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ORIGINAL PAPER

The population, agriculture, and environment nexus in Latin America: country-level evidence from the latter half of the twentieth century

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Abstract Unprecedented population growth and migration accompanied equally unprecedented land use and land cover change in Latin America during the latter decades of the twentieth century. Country-level data are examined with bivariate statistics to determine relationships between changes in population patterns and land use (agriculture and forest cover) from 1961 to 2001. In South America, large forest areas were eliminated during the period, while exceptionally high rates of forest clearing were ubiquitous in the Central America/Caribbean region. These environmental changes accompanied dissimilar initial population densities and different effects of population change on agriculture. While interacting with a host of political, socio-economic, and geographic processes, it appears that both Malthusian and Boserupian demographic processes were important drivers of deforestation. Given continued, though slowing, population growth, increased urban consumption, and future land use constraints, policy makers face myriad challenges in advancing sustainable agriculture-population dynamics in Latin America.

Keywords Population · Environment · Latin America · Migration · Land use · Land cover · LUCC · Demography · Deforestation · Agriculture

Introduction

By the close of the twentieth century, unprecedented population growth and landscape change had dramatically changed the physical and social contours of Latin America. To provide insight into these dynamics, this paper presents

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country-level data to examine potentially divergent patterns of population-environment interactions between the two regions.

The demographic and mobility transitions in Latin America

In the last 30 years leading up to the turn of the millennium, Latin America's population had doubled, to 519 million by 2000. By the middle of the next century, Latin America's population is projected to almost double again to nearly one billion, with all of this net growth occurring in cities, though rural populations will continue to grow in some countries, mainly in Central America. Population grew rapidly during the past half century due to a dramatic decline in mortality that began even earlier, by the 1920s and 1930s. However, due to improved health conditions and economic development, most of Latin America began to experience a rapid decline in fertility as part of its demographic transition beginning around 1970. Latin America as a whole thus has been recently progressing through stage three of the demographic transition (Coale 1973, citing Frank Notestein, who developed the term). Nonetheless, even with a continuation of fertility declines in future decades, the currently young age composition (due to past high fertility) will assure a high number of births (Carr 2004).

Latin America has also been progressing rapidly through the mobility transition (Zelinsky 1971), characterized by high rates of rural to urban migration. From the 1960s through the 1980s, nearly 2% of rural Latin Americans migrated annually, exceeding the rates of other regions (Chen et al. 1998). Most migrated to cities and, consequently, the region is already as urbanized as the developed world, with three-quarters of its residents urbanites. South America has nearly 80% of its population living in urban areas while Central America is rapidly closing in on 70% urban. Even the largest frontier area in Latin America, the Brazilian Amazon, has faced growing urbanization: of the 12 million inhabitants in the Brazilian Amazon in 2000 (7% of the total Brazilian population), approximately 70% were living in urban areas (Godfrey and Browder 2006). More recently, Andean Amazon nations have also experienced rapid urbanization (Barbieri and Carr 2005; Rudel et al. 2002).

Since about 1970, part of the outflow of migrants from rural areas of many Latin American countries has settled in remote rural areas, pushing the agricultural frontier further into the forest. This has been observed in Central America's lowland forests and the Amazon basin, where farm families have moved to areas where land became available due to roads opening up regions, initially for minerals, petroleum, or logging. This helps explain the apparently contradictory finding that deforestation has increased in countries in recent years even where the rural population has declined. Over time frontier lands originally opened mostly by families establishing small farms have come to be replaced often by large commercial interests, as a response to favorable international markets (e.g., soy beans in the Bolivian and Brazilian Amazon: c.f. Grau et al. 2005; Hecht 2005). Nevertheless, the initial forest clearing for subsistence crops and livestock has continued to be mainly by small and medium sized farms in most of Latin America (with the possible exception of Brazil). It is for this reason that this paper attempts to examine relationships between rural population change and changes in forestland as mediated through changes in agriculture, both in land area (called the extensification of agriculture) and increases in productivity per unit of land (agricultural intensification).

Theories of land use response to population change

The literature relating population to agriculture and natural resources has been dominated by two schools of thought. Malthus argued that population growth required an expansion of the agricultural land area in order to feed the population, and that this expansion would occur on increasingly marginal (lower productivity) lands over time (1798, 1803, see 1960 edition; also Bilsborrow and Okoth-Ogendo 1991). Neo-Malthusians have explicitly extended his approach to the environment, claiming that expansion in the agricultural land area must come from forests and other vegetated lands, and hence usually must require deforestation and environmental degradation.

Contrasting this negative environmental perspective is the more optimistic view of Boserup (1965) who theorized that increasing population density could have, under certain conditions, a positive effect on inducing agricultural innovations that would increase output to restore food production per capita and avert a decline in living standards without necessarily expanding the agricultural land area or reducing forest cover. Her approach could therefore be seen as obviating negative effects of rural population growth on the environment. Boserup's approach is akin to induced innovation theory in a broader sense, which views innovations as induced by not only demographic and land constraint factors but also by a host of economic, market-related, and even policy factors (see e.g., Binswanger and Mc Intire 1987; Pingali 1988; Ruttan 1994 on Africa; Angelsen and Kaimowitz 2001; Roy Chowdhury and Turner II 2006 on Latin America). Thus, innovations may be stimulated by economic opportunities related to expanding markets or new methods of production developed elsewhere and communicated from other parts of the world, given the increasingly globalized and interconnected world in which all economic agents operate, farm and non-farm.

In addition, it is useful to cite another, broader theoretical perspective, which incorporates all those discussed above. Kingsley Davis' *theory of the multiphasic response* (1963) offers an approach which Bilsborrow (1987) demonstrates can be expanded to include both Malthus and Boserup and thereby provide a more comprehensive model. Thus, Davis noted that population growth, manifest in larger families (larger numbers of surviving children, from, for example, the decline in mortality in the early demographic transition), would usually induce families to adapt to avoid lowering their living standards. Davis argued that people could respond by postponing marriage, reducing child-bearing within marriage, or migrating in search of other ways to support their families. Davis' approach was explicitly demographic, as he did not consider economic responses of households, for example, linking out-migration to agricultural extensification, as Malthus had done earlier. The theory of Davis was also explicitly *multiphasic*, such that the more one response tended to occur, the less pressure there was for other responses to occur.

