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Linkages among Population, Food Production, and the Environment at Multiple Scales

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Abstract

Human population, its number and distribution on our planet, has a seemingly direct linkage to how much food we consume and how we practice agriculture. How this population-food-environment interface manifests across the globe is complex, non-linear, and both local- and scale-dependent. This essay is an overview of the population-food-environment nexus, providing recent history and statistics on these processes at several crude scales. We include a discussion of theory, review different drivers of the population-food-environment processes, provide a global overview of population and agricultural statistics from 1970 to 2010, and discuss trends and implications for Latin America, as well as some specific multi-scale case studies. We conclude with a review of potential future trends and proposed solutions.

Keywords*:* Population; Food; Environment; Agriculture; Latin America; Boserup; Malthus;

Delivering sufficient caloric volume and a sufficiently balanced diet to the world's nearly eight billion humans is among the most pressing human and environmental concerns of our era. How can we fairly, efficiently, and sustainably provide adequate nutrition to more people consuming more resources per capita? As population, health, and land transitions progress at unprecedented speed through divergent trajectories, understanding these pathways is critical to informing how we will reconcile growing demands for food, fuel, and livestock feed, all competing for space on dwindling available farmland. Dominant historical theories related to population and agricultural production posit a direct relationship between the two when in reality, the population-agriculture-environment nexus is complex, scale-dependent, and non-linear. In this paper, we provide an overview of population processes and their relationship to land and food at a crude scale. Our intent is to provide a rough understanding of both the recent history and current situation of these linked processes. To do so, we open by discussing common conceptual frameworks through which to approach this issue, then examine statistical trends from recent decades in population change and distribution as well as patterns of agricultural expansion and intensification at the global region scale and the national scale for Latin America, a region that in recent decades has undergone transitions reflective of both developed and developing regions. We present and discuss select examples of how space and place context are critical in understanding the population-food-environment nexus. We conclude with some predictions about the future of this complicated relationship.

Population-Food-Environment Theory – Boserup, Malthus, and Multiphasic

The most widely known theories concerning the relationship between population and agriculture have not changed notably over last two centuries. Thomas Malthus, still the go-to reference on the impact of population on the environment today, posited at the end of the 18th century that increasing population would inevitably lead to famine and population loss. He argued that unchecked population grows "geometrically," while food production can only increase arithmetically, (*i.e.*, by adding to the amount of land that is used to grow food). He also presciently noted that the most productive land tends to be exploited first, and, therefore, as agricultural land expands, average production falls (Bilsborrow & Carr, 2001; Malthus, 1803). Malthusian and neo-Malthusian thinking call for population growth to be checked. Malthusian theories also predict that population increase leads to an increase in land devoted to agriculture, referred to here as agricultural *extensification*.

The mass famine predicted by Malthus never happened, at least not on a continental scale. Technological advances in agriculture, a 20th century grouping of which is often termed the "green revolution," allowed for exponential increase in agricultural productivity (*i.e.*, the yield that can be achieved on a per area basis, such as per hectare). At the tail end of this remarkable change in agricultural productivity, Ester Boserup, an economist, advanced the theory that population pressure drives agricultural innovation. Increased population leads to more intensive cultivation of land, or *intensification*.[1]

In practice, increasing population can lead to a number of human responses, including extensification and intensification, as well as changes in fertility-related practices such as postponing marriage, and migration to less pressured areas (Bilsborrow & Carr, 2001; Davis, 1963). Bilsborrow (1987) synthesized these various, or "multiphasic," responses to increased population pressure and categorized their respective natures as being economic (extensification and intensification), demographic (fertility), and economic-demographic (migration) (Bilsborrow & Carr, 2001). Bilsborrow further posits that people respond to population pressure first through their potential economic responses, usually by extensifying and then intensifying. This is followed by temporary or seasonal outmigration, then full migration, followed by active fertility reduction as the final option. Malthus and Boserup's ideas have become so entrenched as to be considered near ontologies or philosophies as much as theories, with more complex contemporary theories often characterized as 'neo-Malthusian' or 'neo-Boserupian.' Although the Malthus, Boserup, and multiphasic population-environment theories specifically arose from population-agricultural relationships, many later theories include a broader range of environmental impacts, such as greenhouse gas emissions. However, as agriculture has the greatest impact of all human activities on the environment, all population-environment theories encompass and highlight the role of agriculture.

