Proximate Population Factors and Deforestation in Tropical Agricultural Frontiers

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Forest conversion for agriculture expansion is the most salient signature of human occupation of the earth's land surface. Although population growth and deforestation are significantly associated at the global and regional scales, evidence for population links to deforestation at micro-scales—where people are actually clearing forests—is scant. Much of the planet's forest elimination is proceeding along tropical agricultural frontiers. This article examines the evolution of thought on population–environment theories relevant to deforestation in tropical agricultural frontiers. Four primary ways by which population dynamics interact with frontier forest conversion are examined: population density, fertility, and household demographic composition, and in-migration.

KEY WORDS: population; land use and land cover change (LUCC); agricultural frontier; tropical deforestation.

INTRODUCTION

The long legacy of forest conversion to agriculture represents the most expansive footprint of human habitation of the earth's surface (Myers, 1991; Parsons, 1994; Lambin, et al., 2003). During recent decades, the nations of the northern hemisphere have experienced reforestation while deforestation has continued (though at recently slower rates) in the tropics (Achard et al.,

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2002). This trend threatens the biological integrity of the richest biome on earth and, in some cases, the progress of rural development and the sustainability of food production (Bongaarts, 1996). A positive correlation between population growth and deforestation is widely recognized at the temporal and spatial macro-scales (i.e., over centuries and globally), but evidence for population links to deforestation at micro-scales (e.g., household and community levels), especially along agricultural–forest frontierswhere most deforestation occurs on the planet[1]—is scant. However, existing evidence suggests that, while population always acts in concert with other processes, and in many cases is not the primary immediate driver, demographic dynamics are crucial explanatory factors in the deforestation of the planet's tropics.

Population growth has long been singled out for its contribution in altering the face of the earth. In 1700 B.C., the Babylonian epic Atrahasis, forerunner of the Noah story of Genesis, recounts the great flood as a reaction by God to unbridled human population growth under whose pressure the earth was ''bellowing like a bull'' (Feen, 1996). The relation between population dynamics and landscape change was later debated by the Zoroastrians around 325 B.C., the Indian sage Kautilya in 300 B.C., and Aristotle (Petersen, 1972). But it is the parson Thomas Malthus who is often credited with developing the first comprehensive theory of population–environment relations.[2] Malthus (1873) predicted that population growth would lead to famine and an eventual population crash since, he noted, food production tends to increase only arithmetically whereas human populations tend to grow geometrically.

The implication for environmental change and poverty was profound. Malthus' assumption of constant technology and fixed land resources, coupled with his premise of unchanged farming techniques, meant that farmers would be unable to yield enhanced food production on land already in cultivation. Population increase would therefore lead to the incorporation into production of new lands of reduced quality.[3] Diminishing returns to land and labor as people would work harder to eke a living from increasingly unproductive lands would lead to mounting rural poverty (Ricardo, 1887).

A recent Malthusian formulation posits that societies become mired in a recursive cycle of high population growth and environmental degradation that results in continued human immiseration (including the inability to produce enough food consistently) and ecological desolation (including deforestation on marginal lands) (DasGupta, 1995). According to this view, the concentration of rural poverty and environmental degradation in the developing world can be framed within the demographic transition, in which fertility decline lags behind mortality decline during modernization until both fertility and mortality arrive at a dynamic equilibrium. Unlike the developed world, where fertility has largely dropped below replacement levels, in recent decades developing regions have progressed through a middle stage, characterized by high but falling birth rates and declining death rates, with the inevitable outcome of population expansion (Teitelbaum, 1975; Van de Walle and Knodel, 1980). While many urban areas in the developing world are at or near replacement fertility levels and evidence from agricultural settlements in the Amazon indicates rapidly falling fertility (Carr and Pan, 2002; McCracken et al., 2002), most frontier regions remain under high-fertility regimes with the recurrent outcome of population pressures on the land, environmental stress, and resource degradation.[4]

Consistent with the demographic transition, most of the developing world falls within Zelinsky's second stage of ''mobility transition,'' characterized by massive movements from the countryside to cities, and the colonization of a minority to rural marginal lands. As predicted by the mobility transition, rapid urbanization has swelled Latin America's cities while a more modest number of migrants have colonized frontier regions. Moreover, consistent with Zelinsky's theory, despite increasing international migration, all but a few million of the several hundred million persons migrating in the world each year do so internally (within the borders of their own country) (Brown & Lawson, 1985; United Nations, 2001). However, research on migration is weighted inversely to actual trends, with the vast majority dealing with immigration (mostly to the developed world). Further, of the academic work on internal migration in developing countries, almost all deals with rural–urban migration, most based upon survey data obtained only in destination areas. This despite the fact that a great deal of migration in developing countries is rural–rural, and this migration flow is directly linked to most of the planet's deforestation.