Bilsborrow broadened Davis' approach in three ways: (a) by including agricultural extensification (Malthusian), both in situ (on one's own farm or in the community; see Carr 2005; Pan et al. 2007) and not (requiring migration to other rural destinations, including forested areas–via rural-rural migration; see Carr 2008a, 2009); (b) by including Boserupian agricultural intensification; and finally (c) by including rural–urban migration, if urban employment opportunities are thought to exist, whether in the formal or informal sectors (see Barbieri and Carr 2005; Aide and Grau 2004). Again, the more a particular response occurs, the less pressure for the occurrence of other responses.

Figure 1 illustrates this approach, with the fertility response added to (a)–(c) above. Evidently, the theory is developed in terms of household behavior, and would best be tested empirically using longitudinal data at the *household* level, but this is beyond the scope of this macro-oriented paper. Bilsborrow (1987) hypothesized that households traditionally exhaust economic options first, through land expansion then intensification, and only then are likely to adopt temporary or seasonal out-migration. Permanent out-migration then follows if temporary or seasonal out-migration proves inadequate for meeting household needs (since migration is more disruptive to family life). Migration flows can be to rural areas in regions with unclaimed potentially arable land and/or to urban areas if jobs are thought available. Thus, for example, where there is potentially arable but unused proximate land available (Carr 2008b, 2009), rural populations seek to expand agricultural use—i.e., land extensification. Conversely, agricultural intensification is more likely when rural populations have access to agricultural technology (Boserup 1965; Zimmerer 1993) and produce and labor markets (Rudel 1983; Carr 2006; Sader et al. 1997; Nepstad et al. 2001; Mäki et al. 2001). Supportive policies (Hecht et al. 2006) including those that provide secure land tenure (Futemma and Brondízio 2003) also may facilitate agricultural intensification. Lastly, where "pull factors" such as economic incentives in urban areas outweigh rural options, rural–urban migration will follow (Bilsborrow 1998).

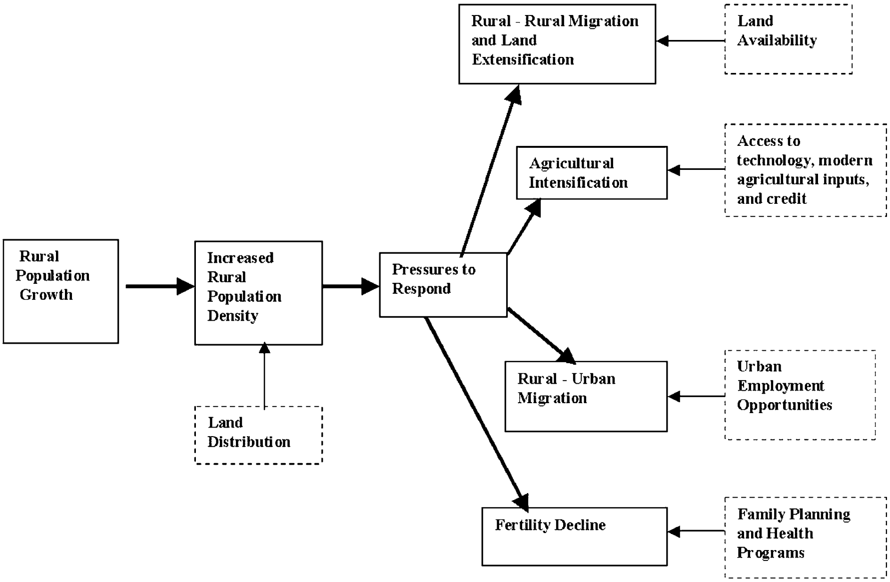

Fig. 1 Economic, demographic, and economic–demographic responses to rural population growth

Hypotheses

The theoretical approaches above yield a number of expected relationships between rural population change and land use/cover change. The main hypotheses we test in this paper following Fig. 1 are the following:

Agricultural extensification

H1 Population growth stimulates agricultural land expansion, mainly through forest conversion (as shown at the household scale in the top box of Fig. 1), to feed the growing population (Malthusian). Population growth in rural areas should have greater land use/cover effects than urban population growth, since the former involves consumption as well as production effects. More specifically, a rural population uses land to feed itself, as well as others through market sales. On the other hand, increasing urban populations affect rural land use through demand for rural food and timber. This general hypothesis has several important sub-hypotheses:

H1a The absolute size of the effect of population growth on agricultural land area (number of hectares cleared) is associated positively with a country's availability of arable land. Therefore, countries with declining rural populations and population density but ample agricultural land (e.g., Brazil) may still experience agricultural extensification and deforestation. This is particularly expected if, for example, rural–rural migration occurs, facilitated by roads providing access to previously inaccessible areas.

H1b On the other hand, the rate of agricultural expansion, mostly through deforestation, is inversely related to the stock of forests available in the country at the beginning of the study period. This rate of land change is in turn positively related to rural population growth. Note the rate of loss of forest cover over time is mathematically the derivative with respect to time of f, or $\mathrm{d}f/\mathrm{d}t$, where $f = F/L =$ proportion of land area, L, covered by forests, F. The smaller the f at the beginning of the study period (in 1961), the faster the decline in F of any given absolute loss of hectares in forest. Thus, a 10,000 ha loss per year in forest cover in a small Central American country would amount to a high rate of deforestation, whereas in a large nation such as Brazil it would be trivial.

H1c Following H1b above, countries with initially high rural population densities and little remaining forest cover are likely to experience low rates of land expansion and deforestation per person.

Agricultural intensification

H2 Population growth is associated with higher levels of agricultural intensification (Boserupian). This is consistent with Fig. 1 at the household level as diagrammed by the box representing agricultural intensification.

H2a The absolute size of the positive effect of population growth on area of land under agricultural intensification is inversely related to a country's availability of arable land (and is therefore positively related with population density).

H2b The rate of change in agricultural intensification is positively related to the rate of change in rural population growth and density and inversely related to the percentage of national lands remaining in forest at the initial time period.