Population-Agriculture-Environment Theory – Moving Forward

To recap many years of theoretical development in a limited space, early theories posited or assumed a direct and/or linear relationship between population, agriculture, and the environment. Current research has drawn some broad conclusions regarding the more complex nature of the relationship between population, agriculture, and the environment. It is now understood that the scale of analysis for population-agriculture-environment is critical. With some frequency, scale can dramatically change the nature and direction of key population-environment interactions (Carr, Suter, & Barbieri, 2005; Hazell & Wood, 2008). It is also now accepted that the population-agriculture-environment nexus is usually complex and non-linear (Hummel et al., 2014). These two conclusions are intimately related. At a village scale, for example, population decline could be associated with reforestation as farms are abandoned, or associated with deforestation as farms are consolidated by livestock ranchers or larger farms. Meanwhile, at the national level, population decline is often associated with reforestation and agricultural intensification (and/or the exportation of extensification) (Carr, 2002; Meyfroidt et al., 2010). Factors such as export agriculture, globalization, diet choices, and transnational agro-businesses complicate this relationship. Despite all this, increased population nevertheless means increased food consumption and environmental degradation to some degree, and the same holds true at most scales of analysis (Schneider et al., 2011).

Population-Food-Environment Interactions

Total Population

At first glance, the most important driver in the population-food-environment nexus would seem to be total population. Unassailably, more population means more demand for resources. However, the type or location of population has important consequences on demand for food and other agricultural resources, and therefore on ultimate environmental impact. When conceptualizing the population-food-environment nexus, it is critical to consider the effects of a population on the environment, including both the direct effects (*e.g.*, clearing land and planting crops) and indirect effects (*e.g.*, consuming high-resource products such as red meat). Usually, direct actions have local ramifications, while indirect actions have distant ramifications. The ultimate impact may vary widely, however (DeFries et al., 2010); for instance, a momentary choice to redecorate a house in teak may have a greater effect on Indonesian rainforests—albeit an indirect one, distant in origin—than years of the direct, local actions of an Indonesian subsistence farmer.

Urban/Developed vs. Rural/Developing Population

Residents of the developed world are responsible for far more per capita consumption of food and agricultural resources, as they eat more total food and, very importantly, more red meat, animal products, and processed food, all of which are more resource-intensive to produce. Tilman et al. (2011) compared groups of the richest and poorest nations and found that per capita consumption of calories was more than 250% higher in the richer nations, and protein consumption was 430% higher. The direction of this relationship is the same when one compares urban residents with rural residents in the developing world. Urban residents consume more in the absolute sense as well as more resource-intensive food products. The impacts of developed and urban populations are more likely to be indirect and distant, whereas the impacts of developing/rural populations tend to be more direct and local.

Fertility

Fertility rate is usually defined as the number of births per woman within a population. Outside of the impact on total population, fertility rate and the consequent number of children per household also influences the population-food-environment nexus. First, households in developed countries and urban areas tend to have significantly lower fertility rates than do their developing and rural counterparts. Simultaneously, when higher fertility rates are seen in developed countries and urban areas, the result is higher population numbers in these high food (and associated resource) consumption areas, while higher fertility rates in developing and rural areas can cause increased direct, local agricultural need (Bilsborrow & Stupp, 1997; Carr, 2009). High rural fertility rates can also lead to migration to developed or urban areas or migration to other rural areas.

Mortality

Mortality (and the average lifespan of a population) is a fundamental contributor to population trends and processes, including those discussed above. The age at which mortality occurs is a basic driver of population growth (or decline), fertility, migration, and resource use. Along with the other transitions that are touched upon in this essay, there has also been a worldwide ‘mortality’ or ‘epidemiologic’ transition, wherein most populations have seen or are still undergoing not only a dramatic decrease in infant and child mortality alongside an extension of the expected lifespan into elderly years but also a dramatic shift in causes of mortality from communicable disease to (or to now including) chronic disease (*e.g.*, Santow, 1997). As with other transitions, this mortality transition has not advanced evenly, and major differences exist along established fault-lines, such as levels of economic development and between rural and urban populations (*e.g.*, Timonin et al., 2016). Although we do not present statistics on mortality in this essay, it should be understood that mortality processes go hand-in-hand with the other population processes discussed here.

Migration

Migration directly and indirectly impacts the food-environment relationship. Migration across international borders is perhaps the most easily recognizable form of this movement, but internal migration, the migration within a country or other political unit, is very common, though harder to track. For example, somewhere between 200 and 400 million people have migrated within China in the last 40 years (Chan & Bellwood, 2011). Various types of migration interact with the food-environment nexus differently, but changing one's type of location tends to change one's behavior. Much of the internal migration in developing nations is rural-to-urban, and most international migrants move 'up' the development continuum of nations from less to more developed (Carr, 2009; Lambin & Meyfroidt, 2011; Levy et al., 2011). Therefore, migration tends to move people to places where higher consumption of food and higher consumption of resource-intensive food occurs. Rural-to-rural migration, despite being less common, can have a disproportionately large effect on the environment due to the direct agricultural activities of migrants in rural areas. These migrants are often the first agricultural users of 'virgin' or 'old-growth' environments and have been noted as key players in the conversion of rainforests to farmland (Carr, 2009; Davis & Lopez-Carr, 2010; Geist & Lambin, 2002).