While rarely citing demographic transition theory explicitly, much of the land use/cover change (LUCC) literature accepts that population change and distribution is a significant driver of global deforestation (Houghton, 1991; Myers, 1991; Vanclay, 1993; Wibowo & Byron, 1999). For example, Mather et al. (1998) estimate that population explains approximately half of the variation in deforestation worldwide while Allen and Barnes (1985) consider it the primary cause of the planet's deforestation. Simlarly, in a review of over 150 case studies throughout the tropics, Geist and Lambdin (2001) found that three-quarters of the literature they surveyed identified population as an underlying or direct cause of deforestation—though always acting in concert with other factors.

Indeed, population's effects on the environment usually operate through a concatenation of interacting political, economic and ecological causes across different scales (Geist & Lambin, 2001; Turner et al., 2001). Population change can lead to various responses, including economic (modifying present resource capture or employment strategies or changing them all together), and demographic (fertility regulation through age of marriage, birth spacing, or migration, including temporary and permanent). Economic responses can have a direct impact on the environment; e.g., when a farmer decides to expand his farmland. Demographic responses will have a secondary effect; e.g., if migration and fertility patterns change labor availability and food demand in forest fringes. These various responses may occur simultaneously or "multiphasically" (Davis, 1963; Bilsborrow, 1987).

Spatial and temporal discontinuities can obfuscate links between population–environment interactions. For example, population change elsewhere can foment frontier deforestation through demand for forest and food products (Kaimowitz & Angelsen, 1998; Bilsborrow & Carr, 2001). Worldwide, as many as one-half of all deforestation cases involves demand for food, fuelwood or timber from distant populations to some degree, as documented in several research projects in Latin America, including Costa Rica (Rosero-Bixby & Palloni, 1998) and Mexico (Barbier & Burgess, 1996).

Some contemporary LUCC literature has framed the causes of tropical deforestation as underlying and proximate (Turner et al., 1993; Ojima et al., 1994; Geist & Lambin, 2001). Proximate causes are immediate factors, usually found locally—where LUCC is occurring—and having transpired in the recent past. Conversely, underlying causes tend to be further removed temporarily and geographically. From the research on tropical deforestation explicitly categorizing proximate causes, three essential types of forest conversion emerge: agricultural expansion, timber extraction, and infrastructure development. The first, often facilitated by the latter two, is by far the number one cause of deforestation on the planet (Houghton, 1994; Geist & Lambin, 2001; Achard et al., 2002). This is particularly the case in Latin America, where frontier deforestation increasingly encroaches on biodiversity-rich "protected" areas (Rudel & Roper, 1997; Carr & Bilsborrow, 2001). A necessary antecedent to this encroachment and subsequent forest conversion is the out-migration of rural households from origin areas to the frontier. The fact that much forest conversion annually is caused by large-scale ranchers and farmers does not refute this. Large farms in agricultural frontiers are usually formed only after consolidating lands opened first by small farm settlers. Ultimately, population change elsewhere in the form of out-migration (often from areas of high population density and unequal resource access) is a prerequisite (even when only initially) to frontier colonist deforestation. Some scholars have noted how population pressures in migration origin areas (from, for example, unequal distribution of land and other resources as well as from population increase from in-migration and fertility) can encourage frontier settlement (Moran, 1993; Wood & Perz, 1996; Barbier, 1997). However, this important point is relatively neglected in the literature.