H2c Following H2b above, countries with initially high rural population densities and little remaining forest cover are likely to experience higher agricultural intensification in absolute terms as well as per person.

Agricultural intensification can occur in a variety of manners, and accordingly may be measured in various ways: thus a growing rural population may be associated with a shift from land in pasture to land in crops (involving much higher labor inputs per ha, and usually higher incomes per ha), or more growth in cropland than forest area; a shift from lower value crops (e.g., grains) to higher value crops; an increase in the use of irrigation on cropland; increased applications of natural or chemical fertilizers, herbicides, or pesticides per hectare of agricultural land; increased use of new, hybrid seeds; and/or decreased fallow time, or increased multiple cropping of land use (multiple crops per year on the same land), which was the original formulation of Boserup (1965).

Data and methods

To test our hypotheses we rely on two major sets of data. First, agricultural intensification and intensification data are derived from recent Agricultural Yearbooks of the Food and Agriculture Organization of the United Nations (FAO 1995a) and FAO online statistical resources (FAO 2005). Supplemental sources are also used for countries with questionable or missing data in FAO tables. Second, demographic data come from the United Nations Population Division (http://data.un.org) and World Bank (www.worldbank.org/data).

The selection of countries is based entirely on data availability (a country must have data available for all the data items for all 3 years). In all, complete data were available for eight countries in South America and nine in the Central America/Caribbean region. Nearly all major countries are included in both regions with the exception of Peru, Uruguay, Surinam, and the Guyanas in South America and Belize in Central America.

The only measures of intensification readily available for most countries at the country level from FAO sources are the proportion of agricultural land in pasture versus crops, the percent of agricultural land irrigated, and the amount of chemical fertilizer used per unit (hectare) of agricultural land in use. No consistent published data are available at the country level on adoption of hybrid seeds or fallow rotations and multiple cropping, and measuring a shift from low to high value crops is a study in itself. Since fertilizer use is a good proxy for the use of other modern inputs (see Carr et al. 2006a, b, c), we incorporate three measures reflecting broad trends in agricultural intensification over time.

As seen in Hypothesis 1 above, rural population density (rural population divided by arable land plus land under permanent crops) is a key measure for analyzing the impacts of population change on agricultural land use and forest cover change. If forest conversion to agriculture exceeds rural population growth, rural population density decreases.

A distinction between the two regions should be noted: Central American nations tend to be much smaller, have much less forest, a much greater rate of deforestation, and greater rural population densities than South American nations (see Fig. 2). Data indicate statistically significant differences between the two regions when comparing means for rural population density, percentage forest of cover, and percentage of agricultural and arable land. The differences in means become strikingly more obvious over time. Therefore, Central America and South America are treated separately.

Data are analyzed to examine relationships between changes in population patterns and land use (agriculture and forest cover) over the four decades from 1961 to 2001. Without falling prey to the ecological fallacy, we can determine only broad patterns. Since the analysis is at the country level, comparisons across regions are based on the *unweighted* data. Otherwise, trends in Mexico and Brazil would excessively dominate regional patterns.

Results

Tables 1, 2, 3, and 4 allow us to test hypotheses regarding population change and agricultural extensification and intensification in Central and South America for the

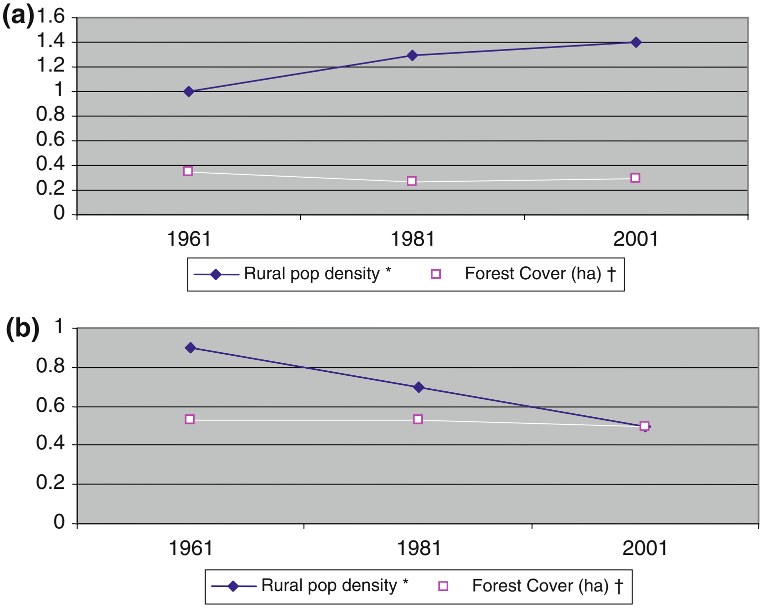

Fig. 2 **a** Central America population density and percent cover (ha) change, 1961–2001. **b** South America population density and percent forest cover (ha) change, 1961–2001

Table 1 Rural population change

	Rural population[b]			Rural population change	Rural population/total population		Rural population density[c]		Rural population density change[d]
	1961	1981	2001	1961–2000 (%)	1961 (%)	2001 (%)	1961	2001	1961–2000 (%)
Central America									
Costa Rica	843	1229	1665	98	66	40	1.8	3.2	81
Dominican Republic	2298	2838	2893	26	69	34	2.3	1.8	−22
El Salvador	1626	2571	2461	51	61	38	2.5	2.7	8
Guatemala	2742	4372	7020	156	67	60	1.8	3.7	106
Haiti	3255	4230	5263	62	84	64	2.8	4.8	71
Honduras	1512	2381	3043	101	77	46	1	2.1	109
Mexico	18425	22822	25555	39	48	25	0.8	0.9	21
Nicaragua	957	1490	2266	137	60	44	0.8	1	29
Panama	675	982	1260	87	58	43	1.2	1.8	51
C.Am. Total	32333	42915	51426	59	56	33	1	1.4	34
C.Am. Avg.[a]	3593	4768	5714	84	66	44	1.7	2.5	47
South America									
Argentina	5417	4771	4374	−19	26	12	0.2	0.1	−34
Bolivia	2153	2928	3161	47	63	37	1.5	1	−32
Brazil	40014	40177	31528	−21	53	18	1.4	0.5	−66
Chile	2443	2078	2144	−12	31	14	0.6	0.9	46
Colombia	8734	10734	10489	20	50	25	1.8	2.5	40
Ecuador	2961	4266	4707	59	65	37	1.2	1.6	34
Paraguay	1216	1851	2442	101	64	43	1.5	0.8	−48
Venezuela	2969	3105	3157	6	38	13	2.1	0.9	−57