Remittances

One of the consequences of migration is remittances: money transferred by migrants from their current location to their origin location. Remittances can make up a large portion of the income in developing countries and produce substantial change in origin area behavior (Levitt, 1998). The relationship between remittances and food and environment are complex and not uni-directional. In some cases, these remittances allow household members to abandon agriculture, meaning less direct environmental impact. In other cases, remittances can allow households to invest in agriculture, leading to intensification and/or extensification and greater direct environmental impact (Davis & Lopez-Carr, 2010; Lambin & Meyfroidt, 2011; Levy et al., 2011). Remittances and other aspects of cross-cultural contact create cultural change on both sides of the migration process (Levitt, 1998). Relevant to our discussion, migration can cause the adoption of urban or developed world diets in origin places, with the resultant indirect environmental impacts (Handley et al., 2013; Levy et al., 2011).

Global-Scale Trends in Population and Agriculture over Time

We now present an analysis of the relationship between population, agricultural extensification, and intensification at the global region scale, with a closer examination of Latin America. Our analysis is at the decadal scale from 1970 to 2010 (when available).[2] We highlight Latin America, as it moved rapidly through demographic transition during this period. Central America and South America also hold a large portion of the world's remaining high-biomass forests, and both regions have been heavily exploited for agricultural production during this period.

We examine population, extensification, and intensification through the following statistics, grouped by category. These statistics were gathered or calculated from the Population Division of the United Nations Department of Economic and Social Affairs (UNPOP) and the Food and Agriculture Organization of the United Nations (FAO): (1) population, including total population, the percentage of total population that is rural, the average number of rural persons per 1000 hectares of arable and permanently cropped land (rural population density), and the percentage change in total population minus the percentage change in rural population; (2) extensification, including the percentage of total land area that is arable and permanently cropped, the percentage of total land area that is in permanent meadows or pasture, and the percentage of total land area that is in 'agricultural use' (created by adding the previous two statistics); and (3) intensification, including the percentage of arable and permanently cropped that is irrigated; fertilizer use, expressed as kilogram (Kg) per hectare (Ha) of cropped land; and engine-driven agricultural machine (tractor) use, presented as tractor per 1000 Ha of arable and permanently cropped land. These indicators were chosen because they are mostly universally available across the space and time periods encompassing this study and because their use in examining associations among processes of population, agricultural extensification, and intensification is established in prior literature.

Global Region Trends

We first present this data at the global region scale, Table 1.

Table 1 - Global Region Population Statistics

	Population		**% Rural Pop**		**Rural Pop Density**		**Total Pop Growth -Rural Pop Growth**
Global Region	2010	1970-2010	2010	1970-2010	2010	1970-2010 %	1970-2010
Africa	1,022,234	177.67%	60.8%	-15.7%	2.42	56.2%	-121.5%
Asia	4,164,252	95.05%	55.6%	-20.7%	4.19	15.5%	-79.6%
Europe	738,199	12.55%	27.3%	-9.8%	0.69	7.8%	-4.7%
Latin America and the Caribbean	590,082	106.05%	21.2%	-21.8%	0.68	-31.0%	-137.0%
Northern America	344,529	48.96%	18.0%	-8.2%	0.29	18.2%	-30.7%
Oceania	36,593	87.60%	29.3%	0.6%	0.24	93.9%	6.3%
Sub-Saharan Africa	822,724	188.61%	63.7%	-16.8%	2.26	62.8%	-125.8%
World	6,895,889	86.57%	48.4%	-15.0%	2.17	31.6%	-54.9%

Between 1970 and 2010, population increased globally by 86% and increased more dramatically in Latin America (106%) and Africa (176%). The percentage of the global population that is rural decreased, dropping from 63% to 48%, though rural population density increased by 32 %, a function of total population growth outstripping rural population growth vis-à-vis urbanization. Latin America is the only region in which rural population density declined, and rural population density increased most dramatically in Africa, especially in sub-Saharan Africa (SSA).[3] Rural population density shows similar trends globally, with the number of rural people per arable land area increasing, except in Latin America, the rural population of which is now equal to that of Europe. Meanwhile, African and Asian rural population density continued to increase despite already high levels. The increase in rural population was far less than the increase in overall population for these regions. Table 2 contains extensification and intensification statistics at the global region level.