This article examines population–environment theories and empirical studies relevant to in-migration and demographic processes following settlement, and the proximate population factors associated with deforestation along tropical agricultural frontiers.[5] While frontier migration and land use are caused by complex interactions among political, economic, ecological, and demographic processes, it is the latter category that is the focus of this paper. Despite regional variation, settler farmers appear to be key drivers of forest conversion along the primary frontier ''hot spots'' worldwide during recent decades (Houghton, 1994; Myers, 1994; Achard et al., 2002). Conversely, the deforestation effects of larger farmers are not as likely to be caused by proximate demographic processes but rather by changing demand for farm products from distal populations (although large frontier farms result indirectly from population effects, since they are usually formed from consolidating lands cleared by earlier small farm families). Specifically, four principal ways by which population can directly affect forest cover change on the frontier examined here are population density, fertility, and household demographic composition, and in-migration (see Figure 1).[6]

PROXIMATE DEMOGRAPHIC FACTORS AFFECTING SMALL FARMER LAND USE IN TROPICAL FOREST FRONTIERS

Population Density

Boserup (1965) altered the current of population–environment discourse by arguing that population growth may stimulate agricultural intensification (increasing production per unit of land), thereby suggesting that population growth can ultimately have a benign or possibly even a positive effect on forest cover. She theorized that as available arable land becomes scarce relative to labor, farmers may react to initial environmental degradation by adopting more labor-intensive techniques that take advantage of increased labor–land ratios (Boserup, 1965). Boserup's theory has been tested with positive results in places not fully integrated into market economies (see, e.g., Turner et al., 1977; Brush & Turner, 1987; Pingali & Binswanger, 1988). Turner et al. (1977) conducted a compelling test of

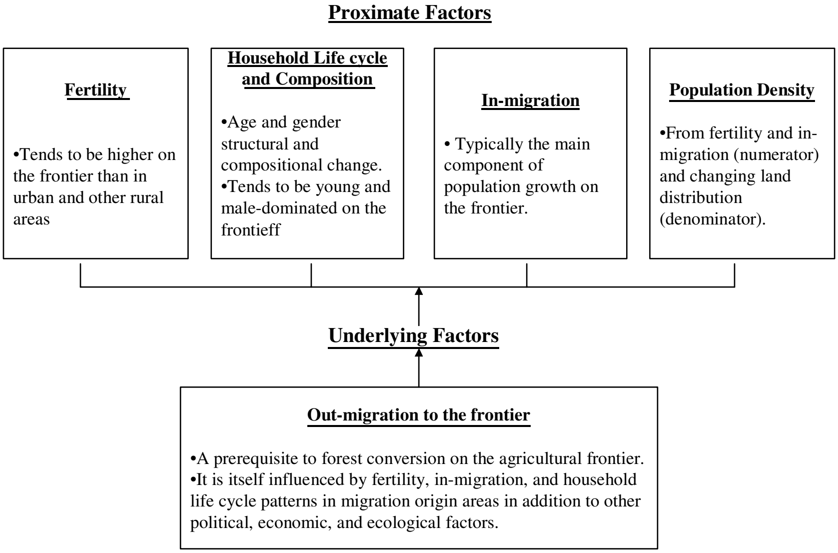

FIGURE 1. Proximate and underlying population factors relating to forest decline on the agriculture frontier.

Boserup's theory. A significant positive relationship was established between land availability and agricultural intensity in a sample of 29 tropical subsistence societies from around the globe. Nevertheless, the authors noted that since density accounted for only 58% of the variation in agricultural intensities, other factors also merited consideration.

Brush and Turner (1987) model of ''modified consumption'' takes other factors into account and considers demand for agricultural intensity as a function of not only population demand but also of biological, social, and market forces. Kinship, culture, taxes, ecological conditions, and market integration were thus posited as potential demands in addition to population pressure (Brush & Turner, 1987). Further, other intensification responses, such as the use of technologies and agricultural inputs (e.g., fertilizers, pesticides, and herbicides), were considered alternative responses to fallow intensification (shortening the fallow cycle).

Since Brush and Turner's (1987) work, and building on pioneering research on induced innovation (Binswanger & Ruttan, 1978; Pingali, et al., 1987),[7] a host of studies have indicated the importance of diverse spatial and temporal intensification responses to demographic and non-demographic demands, including the use of irrigation, farm machinery and agrochemicals (Nietschmann, 1979; Zimmerer, 1991, 1993; Netting et al., 1993; Behrens et al., 1994; Bilsborrow & Geores, 1994; Connelly, 1994; Krautkraemer, 1994; Schelhas, 1996; Turner & Ali, 1996; Ahmed & Sanders, 1998; Shriar, 2000).