Table 1 continued

	Rural population[b]			Rural population change	Rural population/total population		Rural population density[c]		Rural population density change[d]
	1961	1981	2001	1961–2000 (%)	1961 (%)	2001 (%)	1961	2001	1961–2000 (%)
S. Am. total	65907	69910	62002	−6	47	19	0.9	0.5	−44
S. Am. Avg.[a]	8238	8739	7750	−6	49	25	1.3	1	−19

[a] Percentages are unweighted

[b] Expressed in thousands

[c] Rural population divided by hectares of arable and permanently cropped land

[d] Significant at the 0.05 level between Central and South America

Table 2 Forest cover change (per 1,000 ha)

	Forest cover (ha)			Forest cover/total land (ha)^{b}		Deforestation			Change forest/capita^{b} (ha)	
	1961	1981	2001	1961 (%)	2001 (%)	1961–1981 (%)	1981–2001 (%)	1961–2001 (%)	1961–1981	1981–2000
Central America										
Costa Rica	3240	1730	1790	63	39	47	−3	45	−1.72	0.05
Dominican Republic	673	633	1346	14	28	6	−113	−100	0.29	0.25
El Salvador	208	134	107	10	6	36	20	49	−0.06	−0.01
Guatemala	5370	4470	2717	50	26	17	39	49	−0.97	−0.40
Haiti	140	101	68	5	3	28	33	51	−0.02	−0.01
Honduras	6000	3980	5335	54	48	34	−34	11	−0.44	0.57
Mexico	58570	47300	54938	31	29	19	−16	6	−0.20	0.33
Nicaragua	6650	4370	3232	55	27	34	26	51	−3.57	−0.76
Panama	4740	4140	2836	64	39	13	31	40	−2.82	−1.33
C.Am. Total	85591	66858	72369	35	30	26	−2	23	−1.06	−0.15
C.Am. Avg.[a]	9510	7429	8041	38	27	22	15	15	−0.41	0.13
South America										
Argentina	50900	60000	33722	19	13	−18	44	34	−3.17	−5.51
Bolivia	60450	56130	53022	56	49	7	6	12	−3.45	−1.06
Brazil	558200	572570	538924	66	64	−3	6	3	−0.48	−0.84
Chile	16500	15480	13519	22	21	6	13	18	−1.22	−0.94
Colombia	59000	52450	49460	57	48	11	6	16	−1.09	−0.28
Ecuador	18150	14450	10390	66	38	20	28	43	−2.62	−0.95
Paraguay	21550	20550	23345	54	59	5	−14	−8	1.48	1.51
Venezuela	38585	34700	48643	44	56	10	−40	−26	3.39	4.49

Table 2 continued

	Forest cover (ha)			Forest cover/total land (ha)[b]		Deforestation			Change forest/capita[b] (ha)	
	1961	1981	2001	1961 (%)	2001 (%)	1961–1981 (%)	1981–2001 (%)	1961–2001 (%)	1961–1981	1981–2000
S. Am. 1966 total	823335	826330	771025	53	50	5	6	12	−0.90	−0.45
S. Am. 1966 Avg.[a]	102917	103291	96378	48	43	0	−7	6	-0.79	−0.79

Significant at the 0.10 level between Central and South America

[a] Percentages are unweighted

[b] Based on baseline rural population for the period

Table 3 Agricultural extensification

	Pasture land as a percentage of total land			Percent change			Arable and permanently cropped land as a percentage of total land			Percent change[b]		
	1961 (%)	1981 (%)	2001 (%)	1961–1981 (%)	1981–2001 (%)	1961–2001 (%)	1961 (%)	1981 (%)	2001 (%)	1961–1981 (%)	1981–2001 (%)	1961–2001 (%)
Central America												
Costa Rica	18	41	46	128	12	61	9	10	10	6	3	9
Dominican Republic	43	43	43	0	0	0	20	29	33	44	12	38
El Salvador	29	29	38	2	30	24	31	35	44	13	26	29
Guatemala	10	12	24	20	95	57	14	16	18	14	8	19
Haiti	18	18	18	1	−3	−2	42	32	40	−23	23	−5
Honduras	13	13	13	−3	4	1	13	16	13	19	−19	−4
Mexico	39	39	42	0	7	7	12	12	14	−1	16	13
Nicaragua	32	41	40	27	−3	19	10	10	18	6	73	46
Panama	14	16	21	10	32	31	8	8	9	3	20	19
Total	35	37	39	5	6	10	13	13	15	2	16	16
Total[a]	24	28	32	16	13	24	18	19	22	7	16	19
South America												
Argentina	54	52	52	−3	−1	−4	10	13	13	24	−1	19
Bolivia	26	25	31	−6	25	15	1	3	3	134	−8	53
Brazil	14	19	23	33	22	38	3	9	8	158	−9	57
Chile	13	16	17	25	9	26	5	7	3	44	−58	−67
Colombia	34	29	40	−14	39	16	5	5	4	14	−25	−17
Ecuador	8	15	18	92	21	57	9	9	11	1	17	16
Paraguay	34	39	55	15	39	37	2	5	8	139	60	74
Venezuela	18	20	21	10	6	14	2	4	4	172	−9	59

Table 3 continued

	Pasture land as a percentage of total land			Percent change			Arable and permanently cropped land as a percentage of total land			Percent change[b]		
	1961 (%)	1981 (%)	2001 (%)	1961–1981 (%)	1981–2001 (%)	1961–2001 (%)	1961 (%)	1981 (%)	2001 (%)	1961–1981 (%)	1981–2001 (%)	1961–2001 (%)
Total	24	26	30	10	15	21	5	8	8	83	−8	40
Total[a]	25	27	32	7	20	22	5	7	7	48	−5	29