Table 2 - Global Region Agricultural Extensification and Intensification Statistics

	Global Region Extensification Statistics						Global Region Intensification Statistics					
	% of Land Arable or Cropped		% Land in Pasture		% of Land in Agricultural Use		% of Arable or Cropped Land Irrigated		Fertilizer Use		Tractor use	
Country	2010	1970-2010	2010	1970-2010	2010	1970-2010	2010	1970-2010	2000	1970-2000%	2000	1970-2000 %
Africa	8.6%	2.5%	30.7%	0.8%	39.4%	3.4%	5.4%	0.8%	17.41	8.50	2.42	31.4%
Asia	17.9%	3.4%	34.9%	13.7%	52.8%	17.0%	40.8%	14.3%	132.51	106.20	14.48	731.6%
Europe	13.2%	-4.0%	8.1%	-10.2%	21.3%	-14.2%	8.7%	2.7%	72.55	-20.35	35.90	68.8%
Latin America and the Caribbean	9.1%	2.9%	27.3%	3.5%	36.4%	6.4%	12.0%	3.9%	15.68	9.52	10.93	115.7%
Northern America	11.3%	-1.7%	14.1%	0.2%	25.4%	-1.6%	13.0%	3.9%	92.25	25.14	23.47	-2.6%
Oceania	5.3%	-0.1%	43.3%	-10.1%	48.6%	-10.2%	60.7%	12.5%	61.50	30.36	7.92	-15.1%
Sub-Saharan Africa	10.0%	2.9%	33.2%	1.7%	43.2%	4.6%	8.3%	1.3%	29.43	16.15	3.59	60.9%
World	11.9%	0.9%	25.8%	1.6%	37.6%	2.5%	20.6%	7.7%	89.09	40.43	17.79	57.4%

Concerning the extensification of agriculture, between 1970 and 2010, the global percentage of agricultural land mostly held steady at around 11 percent for cropped and arable land and 25 percent for meadow and pasturelands. Percentage of arable and cropped land in the developed regions dropped towards this mean of 11% over time, while the percentages of such land in Latin America and Africa rose to meet it. The exception here is Asia, which was at about 15 percent arable and cropped land in 1970 and rose steadily until 2010. The global percentage of land that is permanent meadows or pasture held mostly steady over the study period, going from 24.2% to 25.8%. Like arable and cropped land, this steady trend hides regional differences. The denominator in these two statistics is total land, the large size of which perhaps hides the dramatic changes these percentages indicate. For example, Africa increased its percentage of arable land area in agricultural use by 3.4 percent. This means that in 2010, there were 100,802,064 more total hectares of arable and cropped land than there were in 1970, an area of land roughly equivalent in size to the nation of Egypt. Previous work has noted that during the 20th century, global cropland more than halved from .075 Ha to 0.35 per person, even though cropland extent increased dramatically (Ramankutty, Foley, & Olejniczak 2002).

Intensification statistics indicate that between 1970 and 2010, the percentage of irrigated arable and cropped land increased across all global regions, especially in Asia, where the percentage of irrigation is very high, at 40.8 percent, much of this due to rice cultivation. Fertilizer use from 1970 to 2000 (country-level numbers are not available after 2002) doubled globally, from 48.6 to 89.1 kg per Ha in 30 years. All regions increased their fertilizer use, save Europe. Latin America and Asia dramatically increased both their percentage of and absolute use of fertilizer, while Africa tripled its rate but remains low in absolute terms. Regarding the use of tractors, from 1970 to 2000, there was an almost 60 percent global increase, along with an increase in most global regions. However, there remain stark differences in the absolute use of mechanical machines for agriculture among continents despite major increases in Latin America, Asia, and Europe.

At this crude scale, is it possible to observe any connection between population change and agricultural practices? Over the period of time examined, increases in population and increases in rural population density were accompanied by increases in both extensification and intensification, although each occurred at different rates in different places. In the case of Latin America, increases in total population and decreasing rural population density were accompanied by increases in both extensification and intensification. We discuss how these overall trends occurred distinctly at national and regional scales in the following section.

Trends in Latin America

Central America. Table 3 contains statistics about population change in Central America from 1970 to 2010.