As these studies invariably showed reduced pressure on the land due to raising yields per hectare, researchers working in humid tropical frontiers wondered if intensification might reduce tropical deforestation in such regions (Sanchez, 1994; Smith et al., 1995; Almeida et al., 1996; Uhl & Nepstad, 2000; Toniolo & Uhl, 1995). Yet the body of research on agricultural intensification generally presumes demand from population density or markets insufficient to compel farmers to intensify agriculture in a labor-scarce and land-abundant environment. Thus, the seminal theories of farmer response to population density are largely inapplicable to frontier environments. In such places, most forms of intensification represent an unnecessary labor burden, are uneconomical, inefficient, or too risky for small, semi-subsistence producers (Fearnside, 1993; Forster & Stanfield, 1993; Kaimowitz, 1995). Further, even when farmers possess the technical means and know-how for intensifying production, they may be constrained in implementing such technology due to local political–economic conditions (Jones, 1990).

Frontiers evolve concomitantly with rapidly changing population–environment dynamics. In the early (most forest-demanding) stages of frontier settlement, increased population density tends to induce continued agricultural *extensification* (farmland expansion). As the frontier evolves with increasing population density arising from in-migration, fertility and land consolidation, land fragmentation may lead to fallow compression and the application of inputs in order to take advantage of ascending labor to land ratios and waning forest reserves. Increasing market penetration in the developing frontier may also compel farmers with reasonable access to those markets to induce intensification (e.g., Brush & Turner, 1987; Goldman, 1993; Shriar, 2000). Researching when and where such responses might occur are keys to understanding the potential for land use changes and further forest clearing in settled areas as well as to understand forest clearing patterns in future frontiers.

Examples from the case study literature underscore the complexities of frontier farming that make application of intensification theories to frontier environments problematic. For example, Shriar's (2000) research on intensification adoption among 118 farmers in the buffer zone of Guatemala's Maya Biosphere Reserve indicated that smaller farms (therefore those on average with higher population density) intensified through intercropping, perhaps in response to population pressures on the land. Yet larger farms of low population density also intensified production but not through intercropping, which demands high labor, but rather through the application of herbicides in compensation for low labor supply (Shriar, 2001).

Fragile and informal terms of occupancy are characteristics of frontier environments and may further discourage intensification since rapid and widespread forest clearing signals *de facto* occupancy, rebuffing the intentions of potential squatters (e.g., Kaimowitz, 1995; Fearnside, 2001). Nevertheless, the link between land title and conservation is not straightforward. For example, Futemma and Brondízio (2003) found the land tenure–land use relation to be highly contingent on scale. They observed that at the settlement level, forest privatization led to increasing deforestation rates while at the farm level, intensification was a function primarily of labor, capital, and natural resource availability.

In contrast to the Boserupian theory, in any case studies from relatively developed frontiers in the Amazon, intensification has accompanied continued forest conversion (Pichón, 1997a, b; Angelsen & Kaimowitz, 2001; Cattaneo, 2001; Vosti et al., 2001; White et al., 2001; Perz, 2003). This trend is corroborated by the greater deforestation observed near roads (Sader et al., 1994; Chomitz & Gray, 1996; Pfaff, 1999). In several cases, this dual process appears to be driven at the farm level by relatively wealthy households who are the most able to afford intensification in the form of inputs, machinery, and hired labor, and who are also the most able to expand farm holdings (Pichón, 1997a, b). Perz (2003) recently conducted research on intensification determinants among 261 households along the Trans-Amazon highway. Consistent with the broader agricultural intensification literature, he found that households with more labor and capital were more likely to adopt modern technologies. However, those with the wherewithal to purchase technologies also cleared more land than non-adopters.