[a] Unweighted (the mean for the countries in each region, as opposed to the weighted totals which report on each regions as one geographic unit)

[b] All time periods significant at the 0.01 level between Central and South America

Table 4 Agricultural intensification

	Percent A&P land irrigated			Fertilizer use (1,000 kg/ha of cropland)		
	1961	1981	2001	1961	1981	2001
Central America						
Costa Rica	5.42	12.97	20.57	19	72	128
Dominican Republic	11.11	11.93	17.23	14	58	98
El Salvador	2.78	4.97	4.95	21	88	73
Guatemala	2.08	3.98	6.82	15	89	183
Haiti	3.02	7.82	6.82	0	6	14
Honduras	3.38	4.65	5.60	6	28	152
Mexico	12.63	22.17	23.15	191	1561	1870
Nicaragua	1.53	6.37	4.38	4	60	23
Panama	2.48	4.83	5.04	5	30	29
Average	10.39	17.75	19.04	30	222	285
South America						
Argentina	3.45	4.55	4.46	16	96	860
Bolivia	4.99	4.44	4.26	0.8	7	12
Brazil	1.73	2.59	4.38	270	2,753	6,773
Chile	28.02	22.74	82.61	46	114	481
Colombia	4.55	7.43	21.18	71	280	640
Ecuador	17.53	20.65	28.98	11	70	231
Paraguay	3.70	3.09	2.15	0.6	9	67
Venezuela	14.46	8.39	16.87	19	146	300
Average	4.89	4.74	7.39	54	434	1,170

time period 1961–2001. We first analyze our first set of hypotheses regarding population and forest conversion trends followed by an examination of land use related to agricultural extensification in each region (i.e., the land uses and covers to which the deforested land was converted.) We then explore our second suite of hypotheses, population links to agricultural intensification. Following the results, we examine links between observed versus hypothesized population-environment trends and implications for sustainable development in the two regions.

Population and agricultural extensification through forest conversion

Central America/Caribbean

Population and deforestation The rural population increased in every country in the region over the 40-year period, rising by 19 million overall, or by almost two-thirds using the weighted data and by fully two-thirds using the preferred unweighted data (Table 1). This occurred even as the *percentage* of the population living in rural areas fell from 56 to 33 due to much more rapid urban population growth (from both high urban fertility and net rural–urban migration). Rural

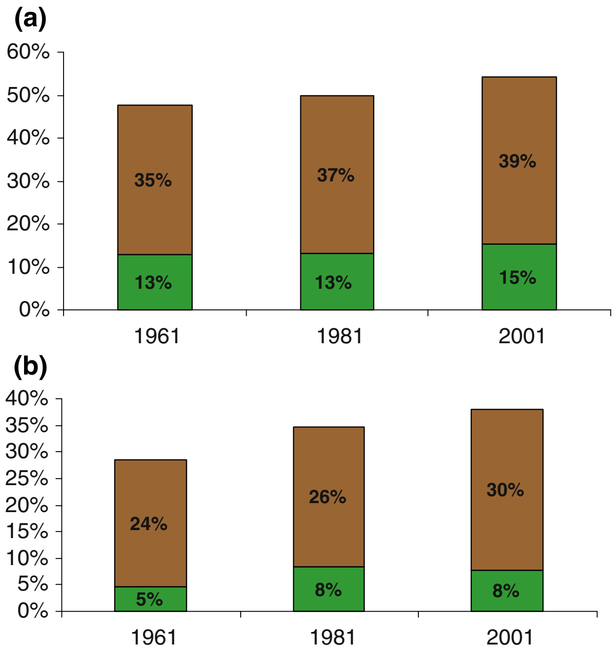

Fig. 3 **a** Central America: pasture and arable and permanently cropped land as a percent of total land. **b** South America: pasture and arable and permanently cropped land as a percent of total land

population density increased by 34% overall, as the increase in rural populations in the nine countries was greater than that in agricultural land (the one exception being the Dominican Republic).

Table 2 reports forest cover change in hectares, as well as mean total change at the national level and percent change between 1961 and 2001. Some of the country figures for both regions appear implausible, including those for the Dominican Republic and Honduras. With this caveat, the data suggest that just under 13 million hectares of forest were cleared in the four decades, over 15% of the region's already depleted 1961 forest cover. Forest conversion was most rapid in the first two decades, slowing toward the close of the millennium: forest cover decreased in 1961–1981 by 26%, accompanied by an increase in rural population density of 34%. In the latter two decades (1981–2000), reforestation appears in some countries (negative values in the deforestation column).

Again, notable country-level variation is evident. Patterns within Mexico resemble the larger South American nations. With such a large forest endowment, Mexico's rural population density was the lowest of all Central American/Caribbean nations. While Mexico harbored half the rural population of the region throughout the time period, it also claimed approximately three-fourths of the forests. Mexico's rural population grew by 39% from 1961 to 2001, slowing in the latter decades. At the same time, Mexico led the region in the absolute amount of deforestation, at 3.6 million hectares despite net afforestation of 7.6 million hectare from 1981 to

2000. The much smaller country of Nicaragua lost nearly the amount of forest as Mexico during the same four decades, with 51% of its forest cover eliminated.

Among the countries of highest population density, Guatemala and Costa Rica still retained millions of hectares of forests at period's end. These two countries are distinguished from Haiti and El Salvador, which had already cleared virtually all but a couple of hundred thousand hectares of forests by 1961. The former experienced both high absolute amounts of deforestation and high annual rates of loss during the observation period, as well as the greatest percentage expansion of both cropland and pastureland in the region by far. Conversely, Haiti and El Salvador, with high population density but scarce remaining forest reserves, cleared only a small fraction of woodland compared to Guatemala and Costa Rica, but lost a high percentage of the forests extant through the middle of the twentieth century. Thus, the countries with the greatest percentage of forest loss had the lowest absolute amount of forest cleared and the lowest amount of forest cleared per rural inhabitant. In these nations absolute deforestation has declined, and must continue in decline as only small forest stocks on less desirable potential agricultural land remain.