Table 3 - Central America Population Statistics

	Population		% Rural Pop		Rural Pop Density		Total Pop Growth -Rural Pop Growth
Country	2010	1970- 2010 %	2010	1970- 2010 %	2010	1970- 2010 %	1970-2010
Belize	312	154.7%	55.0%	6.0%	1.60	20.2%	-134.5%
Costa Rica	4,659	155.9%	35.8%	-25.4%	2.88	27.4%	-128.6%
El Salvador	6,193	65.8%	35.7%	-24.9%	2.48	-31.6%	-97.3%
Guatemala	14,389	164.1%	50.7%	-13.8%	2.98	32.1%	-132.1%
Honduras	7,601	182.7%	48.4%	-22.7%	2.52	103.1%	-79.6%
Mexico	113,423	118.7%	22.2%	-18.8%	0.90	-2.2%	-120.8%
Nicaragua	5,788	141.4%	42.7%	-10.2%	1.16	10.2%	-131.2%
Panama	3,517	132.9%	25.4%	-27.0%	1.23	-15.4%	-148.3%
Central America	**155,881**	**124.0%**	**27.9%**	**-18.3%**	**1.20**	**8.6%**	**-115.4%**

The total population of Central America increased by almost 125% between 1970 and 2010. Only El Salvador's growth was below 100%, which is explained by an outmigration caused by civil war and demographic pressure (Gammage, 2007). Despite this overall population increase, rural population density for the region increased by only 8.6% (although Mexico's large size tends to lower this number, obscuring rural population increases in most Central American countries). A major driver of this population change was the steep decline in mortality in the 20th century because of improved health conditions and concurrent economic development (Carr, Lopez, & Bilsborrow 2009). Additionally driving these trends were changes in fertility rates. Fertility began to fall across the region in the 1960s for a few select countries and in the

1970s for the majority of countries, while a few more rural Central American countries lagged (Ibid). The process of demographic momentum explains much of the continuing population growth despite declines in fertility rates, although demographic momentum is difficult to disentangle from natural population increase (Keyfitz, 1971; Carr, 2004). During the study period, there was much rural-to-urban migration within countries and the region, as well as a large international migration movement, almost exclusively to the United States (Carr, 2004). This population growth and migration left Central America highly urbanized, despite low economic development in many nations.

Table 4 Central America Extensification and Intensification Statistics

	Extensification Statistics				**Intensification**							
	% of Land Arable or Cropped		**% Land in Pasture**		**% of Land in Agricultural Use**		**% of Arable or Cropped Land Irrigated**		**Fertilizer Use**		**Tractor use**	
Country	2010	1970-2010	2010	1970-2010	2010	1970-2010	2010	1970-2010	2000	1970-2000 %	2000	1970-2000 %
Belize	4.7%	2.7%	2.2%	0.6%	6.9%	3.3%	3.7%	1.5%	62.02	-15.4%	11.62	-8.8%
Costa Rica	11.4%	1.7%	25.5%	-1.2%	36.8%	0.5%	18.6%	13.3%	340.82	240.4%	14.29	38.1%
El Salvador	43.1%	12.9%	30.7%	1.3%	73.8%	14.2%	5.0%	1.8%	86.42	-16.9%	3.81	-4.7%
Guatemala	22.8%	8.3%	18.2%	7.0%	41.0%	15.3%	12.9%	9.3%	107.68	261.6%	2.19	8.0%
Honduras	13.0%	-0.7%	15.7%	2.3%	28.8%	1.6%	6.0%	1.7%	126.49	711.6%	3.64	230.1%
Mexico	14.4%	2.5%	38.6%	0.3%	53.0%	2.7%	23.2%	7.7%	66.86	187.7%	11.86	200.3%
Nicaragua	17.7%	7.7%	25.1%	5.3%	42.8%	13.0%	2.9%	-0.5%	13.44	-37.4%	1.32	219.3%
Panama	9.8%	2.4%	20.6%	5.3%	30.4%	7.7%	5.9%	2.2%	44.87	16.0%	11.15	152.3%
Central America	**14.8%**	**2.9%**	**34.8%**	**1.0%**	**49.6%**	**4.0%**	**19.7%**	**6.6%**	**72.17**	**172.3%**	**10.15**	**175.8%**

Concerning extensification, the percentage of land in agricultural use increased for the region as a whole to almost 50 percent, which is the highest for any global region except Asia (Table 2). This increase in both cropped and pastureland has come at the expense of forest (Houghton, Lefkowitz, & Skole 1991). Guatemala and Nicaragua, both with the highest remaining amount of rainforest in Central America, increased their respective percentages of land in agricultural use dramatically. Intensification statistics indicate that irrigation also increased significantly (again, the land area denominator hides a large area of land affected). Fertilizer use from 1970 to 2000 increased dramatically on a per area basis, as well as in total (not shown). Tractor use increased for the region as a whole, but this hides much variability, wherein the more developed nations of Costa Rica, Mexico, and Panama increased their already high use, and the less developed nations remained quite low or even decreased in use. In sum, extensification and intensification occurred simultaneously in Central America, accompanied by growing total population but decreasing rural population density (see Ervin & Carr, 2015 for further discussion). Agricultural intensification increased dramatically along with GDP, as rural-urban migration shifted labor from farms to wage labor and intensive farming operations consolidated land in rural areas.