Much of the forest conversion of wealthier households is due to pasture demand from expanding cattle holdings. In these contexts, traditional agricultural intensification theory is turned on its head. As cattle ranches are usually larger than farms dedicated to semi-subsistence food production, *low* population density is associated with more deforestation. Consistent with Pichón (1997a, b) and Perz (2003), these (wealthier) households are more likely to intensify crop production than are non-adopters of cattle. For example, Carr (2002b) found that the most extensive farmers in a core conservation zone of the Maya Biosphere Reserve (MBR), those with cattle, also tended to intensify maize production through the use of inputs and the cropping of the nitrogen-fixing legume velvet bean (*Mucuna pruriens*). Similarly, frontier farmers in Sarapiquí, Costa Rica were slow to embrace perennials because of the high initial investment and long wait for returns. Thus the wealthiest, most expansive farmers, those with cattle, were much more likely to intensify through perennials such as black pepper (Schelhas, 1996).

Few generalities have emerged from the still emerging body of literature on frontier intensification. This heterogeneity of findings highlights the importance of temporal and spatial scale in examining the relation between population density and environmental change (Walsh et al., 1999; Carr, 2002a). The key questions that remain are who intensifies, where and when does intensification occur, and what kind of intensification (e.g., labor, land, means of production) will be adopted in certain places and at certain times.

A point of wide agreement in the literature is that frontier agricultural intensification and extensification processes will depend on a host of social, political, economic, and demographic, factors of which population density embodies only one. With regard to the effects of population density on deforestation, it is generally agreed that increases in the former may lead to some forms of intensification; but it will also be accompanied by continued agricultural expansion at the regional and farm scales. This trend helps explain why unabated deforestation rates at the national scale are associated with a *declining* national rural population in several nations of the Latin American tropics (Carr, 2002a, b). At the farm level, increased population densityinfluenced mainly by its denominator, land—will tend to be associated with more percent forest cleared but less absolute forest cleared. When holding land constant, the population effect on frontier forest conversion is one of household size and composition, the topics of the following two sections of this paper.

Fertility and Frontier Farm LUCC

Most of the rapid population growth characteristic of agricultural frontiers comes from in-migration. However, frontier migrants tend to have higher fertility than cohorts in origin areas (e.g., Weil, 1981; Rundquist & Brown, 1989; Murphy, et al., 1999). For example, total fertility rate (TFR) for settlers in the Ecuadorian Amazon (known as the ''Oriente'') in, 1990 was 8.0 children, twice the national rate (Murphy et al., 1999). This rate is comparable to those found in early stages of settlement in Brazilian and Peruvian frontiers, and considerably higher than urban and ''non-frontier'' rural fertility (Thapa & Bilsborrow, 1995). Evidence points to falling fertility on the frontier in the Brazilian Amazon (McCracken et al., 2002) and, more recently, in the Ecuadorian Amazon where Carr and Pan (2002) found that the TFR of settler families had plummeted from approximately 8.0 in 1990 to 5.0 in 1999 as most women wished to have no more children. With scant options for reproductive health, however, fertility in the Ecuadorian Amazon continues to exceed national and other regional averagesas consistent with more developed frontiers in Brazil (McCracken et al., 2002).

The cause of high frontier fertility would appear to be, in a general sense, predicated on the same factors governing family size in other contexts, low demand for and/or supply of contraception options (Leet, 1977; Tuladhar, et al., 1982; Robinson & Schutjer, 1984; Singh et al., 1985; Knodel et al., 1987; Lesthaeghe & Surkyn, 1988). Nevertheless, there are several points in the children supply and demand model specific to a frontier context worth mentioning here. First, in a frontier environment, investment in the land is inefficient relative to investments in labor and hence in reproduction (Caldwell & Caldwell, 1987). Moreover as access to health care is poor, mortality is high, inducing compensatory births to ensure child survival (Caldwell, 1976). Second, because of the insecure land tenure characteristic of frontier environments, children are perceived by some to compensate for land insecurity by providing income security to parents in their dotage (Stokes, 1984). Third, scarce wage–labor employment and schooling opportunities for women diminishes the opportunity cost of women's economic participation relative to that of child-rearing (Singh et al., 1985; Singh, 1994).[8] Finally, contraceptive options beyond the rhythm method are non-existent or incur prohibitive time, financial, or cultural costs (e.g., Henriques, 1988; Marquette, 1995; Pichón & Bilsborrow, 1999).

