesses (Reardon et al., 2007).

Second, product quality and safety standards are an important coordinating "institution" in transforming food systems, emerging in three stages.

(a) In the 1970s/1980s in developing countries there was a gradual emergence of public standards of quality to allow for long-distance grain trade with low transaction costs and risk, and phytosanitary public standards to allow for animal and horticulture product trade.

(b) With product differentiation and the rise of trade in perishables, private standards for quality and safety began to emerge in the 1990s and 2000s especially manifest in export and processing. These were formulated by supermarket chains, large processors, and fast food chains to reduce losses in processing, increase shelf life, control quality and consistency, and assure safety (Reardon et al., 2001; Henson and Reardon, 2005; Swinnen, 2007). Examples include Nestlé's quality certification for grated coconut in Brazil (Farina et al., 2000) and potato variety specification for French fry production by McCain's for McDonald's in Argentina (Ghezan et al., 2002).

(c) Gradually governments have instituted public food safety regulations for retail and food service (for example, in China, Jia and Jukes, 2013).

Third, finance arrangements evolved as coordination mechanisms, in three stages.

(a) In traditional systems, traders "tie credit," advancing money or inputs to the farmer at the start of the season and expecting the harvest from that farmer at a prearranged price and with an implicit interest rate (Bardhan, 1980).

(b) In transitional systems, there is competition among traders and risks of side selling, and farm households have off-farm cash sources. Tied credit disappears or is rare (e.g., Adjognon et al. 2017 for Africa). These show that formal and even informal finance are rare for farmers for agricultural investments; most cash is supplied from retained earnings form off farm jobs and farm product sales.

(c) In modern supply chains, in the cases where food industry firms must rely on small farmers to complete their supply, and small farmers face "idiosyncratic market failures" for credit and inputs, food industry sometimes use "resource provision contracts" (Austin, 1981) (for Latin America, Key and Runsten, 1999, for Madagascar, Minten et al., 2009).

5.3. Technological change along the chain

5.3.1. Farm technologies

Breeding research and variety change have been fundamental forces in fueling the "throughput" of feedstock in the transforming food system. R&D supply chains for new seeds and other inputs depend critically on a combination of the development of private seed markets as well as private and public sector breeding of improved seeds.

There are two ways we can link product demand change (diet change) over a product cycle (niche to commodity to differentiated products) and food system transformation, to breeding research.

The first path has received the most attention: grain breeding for drought or flooding and disease resistance and adaptation to small farmer conditions. The best known example is the Green Revolution and the system of NARS and IARCs that emerged to form R&D supply chains of new seeds (Lipton with Longhurst, 1989; Hayami and Ruttan, 1971, Binswanger, 1978). Another example is the shift from local varieties to breed for broad agroecological adaptation, such as the breeding of maize to fit drier areas an institute in Zaria in Northern Nigeria in the 1980s (Byerlee and Eicher, 1997).

The second path links product cycle, breeding, and "commoditization." This path has received little attention in the literature. One variant has been a focus on breeding for traits of quality and ability to store and process. A good example is the shift from traditional flint to innovated/bred dent maize in output composition induced by the take-off of industrial maize milling in the mid-

1800s in the US. Research to breed for quality and processing has recently emerged in developing countries as urban demand rose. An example is teff variety breeding for quality for the urban Ethiopian market (Minten et al., 2016) and rice quality in Bangladesh (Minten et al., 2013).

5.3.2. Non-seed inputs to support farming intensification

Supply chain development, urbanization, and industrialization of external input supply tend to be correlated. This drives down the cost of capital inputs (irrigation equipment, seeds, fertilizer, insecticides, herbicides, tractors and combines and sprayers), inducing their diffusion. Both the private sector, IARCs, and NARS have been engaged in R&D over the past century that have influenced the quality and cost (and existence) of these inputs. Four examples of private sector R&D cum extension supply chains of these innovations are of interest.