South America. Data for South America indicate that the population for the region as a whole grew over 100%, although a few countries such as highly urbanized Uruguay and highly rural French Guiana and Suriname grew far less than that. Rural population density fell by more than 40% for the region, although the three countries of Chile, Colombia, and Ecuador all increased their rural population density. Similar to Central America, South American demographic changes during the study period were driven by a decline in fertility rates, high rates of internal rural to urban migration, and some international migration. However, South America experienced a decline in fertility rates earlier, had higher rates of rural to urban migration, and less international migration, which was largely to Europe (Carr, Bilsborrow, & Barbieri, 2003).

Table 5 South America Population Statistics

	Population		% Rural Pop		Rural Pop Density		Total Pop Growth -Rural Pop Growth
Country	2010	1970- 2010 %	2010	1970-2010 %	2010	1970-2010 %	1970-2010
Argentina	40,412	68.5%	7.7%	-13.5%	0.08	-57.0%	-125.5%
Bolivia	9,930	135.5%	33.6%	-26.6%	0.84	-43.8%	-179.3%
Brazil	194,946	102.9%	15.7%	-28.4%	0.39	-61.6%	-164.5%
Chile	17,114	78.7%	11.1%	-13.7%	1.10	89.3%	10.6%
Colombia	46,295	117.0%	25.0%	-20.2%	3.45	80.0%	-37.0%
Ecuador	14,465	142.2%	33.1%	-27.6%	1.86	31.0%	-111.2%
French Guiana	231	376.0%	23.8%	-8.8%	3.55	-77.6%	-453.6%
Guyana	754	4.7%	71.7%	1.1%	1.21	-11.5%	-16.2%
Paraguay	6,455	160.0%	38.6%	-24.3%	0.62	-63.3%	-223.3%
Peru	29,077	120.5%	23.1%	-19.5%	1.50	-24.8%	-145.3%
Suriname	525	40.9%	30.7%	-23.4%	2.64	-50.2%	-91.1%
Uruguay	3,369	19.9%	7.5%	-10.1%	0.15	-57.7%	-77.6%
Venezuela	28,980	171.3%	6.7%	-21.5%	0.60	-30.5%	-201.9%
South America	**392,555**	**105.0%**	**17.2%**	**-23.1%**	**0.48**	**-43.9%**	**-148.9%**

Table 6 South America Extensification and Intensification Statistics

	Extensification				**Intensification**							
	% of Land Arable or Cropped		**% Land in Pasture**		**% of Land in Agricultural Use**		**% of Arable or Cropped Land Irrigated**		**Fertilizer Use**		**Tractor use**	
Country	2010	1970-2010	2010	1970-2010	2010	1970-2010	2010	1970-2010	2000	1970-2000 %	2000	1970-2000 %
Argentina	14.0%	4.1%	39.6%	2.2%	53.6%	6.4%	4.3%	-0.4%	30.13	832.2%	10.45	67.1%
Bolivia	3.7%	2.1%	30.5%	4.1%	34.1%	6.2%	4.4%	-0.3%	2.37	160.1%	1.89	46.1%
Brazil	9.2%	4.3%	23.2%	4.9%	32.3%	9.2%	6.7%	4.8%	100.74	314.8%	12.36	207.5%
Chile	2.3%	-3.2%	18.8%	4.1%	21.2%	0.9%	110.0%	81.2%	228.44	623.3%	25.59	208.6%
Colombia	3.0%	-1.5%	35.3%	1.0%	38.3%	-0.5%	31.3%	26.3%	144.82	404.5%	4.62	2.3%
Ecuador	10.4%	0.1%	19.8%	10.5%	30.2%	10.6%	38.0%	19.6%	55.19	313.5%	4.92	305.4%
French Guiana	0.2%	0.2%	0.1%	0.1%	0.3%	0.2%	38.7%	-61.3%	75.00	NA	26.19	-31.1%
Guyana	2.3%	0.4%	6.2%	1.2%	8.5%	1.6%	33.6%	2.6%	26.33	-2.6%	7.59	-15.2%
Paraguay	10.0%	7.7%	42.8%	16.4%	52.8%	24.1%	1.7%	-2.7%	20.96	113.6%	5.31	1.4%
Peru	3.5%	1.3%	13.3%	1.5%	16.8%	2.8%	26.8%	-12.6%	59.34	98.0%	3.08	-21.1%
Suriname	0.4%	0.1%	0.1%	0.0%	0.5%	0.2%	93.4%	19.8%	86.57	53.7%	19.85	-18.0%
Uruguay	9.9%	1.7%	72.2%	-5.7%	82.1%	-4.0%	12.6%	8.9%	73.58	51.7%	23.16	11.8%
Venezuela	3.7%	-0.3%	20.4%	1.8%	24.1%	1.5%	32.5%	24.6%	83.06	389.3%	14.43	163.3%
South America	**8.0%**	**2.9%**	**26.3%**	**3.9%**	**34.4%**	**6.8%**	**9.7%**	**3.4%**	**79.29**	**340.2%**	**11.04**	**115.1%**