Household fertility has been linked to forest conversion on the frontier where larger families are associated with demand for subsistence crops for household consumption and labor demand for clearing land for crops. For example, in Costa Rica, deforestation was relatively low on farms with three to four children compared with farms of six or more children (Rosero-Bixby & Palloni, 1998). Similarly, regression analyses from surveys collected from settler households in the Ecuadorian Oriente, (Rudel & Horowitz, 1993; Pichón, 1997a, b) and Guatemala's Petén (Carr, 2002b) found household size to be negatively associated with land in forest. This relation can become reversed, however, with the introduction of cattle, which often follows the initial clearing of land for annuals (usually by relatively wealthier families). Cattle require less labor input over time (the reverse of crops) and thus may reduce demand for household farm labor. Yet they have a much greater demand on forest conversion than do crops. As explained in the following section, cattle adoption is also a function of the household lifecycle.

Household size also relates indirectly to forest conversion in that has been found to be positively linked to farm size (which not surprisingly is highly positively correlated with forest cleared on the farm; see e.g., Pichón, 1997a,b; Carr, 2002b). Two main arguments explain this relation: (1) the demand for labor to take advantage of the resources available on a large farm on the one hand, and (2) the desire to expand farm size to accommodate a growing family on the other (Chayanov, 1986; Binswanger & Mc Intire, 1987; Clay & Johnson, 1992; Ellis, 1993). Perhaps the most striking study positively relating fertility and farm size was the Philippine Rural Survey of 1952 (Hawley, 1955), in which average total fertility was much higher on farms over 4 ha (a mean of 7.0) compared to those under 1 ha (mean of 4.8). Stokes et al. (1986) cite more recent evidence supporting this relation from among the diverse environments of Bangladesh, Philippines, India, Latin America, Mexico, and Brazil (see also, Merrick, 1978). Since most of these studies were conducted in long-settled agricultural areas of relatively high population density, one must be cautious in extending their application to environments of relatively great land availability (Cain, 1984). Further, a host of other studies find insignificant differences in family size relative to resource access (Firebaugh, 1982; Tuladhar et al., 1982; Nagarajan & Krishnamoorthy, 1992). And there are several critiques of the relationship between resource access and fertility. First, a larger farm may lead to high fertility not because more children help to fill an increased labor demand but rather because a large farm allows for greater resource security and thus, for more surviving children (Clay & Johnson, 1992). Thus, the effect of resource access on fertility is hypothesized by some to be reversed when secure tenure of resources is established (Schutjer et al., 1981, 1983).

In sum, fertility, while trailing in-migration relative to its contribution to population growth on the frontier, remains notably higher than in urban and other rural regions. On the one hand, children are sometimes desired to contribute to farm labor, while on the other, more crops are sown to feed more children. However, even if families desire fewer children, the gross dearth of health care facilities and contraceptive options on the frontier disenable family planning desires. A further issue is that frontier areas tend to be composed largely of rural households which may not have been exposed to the more progressive values of the city and which justify high fertility based on traditional ethnic or religious beliefs. Land size and tenure appear to affect household size desires. Land tenure can effect labor allocations as it allows families to receive loans which usually changes land-use strategies toward a more market-oriented economy. When this means investments in cattle, fewer children are necessary for labor on the farm than if families invest in labor-intensive annuals. Some evidence indicates that families expand household size to take advantage of available resources such that families will have more children on larger farms. Nevertheless, a key critique of relations between land, land use, and fertility and household size is that these links inadequately take into account the effects of family age structure and life cycle features, as described in the following section.

Household Demographic Life Cycle and Frontier Farm LUCC

A relatively understudied aspect of population–environment relationships is the role of the family life cycle. Chayanovian theory (Chayanov, 1986; Thorner et al., 1986) represents a useful framework for analyzing the relation between household demographic factors and land clearing in an agricultural frontier. According to this perspective, the age and sex composition of households affects labor and, therefore, land use and forest conversion (e.g., Murphy et al., 1999). Whether household age structure or household wealth has a greater effect on farmer land use is still a question of debate (e.g., Grossman, 1998). Moreover, even if we accept that household effects are important, rigid divisions between subsistence and commodity farming need to be relaxed when applying Chayanovian theory to frontier farmers today. For example, Chayanov (1986) assumed that certain staple crops are irreplaceable to subsistence farmers, yet shifting a greater share of production to market crops is a common strategy among many frontier farmers today, especially as transportation infrastructure improves over time (Stewart, 1994). To the extent these crops require different labor inputs, family size preference and, ultimately, fertility, may be modified.