Land use and agricultural expansion Deforestation in Central America resulted from changes in rural land use in each country, viz. the area in agricultural land—the sum of cropland and land in pasture. The total unweighted mean percentage of the countries' land in agricultural use was quite high in Central America/Caribbean even in 1961 at 42 but it rose further to 54 by 2001. From 1961 to 2001, the amount of pastureland in Central America/Caribbean increased by 10 million hectares, or 10% of the total area in pasture in 1961 (see Table 3; Fig. 3). The more relevant unweighted average increase was 24%, with Mexico's modest increase of only 7% holding down the weighted mean figure. For the nine countries overall, land in pasture rose from an average of 24% of the total land area to 32%, based on unweighted data (Table 3; Fig. 3).

Pasture expansion was accompanied by a 16% overall increase in arable and permanently cropped land, corresponding to 5.8 million hectares. The (unweighted) mean country percentage of land in crops rose from 18 to 22, or by about one-fifth. Cropland expansion was more than twice as high in the latter two decades compared to the first two, suggesting increasing pressures on land to feed growing populations. As predicted, Haiti and the Dominican Republic, countries of high population density and little potentially arable land not under agricultural use in 1961, both experienced no increase in pastureland between 1961 and 2001. In contrast, Guatemala, which despite relatively high population density, still had ample forestland remaining in 1981, experienced rapid growth in pastureland and modest growth in cropland. Costa Rica's pastureland doubled, all of it in the first half of the period. The shock of the loss of forests stimulated Costa Rica to adopt strict controls over environmental losses starting in the 1980s, including the creation of many national parks and protected areas, resulting in virtually no further increase in agricultural area since 1981. In both countries, rapid rural population growth outpaced the expansion of agricultural land and, as a result, rural population density increased from 1.8 in both in 1961 to 3.2 and 3.7 persons per hectare of agricultural land in Costa Rica and

Guatemala, respectively. In countries of lower population density, pastureland either already represented a substantial proportion of national territory in 1961 (e.g., Mexico at nearly 40%), or growth in pasture area was vigorous (e.g., Panama and Nicaragua). With little possibility for further agricultural expansion in these countries, greater land intensification and/or out-migration is expected.

South America

Population and deforestation In contrast to Central America, in South America, earlier and greater rates of rural–urban migration and earlier fertility declines combined to result in an overall slight loss of rural population, by 3 million overall (a 6% decrease). At the same time, in the eight countries between 1961 and 2001, 6% of the region's forests was eliminated. The combination of the two resulted in rural population density falling steadily from 0.9 to 0.5 persons per hectare of agricultural land (Table 1). But this decline is mainly due to the reduction in population density in rural Brazil (1.4–0.5 persons per hectare), which exerts heavily on the weighted average. Unweighted figures suggest a more modest rate of decline of 19%, from 1.3 to 1.0 persons per ha. It is striking that the unweighted region means in South America and Central America/Caribbean were similar in 1961 (1.3 and 1.7, respectively), but became notably different by 2001 (1.0 and 2.5, respectively), due to divergent trends in both rural populations and land areas.

This huge decline in the weighted rural population density noted above is deceiving because of the rapid forest loss in the large Amazon forest stock in a single country, Brazil. Brazil accounted for about 37% of the regions' forest clearing during this time. Nevertheless, most countries in South America deforested much greater percentages of their forests than did Brazil, as reflected in Table 2 showing the overall unweighted loss for the region of 6% vs. 3% for Brazil. Nevertheless, the figures for Paraguay and Venezuela appear implausible.

Unlike Central America/Caribbean, forest conversion continued at a relatively steady pace during the 40-year period in South America, even though rural population levels and density declined slightly overall (Tables 1, 2). In terms of overall population-forest cover dynamics, two types of countries are evident in South America. With the second highest rural population density in the region, Ecuador cleared a full 43% of its forests between 1961 and 2001, leading the region, followed by Argentina, Chile, and Colombia.

Over the four decades, Brazil had the lowest *rate* of deforestation in Latin America (3%), while at the same time its rural population declined by 21% from 1961 to 2001; rural population density remained under 0.5 persons per hectare in 2001 (the second lowest in the entire Latin America region, after Argentina). But by losing over 19 million hectares, Brazil's area of forest loss, primarily in the Amazon basin, far exceeded that of any country not only in the region but in the world.

Land use and agricultural expansion A notable difference is evident in land use transitions between the two regions (Table 3). The mean unweighted percentage of land in agricultural use was lower in South America, as expected given the much lower population densities. In 1961, 30% of the land was in agricultural use (vs. 42% in Central America/Caribbean), rising to 39% by 2001 (compared to 54%). Unlike Central America/Caribbean, where both significant urbanization and international out-migration occurred more recently, urbanization was dominant in most of South America in earlier decades and frontier colonization of the Amazon basin was most striking from the 1960s through the 1980s. Thus, in South America, agricultural land ballooned during the 1960s and 1970s largely due to frontier colonization linked to rural–rural migration, but pastureland expanded most during the two most recent study decades. During the 1980s and 1990s, urbanization slowed, rural out-migration decreased, and international migration became an increasingly important migration flow. Neo-liberal economic policies, including a focus on export-led growth and free trade in the region starting around 1990, have contributed to a consolidation of farmland in the hands of large-scale export agriculturalists, thus slightly decreasing the amount of land in crops between 1981 and 2001 even as food production and population both increased.

A steady increase in pasture area explains much of the deforestation during the 40 years (with the exception of Argentina, where pasture already made up a large portion of the nation's land cover in 1961). The further increase in pasture area is likely due to several factors, including ample land availability and more rapidly rising urban demands for beef due to greater urbanization and higher economic growth and per capita incomes of urban dwellers. On the other hand, in three nations, rural populations declined, providing a more suitable environment for converting land to pasture rather than crops. Thus, even where rural populations did not rise and areas in crops stagnated, agricultural frontiers have still expanded as small farms on the colonization frontier (particularly in Brazil) have been abandoned and replaced by large cattle ranches (c.f., e.g., Hecht and Cockburn 1990; Walker and Moran 2000) and more recently, soy plantations (Fearnside 2007).