First, as labor costs rose in the US and the UK in the 1940s, herbicides were created by private companies and government and were used to substitute for hand weeding. This innovation diffused in the US over the 1940s to the 1990s (Swinton and van Deynze, 2017). Due to increases of labor costs in developing regions, a parallel adoption of herbicides has occurred in waves similar to the system transformation waves from the 1970s to the 2010s (Haggblade et al., 2017).

Second, as demand for machine use rose in the US in the 1800s as farms extensified and labor constraints appeared, the combine was invented by private persons in the US and Scotland. It diffused over the century, shifting from horse to steam to gas engine powered, with a string of innovations by companies such as John Deere. It was then adapted for small farms in the 1970s in Japan by Kubota, and from there diffused widely over developing Asia and into Africa in the subsequent decades.

Third, as demand for water in horticulture rose in Germany, Australia, Israel, and California from the 1860s to the 1960s, there were a series of innovations from clay to plastic tubing that came to be termed drip irrigation. Again, as with the innovations above, starting in the 1970s it was adapted and diffused to developing countries, with innovations by companies like Netafim of Israel and then Jain Irrigation of India.

Fourth, Notore Chemicals in Nigeria are a major supplier of agro inputs. They have developed a system for training and input distribution which uses local rural people to be their sales agents and credit and extension officers (Liverpool-Tasie et al., 2015).

5.3.3. Post-farmgate technology change

As with farm technologies, a gradual increase in wage rates combined with a decrease in physical capital prices (from local industrialization and imports) induced midstream and downstream capital intensification and productive capital upgrading. Demand side factors such as demand for new products, new quality and safety attributes, and greater and more storable volumes also induced technology change.

R&D supply chains to create and deliver new off-farm technologies noted below developed along with investments in the off-farm segments as "induced technological innovation." These sometimes started as basic science innovations in public research institutions with subsequent adaptation and further innovation by private companies. Many were the inventions of individual inventors, or of R&D units of companies. Some were all three of these, such as the cluster of inventions and improvements around freezers or tractors. As in farm technologies, much of the initial innovation occurred earlier, in currently developed countries historically, and then was transferred and adapted to developing countries. We provide several prominent illustrations.

(a) Logistics innovations

These have been fundamental to the elongation and de-seasonalization of the food system. Minten et al. (2016), for Ethiopia, show a rapid shift from transport of teff by foot (head loads) to animal transport (donkey/horses, carts), to motorized transport, and then from small trucks of 4-5 tons to truck-trailers of 20 tons – a thousand years of transport change in a decade. Systems that had been relatively local switched to long distance commerce as large trucks and train lines combined to move potatoes from Northern to Southern India, abetted by potato varieties with tougher skins to transport further and store longer (das Gupta et al., 2010). A surprising case occurred in Myanmar: in 2011, bus transport was privatized and liberalized; bus lines proliferated and competed. One way they competed was by adding an iced cold shelf in the buses for fish to be transported from aquaculture areas in the south to Mandalay in the north. This gave rise to nearly 200,000 tons of fish moved by small merchants via many buses (Belton et al., 2017). Zhang and Hu (2014) note the large role of infrastructure investments in improving logistics in the potato value chain from hinterland Gansu to the coastal cities.

(b) Processing scale and clustering innovation

For example, as animal product value chains have transformed, poultry, fish, milk cow, and hog rearing has shifted its center of gravity from scattered small farms to peri-urban agglomeration to clustered sites with small and medium commercial farms further from cities near cheap input bases (for aquaculture in Bangladesh, see Hernandez et al., 2017; dairy in Brazil, Farina et al. (2005); hogs and chickens in Thailand, see Poapongsakorn, 2012; for hogs in China, see Schneider (2011). There has been a concomitant rise of large processing firms for pigs and chickens, with location of large farms and large processing firms near the cities of China and Thailand, in a major shift away from scattered countryside processing operations in the 1990s and before.

(c) Freezing and Packaging innovations

These are important to elongation of supply chains from near cities to near areas with low cost natural resources. For example, with rapid development of the frozen fish industry, fish is increasingly shipped longer distances within countries. An example is frozen fish from aquaculture areas in the South of China to Beijing, mainly developed in the 2010s as an outgrowth of an initial export operation base (Bai et al., 2017). Another case is the rise of frozen potatoes shipped long distance in Argentina to the burgeoning fast food chains (Ghezan et al., 2002), and frozen green vegetables and sweet corn in Chile (Milicivec et al., 1998).