Despite considerable geographical variation, a general process of frontier evolution appears to recur throughout the Latin American tropics. The frontier settler family life cycle commences with migration to a new farm plot. Recent settler families tend to be young (with household heads and spouses usually in their, twenties and thirties) with a few small children. Risk aversion, limited frontier farming experience, and low capital and labor inputs initially encourage the primacy of cropping annuals. Forest clearing is greatest during the first several years of settlement as forest is initially cleared for the opening of the farm for the production of annuals and to demarcate farm occupancy in order to rebuff the intentions of potential squatters or absentee landowners. During early child-rearing years, families will face the greatest pressures to increase agricultural production on the demand side (Pichón, 1997a, b; Marquette, 1998).

As the household evolves, the increasing labor supply of maturing children and financial stability induces expansion into new farming efforts, including perennials and cattle (Stewart, 1994; Perz, 2001; McCracken et al., 2002; Walker et al., 2002). At this stage, larger households may be associated with decreased deforestation as available forest land is diminished on the farm and increased labor may encourage intensification. Conversely, smaller households may be encouraged to purchase cattle due to the low labor demands of maintaining pasture.

As children become adults, they may either out-migrate (permanently or temporarily), decreasing demand for crops for household consumption but possibly encouraging livestock adoption and or a transition into perennials as household labor decreases and household financial security increases through remittances; or they may remain, increasing incentives to intensify agricultural production (Findley, 1988; Laurian et al., 1998; McCracken et al., 2002). This latter response may be further encouraged by increased capital accumulation (Brondizio et al., 2002).

Among second-generation frontier households, Laurian et al. (1998) found that cattle retained potential migrants while an orientation towards crops led to migration. This may be counterintuitive from a labor perspective since crops are more labor-demanding than cattle (although pasture maintenance is quite labor-demanding especially when recently sown grasses compete with invasive weeds). Nevertheless, cattle is usually associated with ample land ownership and is therefore a good proxy for socioeconomic status on the frontier. Here again, however, scale is important since even though at the farm level more cattle may retain second- and third- generation children, the consolidation of lands associated with cattle ranching at the community and regional levels will tend to serve as a migration push among households whose lands have been consolidated (Laurian et al., 1998).

In conclusion, although fertility and family size in themselves can affect household net labor allocation and consumption patterns, and thus land use and forest clearing, household demographic composition and life cycle effects appear to be equally, if not more important. Very young children contribute little to household labor or consumption while grown children contribute in widely diverse ways, whether through labor on the farm or labor allocated elsewhere which augments capital investments on the farm. Forest clearing on the farm occurs in pulses rather than continuously. Understanding the frontier family life cycle helps explain when and how these will occur, for example, initially following settlement for opening land to produce subsistence crops, and later to expand into cattle or market-oriented crops.

Of course, external changes affecting a frontier region, or period effects, makes the experience of different cohort groups (based on time of arrival on the frontier) unique and independent of the age-structure patterns described above. A large sample size, distributed across cohorts is necessary to tease apart period, age, and cohort effects (e.g., Brondizio et al., 2002; McCracken et al., 2002). Nevertheless before we can examine the effects of population density, fertility and household size, and household compositional and life cycle effects, families have to migrate to the frontier in the first place, the last population effect on deforestation examined here.

Frontier in-migration and LUCC

In addition to promoting young and large households, resource abundance and labor scarcity characteristic of a frontier environment encourage in-migration, the main source of population growth in agricultural frontiers (Lutz, 1996; Geist & Lambin, 2001). In-migration is a prerequisite to frontier forest conversion. It proves to remain a key process in the future since the potential for most future deforestation will be not on lands already settled but rather on lands yet to be occupied beyond the forest fringe. The population most at risk for settling in these lands will likely be the second and third generation of frontier colonists whose comparative economic advantage is skill in frontier farming and whose comparative disadvantage is competing with laborers with different sets of skills in urban and international environments.