South America as a whole increased its percentage of land in agricultural use, although again, country rates vary widely. Brazil's massive land area pulls the continent's average towards its value, obscuring lower rates of agricultural extensification in almost all other countries. The total amount of South American land converted to agricultural use in the period was approximately 120 million Ha, roughly the size of the nation of Columbia. Much of this extensification came at the expense of tropical forest. Intensification statistics indicate large increases in the amount of land irrigated, large increases in the number of agricultural machines, and a notable increase in the use of fertilizer.

Trends for South America largely mirrored Central America. Urbanization and international migration became increasingly important demographic processes (Carr et al., 2009). Fertility rates declined notably, particularly in urban areas. However, rural areas lagged in the demographic transition, with continued high infant mortality and high fertility rates, with the southern cone nations of South America, Chile, Argentina, and Uruguay being notable counter-examples (Carr & Pan, 2006; Pan & Lopez-Carr, 2016). Elsewhere, remote rural areas in both Latin America and South America were associated with continued high (though declining) numbers of small farm, (semi-) subsistence agriculture, particularly in less desirable lands. Meanwhile, pastureland and intensive export agriculture surged, largely to meet demand from higher earning urban populations both within Latin America and also abroad. These exports are primarily destined for the rapidly growing urban populations of China and Southern Asia. Already complex relationships between population size, structure, and distribution have been rendered yet more complex by increasing demand for food, especially meat and dairy products from populations outside of Latin America.

Does this mean that demography has become a less predictive factor of land change in the region? Perhaps demography, rather than losing importance in relation to land change, has qualitatively changed as a driver (Aide et al., 2013). Local population size, growth, and structure driving demand for food and thus local land conversion are less important. More important is the demand coming from an urbanizing developing world, both in Latin American and elsewhere, particularly Asia. While rural-rural migration of farm households has for decades been a major driver of forest clearing in Latin America, increasingly rural-urban and international migration (both within the region and elsewhere) are now shifting labor from agricultural to urban service applications, accompanied by rising wages and increased adoption of western diets, characterized by more processed and animal-based products, with relatively higher impacts on energy and land conversion when compared to the impacts of the grains and legumes that have historically been cultivated as the staple of rural populations (Ervin & Lopez-Carr, 2015).

Case Studies

We have examined population, agricultural extensification, and intensification at the global scale, the global region scale, and at the country scale. We now present three case studies at three different scales: country-regional, municipal, and “county,” where population changes were associated with different outcomes for agriculture and the environment.

Population Decline and Extensification: Amazonian Brazil

From 1970 to 2010, Brazil’s absolute rural population declined from around 42 million to 32 million, while the nation doubled in total population (UNPOP). During this period, the Brazilian government encouraged the conversion of the Amazon to agricultural use through the construction of roads and cities in the region, as well making land, credit, and even food available for settlers (Hecht & Cockburn, 1990; Stewart, 1994). Small-scale agriculture proved not to be viable for many of the initial settlers, who then out-migrated to cities or to other rural frontiers. The initial farmland was consolidated and converted into pastureland for cattle ranching, and the conversion of forestland to ranchland continued despite a declining rural population. Although high fertility rates and other contributors to land scarcity in outmigration areas led to initial conversion of much of this area, environmental degradation for agriculture continued also despite declining local rural population (Ibid.). Similar trends have been observed recently in the Ecuadorian Amazon (Barbieri & Carr, 2005; Pan et al., 2007).