A similar change took place in dairy in Brazil (Farina et al., 2005). There was a combination of four internationally-transferred technology and organizational innovations that led to a massive increase in milk consumption, a rise in average dairy farm size and the exit of many small farms, and a spatial shift from peri-urban production to dairy production in cheap grain areas. The innovations include: (1) large scale dairy processing, brought by Nestlé and Parmalat who intensively invested in Brazil in the late 1980s after liberalization of FDI; (2) supermarket chains spread in the late 1980s and early 1990s with liberalization of retail FDI; the chains sought to source from large dairy companies to cut transaction costs; (3) the introduction by the large companies of UHT (ultra-high temperature) treatment of milk (invented in Denmark in 1910) which allowed milk to be stored at ambient temperatures if in vacuum packed containers, and thus the spread of milk retail even to areas yet without home refrigerators; (4) the layered vacuum-packed container technology invented in 1952 by Tetra Pak of Sweden, and brought to Brazil in the 1980s to facilitate mass processing of UHT milk. Farina et al. (2005) show that UHT milk went from 10% to 90% of milk consumed in Brazil just in the decade of the 1990s.

(d) Extrusion for feed and noodles

Food technology breakthroughs have been part of revolutions in food systems for a long time, from the invention of beer brewing in China and Egypt six millennia ago, and tofu and miso processing two millennia ago in China. With the recent rapid transformation of the food system, a dense cascade of such innovations has occurred this time packed in short time. These innovations reduced the cost, increased the shelf life, and vastly increased the hedonic attributes range, of processed products. For example, in baking there were a series of advances in extrusion, frozen dough production, emulsifiers and enzymes, microwaves, ovens, and automation over the 20th century (Kamel and Stauffer, 1993). These innovations mainly started in Europe and the US, and then were transferred to developing regions. The same occurred with extrusion used for pelleted feeds and noodles. This led to rapid diffusion of pelleted, floating feed for example in Bangladesh aquaculture (Hernandez et al., 2017), and diffusion of Japanese ramen noodles manufactured by Indofoods in Nigeria (Liverpool-Tasie et al., 2017).

(e) Traceability, inventory, and safety monitoring technologies

Demand for time saving in shopping induced transfer of retail "technologies" and organization, like supermarkets and chain stores. An example is the adoption of bar codes and electric scanners for inventory control. Food safety concerns among urban consumers of perishables and rural and urban consumers of maize and peanut products induced food safety cum waste control measures like pasteurization of milk, addition of aflatoxin binders in stored maize by traders and millers, and humidity measuring devices and grain driers by traders and warehouse owners.

5.3.4. Emerging "Disruptive Technologies" in the Food System

In the past century there has been an intense stream of major technological innovations in agriculture and rest of the food system. At the time of their emergence, many of the technologies we discussed above were "disruptive" in the sense that they quickly and fundamentally changed the spatial or industrial organization structure of the system, its overall volume, its seasonality, and so on. Recent times have also brought a new generation of technologies that promise to, and have started to create sweeping changes in the overall global economy as well as food systems. We note three examples.

The first is the emergence of gene-editing, CRISPR (Ledford, 2015). This promises to reduce the cost and time and increase the breadth of applications of genetic modification. That may change the amplitude and frequency of changes in the system, such as rapid iteration of changes in disease and drought resistance, improving quality, and increasing shelf life of products.