In the southern cone nations, an increase in fruits and vegetables to serve North American markets during the northern hemisphere winter in Chile and soybean expansion in Argentina were major factors in recent forest conversion (Grau et al. 2005). Pastureland decreased slightly and cropland grew in Argentina, while in Chile land in crops decreased as small farmers migrated to the booming economies of the cities and were replaced by intensive export agriculture, as happened in the US during the late 1800s and early 1900s. Tree plantations for paper, pulp, and construction materials—the result of growing consumer demand from developed countries rather than population growth—also contributed to this change. By 1995, Chile and Argentina had 1.6 and 0.8 million hectares, respectively, in sustainable tree plantations, but many hectares were being logged without reforestation (Cubbage et al. 1996).

Population and agricultural intensification

Central America/Caribbean

The mean percentage of land irrigated rose from about 5 to 10 in the region, while fertilizer use swelled nearly tenfold, as population density increased; both these figures are dominated by Mexico (Table 4). However, levels of intensification measured by fertilizer use and irrigation in 2001 do not appear closely linked to rural population density, but rather with per capita income. This trend persisted in the region despite the fact that the need for agricultural intensification is greater in densely populated, poorer countries. Thus, Mexico far exceeded other countries in the region in both fertilizer use and irrigation, and generally maintained its advantage over the period (though Costa Rica and the Dominican Republic were not far behind in irrigation by 2001), even though its rural population density is the lowest in the region. Mexico's intensification advantage includes a greater economy of scale, with higher levels of agricultural technologies, and proximity to the major US consumer market. Meanwhile, the poorest nations in the region, such as Haiti, Nicaragua and Honduras, show very little evidence of agricultural intensification.

In regards to potential links to changing population trends, countries with the largest (and smallest) increases in rural population density (see Table 1) are Guatemala, Costa Rica, and Honduras (Dominican Republic, El Salvador, and Mexico), while the countries with the biggest (and smallest) absolute increased in land areas irrigated over the 40-year period were Costa Rica, Mexico, and Guatemala (El Salvador, Honduras, and Panama). Looking at fertilizer use, the countries with the biggest increases over time were Mexico, Honduras, and Guatemala, while those with the smallest increases were El Salvador, Haiti, Nicaragua, and Panama, again, showing little relation. Data at a more disaggregated or local level are needed to better examine nuances in Central America in regards to population density and land intensification, such as at subnational, community, and farm household levels.

South America

As in Central America/Caribbean, fertilizer use appears largely exogenous to population density trends. Compared to Central America/Caribbean, South America has a lower population density but higher levels of use of both irrigation and fertilizer (Table 4). Second, with respect to fertilizer use, as in Central America/Caribbean, the countries with the highest *levels* of fertilizer use (Brazil, Argentina, and Colombia) are not generally the ones with the highest rural population densities (Colombia, Ecuador, and Bolivia). However, there is some indication that the two are linked with respect to irrigation, since the three countries with the highest use of irrigation are Chile, Ecuador, and Colombia. In the case of Ecuador and Colombia, perhaps rural population pressure was a factor in stimulating irrigation, though in Chile it was more likely due to the expansion of export agriculture on arid lands. Nevertheless, with the exception of Venezuela (for reasons indicated earlier regarding data quality concerns), the rank order of countries by rural population density and use of irrigation suggests some evidence of a link between the two.

There is evidently little relationship between change in rural population density and change in fertilizer use in the region. The countries with the highest (and lowest) increases in use of irrigation were Chile, Colombia, and Ecuador (Paraguay, Bolivia, and Argentina), while the countries with the largest (and smallest) increases in fertilizer use over the period 1961–2001 were Brazil, Argentina, and Chile (Bolivia, Paraguay). The countries with the largest increases in rural population density were Colombia, Ecuador, and Chile, with density falling in the other countries.

Discussion

The rapid conversion of the region's forests to agriculture has been especially evident in areas still rich in forests, such as South America's Amazon region and the lowland forests of Central America. Indeed, Latin America has lost more forests since 1990 than any other major world region (FAO 2005). While most of this forest clearing occurred in the Amazon region of South America, the world's highest *rates* of forest clearing among any major subregion were dominated by Central America/Caribbean nations. Thus, during the first half of the 1990s, Latin Americans deforested 5 times more forest per rural person than Africans and 40 times more than Asians (derived from data in FAO 1997). Furthermore, reforestation has been minimal in Latin America. Increases in agricultural output in Latin America have been mostly associated with the expansion of cultivated land, in contrast to other world regions. For example, global cereal output rose between 1961 and 1996 by 107% but the area harvested increased by only 10% (Bender and Smith 1997).

A key lesson in this study is the difficulty of identifying a signature Latin American population-land use nexus. The diversity of the region in demographic, agro-ecological, and institutional contexts calls for further integrated analyses. Despite salient country-level and temporal variability, some general patterns emerged relative to population and land use/land cover change during recent decades in Hispanic America. These will be discussed in conjunction with the evidence pertaining to the specific hypotheses presented at the beginning of the paper.

First, our results suggest that rural population densities in South America were already starting to decline in the latter half of the 40-year study period. The decline in rural population densities occurred in tandem with the opening up of new lands for agriculture in frontier areas (mainly forests), which greatly increased the absolute amount of land available for agriculture and the amount of forest cleared. These trends were also linked to declines in rural fertility and out-migration from rural areas by people searching for better economic opportunities in urban areas and frontier regions. Thus, the results for South America validate the hypothesis (H1a) of higher *absolute* areas of forest clearing in countries with large untapped forest areas and thereby low population density in the beginning of the study period in 1961: This is seen by comparing the absolute changes in forest cover between 1961 and 2001 (Table 2) for Argentina, Brazil, and Mexico with the changes for countries with smaller initial forest stocks. Note that rural populations declined in the first three countries, indicating that increases in rural population could not have in themselves played significant roles in the loss of forest stocks in South America (failing to support H1). However, even in countries such as Brazil where rural population density declined, demographic factors were still important drivers of agricultural extensification, if not as proximate causes then as underlying factors, in the initial forest clearing of the agricultural frontier through earlier rural–rural migration to the Amazon region.