Population Growth and Extensification: Petén, Guatemala

Petén is the largest department of Guatemala, and at 12,960 square miles accounts for about one third of the country’s total area (Curtis et al., 1998). Historically, Petén was densely forested, almost inaccessible, and had a very low population. Two actions by the Guatemalan government caused population to increase rapidly: offering land at very cheap rates to Guatemalans who were willing to cultivate it in the 1960s, and building functional roads to connect the region to the rest of Guatemala in the 1970s. The result of this was large in-migration to the area. Driving this was a lack of agricultural land in the remainder of Guatemala, itself caused by high rural fertility rates, rural poverty, and concentration of agricultural land (Schwartz, 1990). In Petén, this in-migration, and to a lesser extent high fertility rates among the existing population, resulted in incredible population growth in the region, along with extensive conversion of forest to agricultural land (Grandia & Schwartz ,1999; Schwartz, 1990). This conversion of forest to cropland, and then grazing land, persisted from the 1960s and has continued to the current day, despite the creation of vast reserves and parks in 1989 (Carr, 2005). This is a clear example of rural population growth driving extensification (Grandia & Schwartz, 1999; Schwartz, 1990).

Population Growth and Intensification: Sarapiquí, Costa Rica

Sarapiquí, a canton (equivalent to a county) of the Costa Rican province of Heredia, experienced intense population growth beginning in the 1960s. In-migration beginning in 1967, spurred by a banana plantation, led initially to extensive conversion of forest land to agricultural land (Schelhas, 1996). High fertility rates led to increased population density and declining land available for households. In this case, however, these conditions did not primarily lead to further land conversion or migration to other rural frontier areas. Instead, the main response was off-farm employment and agricultural intensification on existing plots where small scale farmers raised the market products of dairy cattle, coffee, or black pepper (Schelhas, 1996.).

These case studies at three different scales demonstrate that population growth or decline can be associated with the primary response of extensification, intensification, and in- or out-migration. There are multiple factors contributing to these outcomes besides local population change, including population processes occurring in other areas, land availability, quality, and distribution, political systems, and agricultural market influences, global or otherwise. However, these case studies suggest that population growth, population density, and scale remain important and sometimes misunderstood when examining the population-food-environment nexus.

Conclusion

Much of the food produced in the developing world is no longer produced to meet the needs of local or regional populations but to feed swelling middle class urban populations in the developing world and the relatively wealthy in the developed nations. How does this change relate to Boserupian or Malthusian theory? Are we now facing purely economic pressure to innovate, or do demographic drivers remain but in a changed guise? It is clear that population processes are just one of several important drivers of agricultural development and food consumption and that the relationship between population and the environment is difficult to predict, especially without a strong understanding of local context (*e.g.*, Doepke, 2004; Myrskylä, Kohler, & Billari, 2009). However, it also remains seemingly unavoidable in the short- to middle-term that global food demand will rise due to increased population and increased meat and dairy consumption. One recent estimate expected a doubling of crop production by 2050 (Tilman et al., 2011). The best arable land is already in production, and remaining available arable land not currently in production is a rare and dwindling commodity. In order to meet this demand, where will there be extensification? Where will there be intensification? Where will both occur? Will there be new intensification technologies? What will be the implications of these shifting inputs to food production? Foley et al. 2011 predict that doubling food production could be achieved without agricultural expansion, using intensification methods, and reducing animal product consumption and waste. Godfray et al. 2010, among others, discuss the potential of increased aquaculture to meet future food demand.

Evidence suggests that without major behavioral changes or technological breakthroughs, more people eating more food, especially more meat and dairy products, will continue to threaten the sustainability of food systems and natural habitats. What can we do? International coordination in *where* agriculture is produced may be a proverbial “low hanging fruit” towards increased food production efficiency with mitigated environmental impact. Each unit of land cleared in the tropics vs. temperate zones causes twice the carbon stock loss while producing less than half of the agricultural yield (West et al., 2010). While we anticipate continued technological innovation, the pace and magnitude of future advances cannot be predicted. Yet we have the ability through political will to make meaningful changes now. Behavioral changes away from red meat consumption and towards plant-based protein among inhabitants of developed countries and the rising middle class in the developing world would have an immediate impact, freeing up most of the world’s agricultural land for conversion to more efficient crops or wildland regeneration (*e.g*., Hallström, Carlsson-Kanyama, & P. Börjesson, 2015; Tilman & Clark, 2014).

Notes

[1] For further reading on Malthus and Boserup, Price (1998) is one of numerous well-written reviews of Malthus and his long-lasting impact, while Grigg (1979) provides an excellent overview of Boserup’s theories as well as some critical interpretation.

[2] 1970 is the start date for our analysis due to much of the data not being available for earlier decades.

[3] Sub-Saharan Africa is broken out as a region in the original data and in this analysis, as the region is dramatically different than the rest of Africa in many respects and is often discussed as its own region in similar research.

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