The second is the rapid development of robots in the food system (Reardon et al., 2017). The general path of diffusion has been from upstream to downstream, and from developed to developing countries. The innovation has moved from incorporation of computer elements into existing machines (such as precision farming tractors and electric-eye conveyor belts for sorting fruit) to stand-alone non-autonomous machines (such as directed farm surveillance drones, restaurant food preparation robots such as at Zume Pizza in San Francisco) to stand-alone autonomous machines emerging (pre-programmed or real time self-directing such as Bayer's pilot "spider robots" that walk fields and monitor and perform activities such as spot application of herbicides, or warehouse box packers and stackers). These technologies are being applied both where labor is becoming more expensive but also in situations of cheap labor but other factors determining their use (such as the recent emergence of cashier-less supermarkets in India; Indiaretailing Bureau, 2017). The rapid rise of robots will have a series of easily foreseen consequences for the food system (such as a reduction in unskilled labor in all segments) and unforeseen and complex changes wrought on the structure and conduct.

Third, the application of emerging big data tools for food systems research may also speed up the way we organize, convene, and inspire new agricultural research opportunities in the future (http://bigdata.cgiar.org)

6. Food system transformation's impacts

The immense changes wrought by the rapid and recent food system transformation have had a series of impacts. Here we indicate emerging evidence and points of debate on these impacts. However, a thread that runs through all the impacts is that the results have been mixed, with transformation being a two edged sword bringing benefits and challenges.

6.1. Impacts on the entire food supply chain: debunking the "waste myth"

System transformation has increased the volumes and length of supply chains, and de-seasonalized supply. One thus moves away from "niche" local markets to nationally integrated and often more efficient markets. This leads to better price integration and smaller marketing costs (as shown in cereal market analysis in Ethiopia; Minten et al., 2014b).

But the elongation of supply chains as well as the increase of perishables has raised concerns internationally, since the 1970s, that waste and loss in developing country food supply chains are substantial; for example, FAO (2011) hypothesizes, repeating a position taken for decades, that there is as much as 20%-30% waste and losses for cereals and pulses and meat and milk and fish, 40% for roots and tubers, and 50% for fruits and vegetables.

However, the hypothesis of high shares of waste is quite doubtful as revealed by empirical field studies. Bellemare et al. (2017), Affognon et al. (2015), and Sheahan and Barrett (2017) argue that measures of food waste are conceptually flawed and have led to an over-estimate of waste in food systems. Most systematic survey-based studies of actual actors in the supply chains tend to have much lower figures than the FAO hypotheses. Several of many possible examples follow:

a) Lipton (1982) in India had direct measurement-based findings of low loss rates, and at that time questioned the then extant FAO estimates of 30-50% loss in grains.

b) Greeley (1986, 1987) had similar findings of low waste/loss in rice in Bangladesh and shows that high waste/loss assertions/estimates from the 1970s that had become common wisdom were actually based on flawed data or no data.

c) A unique "stacked survey" based loss/waste measurement approach (Minten et al. 2016b and Reardon et al., 2012) that included details on waste in each segment of the value chains of potatoes and rice in China, India, and Bangladesh. They found only about 5% loss/waste over the whole supply chain for potato (excluding consumer level waste) and about 1% for rice.

d) A similar stacked survey estimate for post-harvest losses in the teff value chain in Ethiopia were found to be 2.2-3.3% of the teff harvest (Minten et al., 2016c).

e) Kaminski and Christaensen (2014) used national level representative surveys of farm households for post-harvest losses in Malawi, Uganda, and Tanzania, and found a range of 1.4% to 5.9%, much lower than the post-harvest loss estimate of 8% for grains by FAO (2011). They found that loss was concentrated among 20% of farms in hotter and humid areas, with less market access.

f) Reyes et al. (2016), in a survey of 575 wholesalers and retailers in Nicaragua and Honduras, found post-harvest losses among them to total 8% for beans and 21% for tomatoes.

6.2. Impacts on nutrition

There is mounting evidence that transformation of food systems has lowered the cost of food and reduced sharp seasonality in its supply. Some of the evidence is from the "quiet revolution" where the diffusion of SMEs in supply chains accomplished this; we return here to the example of potato cold storage proliferation in India (das Gupta et al., 2010; Minten et al., 2014), and processed teff for poor consumers in urban Ethiopia (Minten et al., 2016). Other evidence shows this for the "modern revolution" such as in dairy in Brazil and Argentina (Farina et al., 2005), grains and vegetables in Delhi supermarkets versus traditional markets (Minten et al., 2010, and for an overall review, Minten and Reardon, 2008.).