In Central America/Caribbean, in contrast, the rural population continued to grow throughout the period in virtually all countries. Rural Central America was more densely populated than rural South America and that population density gap widened considerably over the 40 years: the connection between rural population growth (and rising density) and land use change was greater there (Hypothesis 1). In addition, the data for Central America/Caribbean support the hypothesis that a higher rural population density is followed by a smaller *rate* of forest clearing, since the initial stock of forests is so much smaller. In fact, hypotheses H1b and H1c receive support from both regions based on data in Table 2. Thus, comparing the values for the two largest countries, Brazil and Mexico, in both loss of forest cover in 1961–2001 and change in forest cover per person with the values for the other, smaller countries, we observe that those countries with little land in 1961 tend to have higher *rates* of forest loss but smaller absolute declines in forest area per rural person, and likely smaller increments in additional land per person. Regarding population and land relations *dynamically over time*, results indicate some support for a Malthusian hypothesis (H1) in Central America/Caribbean, where population densities were already high at the beginning of the study period, but little support for it in South America.

Hypothesis H2 is concerned with various ways of examining the relationships between changes in the rural population and agricultural intensification. Evidence is mixed. First, regarding the notion that greater population growth is linked to relatively larger increases in cropland relative to pasture land, the data at the region level (see Table 3) are unsupportive. Central America/Caribbean, with a mean growth in the rural population of 84%, has a smaller proportionate increase in cropland and a slightly higher increase in pasture area over the 1961–2001 period than South America, where the rural population decreased overall by a mean of 6%. In neither region does it appear that countries with higher rural population growth experienced relatively greater increases in cropland than pasture area. For example, Guatemala, Nicaragua, and Honduras, in that order, had the largest increases in rural populations, but it was the Dominican Republic, Nicaragua, and Mexico that had the most expansion in cropland compared to pasture land. Finally, in the discussion of the results above based on Table 4, it was noted that while there was no systematic relationship between rural population growth and increase in fertilizer use, some positive relationship did exist in both regions with respect to increased cropland under irrigation.

Overall in Latin America, agricultural extensification has continued unabated despite dwindling forest reserves and heightened concerns about conserving tropical forests and increased policy initiatives in many countries. Despite some support for the hypotheses, the results are ambiguous on the relationships between land intensification and rural population density between the two regions. It appears that the combination of greater urbanization as well as greater land availability, particularly in South America, is likely to be associated with continuing expansion of cattle ranching and large-scale export crops such as soy. In contrast, Central America/Caribbean, with its much higher population density and reduced possibilities of land extensification, is likely to have proportionately greater increase in subsistence cropland relative to pastureland and export agriculture in future decades. Evidently political and economic factors were of equal or superior importance to population in affecting land use outcomes during the latter half of the twentieth century in Latin America.

Conclusion

With continuing population growth, diminishing available land, and future intensification constraints, policies at all levels will be challenged to promote sustainable agriculture–population relationships in Latin America. Among the policy imperatives that may be usefully considered are the following: (1) help rural farmers intensify production through more technical assistance and credit targeted toward raising crops but not cattle; (2) improve the quality of and access to education and reproductive health and family planning services in rural areas; (3) increase off-farm employment opportunities, for rural farm families; (4) create or rejuvenate domestic agricultural research and extension as well as assistance to stimulate new crops and higher yields from existing crops; (5) conserve the precious remnant vestiges of tropical forest through charging much higher royalties for logging concessions, more rational and limited road building policies, developing low-impact forest extractive activities that maximize value-added to extractive resources, and (6) involve local populations much more in protecting conservation areas, including indigenous populations.

Considering the results in light of the theoretical constructs of population–environment relations, it appears that demographic processes (both Malthusian and Boserupian) have indeed been implicated in deforestation. However, this relation is particularly powerful in frontier settlements and is more attenuated in regards to large-scale export agricultural land use which is more dependent on international urban consumption than population size or change per se. The “extended theory of the multiphasic response” (ETMM) may be a particularly useful theoretical approach for future analysis of population and land use dynamics as response to changes in land management (extensification and intensification) and demographic behavior (fertility and migration). Previous attempts to use this approach to explore relationships at the level of continents (Bilsborrow 1987) or countries (Carr and Bilsborrow 2001; Carr et al. 2006a, b, c) all used shorter time scales and less data. Further work could fruitfully expand on ETMM by examining migration and fertility, as these are two key demographic options not explored here in our conceptual framework (see Fig. 1) but are intimately related to land cover change as well as human and economic development.

Since the theory is inherently household-based, empirical studies are needed based upon detailed longitudinal data for households. While in-migration is the major proximate demographic process driving agricultural conversion, areas of rapid agricultural expansion also tend to have high fertility and therefore high natural population growth (Carr 2004). Population growth has attended both agricultural extensification and intensification, but only local case studies can better reveal where one has occurred more than the other (Carr 2002; also see Turner et al. 1977, for a cross-local analysis), though extensification will typify areas of low population density and low market integration while intensification will tend to occur more in quite opposite locales. Our observation of an effect of economic development on fertilizer use also illustrates that multivariate analysis of changes over time in the agricultural indicators here is ultimately desirable to sort out major factors. Further, current approaches may be usefully contextualized within political, economic, and ecological processes at multiple scales of analysis (Hecht et al. 2006; Geist and Lambin 2001; De Sherbinin et al. 2007). Political and economic processes underlie population pressures and resource inequalities that foment deforestation and unsustainable land uses.

Although continued research is necessary to discover under what conditions and at which spatial scales demographic or other socio-economic and political forces affect land use and land cover change, a priority of population–environment research must be recently settled frontiers if intimate population-LUCC dynamics is of concern. Despite recent efforts, a dearth of studies exists on land use in the remotest of the world’s settlements notwithstanding the fact that a disproportionate amount of forest conversion occurs there. In the frontier context, research is particularly needed to tease out the effects of fertility and household life cycles on *farm land use* and to connect these to larger-scale processes. Such research will surely test the orthodoxy of population density leading to agricultural intensification since most such studies are set in traditional peasant villages or in contemporary, population-dense rural regions, rather than in frontier environments characterized by land abundance and labor scarcity. Lastly, since most forest conversion in the future will likely occur where human populations are small or currently nonexistent, researchers need to begin to explore the fundamental question of who is migrating to agricultural regions, from where, and why (Carr 2008a, 2009).

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