Moreover, processed foods and other time saving devices have positive consequences of liberation of women's time for education, labor market participation, and child care (for Nigeria, see Liverpool-Tasie et al., 2016b).

Yet there are a series of well-documented concerns of the rise of fast food and ultra-processed foods leading to obesity and health problems such as diabetes (Popkin, 2014, for Asia and Popkin and Reardon, 2017, for Latin America).

6.3. Impacts on inclusion or exclusion of small farmers

There are several recent reviews of the impacts of food system transformation on small farmers and the evidence tends to be mixed (Reardon et al., 2009).

On the one hand, longer supply chains link rural areas to growing urban markets; diversifying food systems open opportunities to farmers to grow high value crops, meat, fish, and dairy. Some farmers enter resource provision contracts as discussed in Gow and Swinnen (1998); and others enter contracts offering price stabilization compared with traditional spot markets (Michelson et al., 2015).

On the other hand, the available evidence shows that it tends to be the upper tier or half of small farmers who can access the modern channels, the urban markets, and the non-grain markets, as they require placement near enough to roads, water access, and specialized skills and equipment. Eventually as the chains modernize and increasingly demand quality and safety, those farmers reached must make basic investments in those attributes and that narrows the winners. The evidence shows that small farmers can still be included, but tend to not be the hinterland or asset-poor farmers (Reardon et al., 2009).

6.4. Impacts on off-farm employment in rural areas

Both from the high-value diversification products being produced, and the large amount of activity post-farm gate occasioned by longer and more developed supply chains, there is a great deal of rural nonfarm employment linked to food supply chains generated by the transformation. There is growing evidence that women and youth are especially benefitted as these are low entry barrier jobs in transport, commerce, food preparation, and small scale processing (for Africa, see Tschirley et al., 2016).

As the food system modernizes there is, however, a challenge presented by cheaper urban processed foods penetrating rural areas and displacing traditional small enterprises (Reardon et al., 2007b), as well as dis-intermediation and large scale distribution firms displacing petty traders.

6.5. Vulnerability of longer food supply chains

Developing countries face the trade-off between efficiency and reduction of supply risk to cities via diversification of supply sources as food systems develop, and increasing risks that can accost long exposed supply chains such as from shocks from climate, environmental degradation, food safety, disease, sociopolitical unrest, and energy costs. Reardon and Zilberman (2017) argue that the strategies and investments that supply chain actors are and will take to mitigate or cope with those shocks will probably hasten the transformation, and in particular the concentration of the system. This is a particular challenge to governments to help the hinterlands and asset-poor.

7. Implications for the agricultural research community

There are several key implications of our analysis of the pathways of transformation of food systems for agricultural research strategies of the IARCs and NARS.

First, IARCs and NARS have a strong vested interest in researching, understanding, and taking into account the whole food system and its transformation, adapting their strategies, plans, and choice and design of innovations in technologies and products. This also includes understanding the changing government policies, as well as private sector institutions (such as private standards) and procurement system and marketing organization. This is important for several reasons. Opportunities and bottlenecks along all three sets of supply chains determine the potential success of IARC/NARS innovations in the farming segment. Emerging requirements of the changing food system – in terms of product types, quality and safety attributes, shelf life, cost, consistency, seasonality, volumes, and so on - should influence priorities for IARC/NARS innovations. This will help to determine whether innovations in farm technology and products lead to profitable marketed output by farmers, and thus ultimately, whether farmers will have the incentive to adopt new technologies. It is important for the research community to take into account that farmers themselves have deeply changed from just a few decades ago, far more involved in markets, commercialization, having intensified and diversified farming, and IARC/NARS strategies need to keep up with that change.

Second, IARCs and NARS innovations need a supply chain to implement the innovations they generate. The upstream innovation is the beginning, not the end, of the process. The private sector in the food system is the centerpiece of the supply chain that delivers that upstream innovation. It is essential that IARCs/NARS understand the strategies, behavior, and needs of these two powerful sets of private sector actors, as the latter are essentially and in practical terms in charge of the direction of the entire food system. 25 years ago the private sector in the food system could be just a sidelight and "specialized" issue at the margin of food system thinking and agricultural research strategies: by becoming the dominant, central player in the food system, the private sector cannot be relegated to just a potentially interesting group to consult and observe at the edges. It is now at the center. It is now the group that decides what systems and structures will market and implement the innovations of technologies and products generated by the IARC/NARS. The ability of the latter to understand, adapt to, and selectively partner with the private sector will in the next decades be an important part of determining the performance of IARC/NARS innovations. In addition, important innovations are needed in transforming research institutions, investing in institutional change that would then be a key driver for technical change. There is a risk that rapidly transforming food systems would leave behind international and/or national public research organizations that are not transforming themselves to the new realities.

Third, the public research community needs to understand the importance of research on the off-farm components of the food system. Research on and productivity of processing, packaging, logistics, and commerce technologies have equal weight in the performance of the food system relative to the farm sector, and investment in research and development (R&D) value chains for these technologies and value chains for the inputs to these segments need a much higher profile in the context of the transformed food system where post farm segments occupy 40-70% of value added. An argument for post-farm-gate research (so that it allows reduction of marketing margins in value chains to improve efficiency in the value chain) is usually a win-win for consumers as well as for producers. Moreover, returns on research (RoR) at the farm level clearly depend on concomitant innovations in the supply chain to supply inputs for or market the output of the innovation.

Finally, we have signaled the importance of universities and CGIAR and NARS and companies forming public-private partnerships to generate and embody an "educational-industrial complex" (Zilberman et al. 2012) where innovation starts at university research centers and ideas are then further developed either by applied research centers (like the CGIAR and NARS) or by private sector entities (startups, small companies, and major corporations). The involvement of university researchers in further development of the innovations has been identified as the contributor to success as well as effective marketing extension and outreach that is an important component of the overall supply chain that renders innovation into marketable products that generate income and employment for actors all along the food system.

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Table 1: Domestic food supply quantities (approximation of consumption by disappearance) & composition in millions of tons & population			
	1970	1990	2013
Africa food supply quantity (ton/capita/yr)	0.46	0.49	0.59
population (in millions)	339m	581m	995m
Africa total domestic food supply	156	285	587
Imports into Africa, tons (share of total domestic food supply)	11 (7%)	42 (15%)	123 (21%)
Exports from Africa, tons (share of total domestic supply)	17 (11%)	15 (5%)	39 (7%)
Staples: cereals (% total)	44 (28%)	84 (29%)	150 (26%)
Staples: roots & tubers (not potato) (% total)	34 (21%)	53 (19%)	116 (20%)
Non-staples (% in total)	79 (50%)	148 (52%)	320 (55%)
Asia food supply quantity (ton/capita/yr)	0.37	0.43	0.65
population	2.07b	3.13b	4.26b
Asia total domestic food supply	758	1,357	2,786
Imports into Asia, tons (share of total domestic food supply)	70 (9%)	176 (13%)	507 (18%)
Exports from Asia, tons (share of total domestic supply)	30 (4%)	90 (7%)	284 (10%)
Staples: cereals (% total)	300 (40%)	507 (37%)	663 (24%)
Staples: roots & tubers (not potato) (% total)	111 (15%)	87 (6%)	70 (3%)
Non-staples (% in total)	348 (46%)	762 (56%)	2,053 (74%)
LAC food supply quantity (ton/capita/yr)	1.57	1.67	2.02
Population	284m	441m	611m
LAC total domestic food supply	447	737	1,232
Imports into LAC, tons (share of domestic supply net of exports)	15 (3%)	42 (6%)	107 (9%)
Exports from LAC, tons (share of domestic supply)	48 (11%)	84 (11%)	271 (22%)
Staples: cereals (% total)	99 (22%)	162 (22%)	230 (19%)
Staples: roots & tubers (not potato) (% total)	38 (8%)	38 (5%)	65 (5%)
Non-staples (% in total)	310 (69%)	536 (73%)	937 (76%)