Whereas household size and composition have direct impacts at the farm level, the direct effects of colonization on LUCC are mainly at the community and regional levels. The proximate or direct impact of migration at the farm level occurs only in the minority of cases when migrants settle on already established farms (rather than clearing forest to create new ones). Examples of rapid forest conversion at the regional scale following colonization are abundant in the deforestation literature.[9] Some selected examples of this phenomenon include: the Ecuadorian Oriente, where population grew at annual rates exceeding 6% through the 1970s and, 1980s—more than double the national average as agricultural colonists claimed over one-third of the Ecuadorian Amazon region (Southgate et al., 1991; Pichón & Bilsborrow, 1999); the Brazilian Amazon where deforestation (low in percentage terms but the highest in the world in absolute amount deforested) was closely linked to levels of in-migration (e.g., Wood et al., 1996); and Guatemala's Petén where half of the vast departments' forestland has been cleared since the 1970s by agricultural colonization (Valenzuela, 1996). Less is known about how, at the farm level, settlement on existing plots may affect forest conversion (Pan & Bilsborrow, 2004). Out-migration from the frontier (rural–rural and rural–urban) can also effect land cover change on the farm, in that it alters labor availability, initially decreasing it by the absence of household labor (Barbieri & Carr, unpublished data). However, if out-migrants send remittances to the origin household, labor can be replenished through hired farm workers.

To summarize, in-migration is the main cause of population growth on the frontier. Some of the characteristics of the frontier that promote high fertility, namely land availability and labor scarcity, also pull migrants from more population-dense, land-scarce regions. Yet the frontier migrant is relatively rare since he eschews better-paying and more diverse labor markets, superior public education, health care, and community infrastructure to live in a remote, disease-infested wilderness where growing crops with little to no public infrastructure or services, limited technology, and precarious environmental conditions. Perhaps counterintuitively, such migrants usually claim that they are better off than in their areas of origin (see, e.g., Murphy et al., 1999; Carr, 2002a, b); this highlights the overwhelming allure of the one thing the frontier offers over other destination alternatives: land. I have discussed some ways in which population variables can have a proximate effect on frontier forest conversion in the tropics. Fertility, age and gender structures, various components of the household life cycle, and rural–rural migration interact with political, economic, and ecological processes in the retreat of frontier forests. A considerable body of literature on population–environment dynamics has been amassed. Yet key questions remain unresolved theoretically and empirically. I now return to the theoretical discussion in the introduction to reconsider the Malthus versus Boserup debate in light of the evidence cited in this paper.

RECONCILING MALTHUS AND BOSERUP: SCALE, PLACE, AND FRONTIER LUCC

Several population–environment relations are theoretically cogent and empirically supported. Why then do researchers remain mired in unsettled Malthus versus Boserup debates? Complementary nuances of Malthusian and Boserupian arguments are belied by dualistic ''straw-man'' arguments. Contemporary human–environment discourse has sometimes dismissed Malthusian arguments as overly simplistic and as failing to account adequately for exploitative and unequal economic and institutional structures

(Lee, 1986). Although Malthus failed to take into account the tempering effect of technological advances (after all, technology changed little over a peasant family's reproductive life in Malthus' England of the early 1800s), undeniably the growth of human populations will, all variables held constant, augment human impacts on the landscape; irregardless of migration and mortality patterns, over time and at the global level, this growth will not occur unless women have at least two children, on average. When women have considerably more than two children, as is typical in frontier environments, more labor to invest on the farm and more mouths to feed will provide higher pressure on forest resources, without compensating mechanisms. Though fixed variables would be highly uncharacteristic of a complex open system, as is the relation between humans and the earth, data generally support a positive association between deforestation and population growth at the farm, national, and regional levels (as discussed above). Ricardo's corollary of diminishing returns has proved similarly portentous; farmland expansion has increasingly claimed climatically and edaphically challenged lands. Boserupian theory cannot refute this.

Nevertheless, Boserup clarified an added dimension in the debate. Except in the very poorest sub-regions of the world (e.g., sub-Saharan Africa), agricultural intensification has compensated for mounting population densities, enabling an increase in the food/person ratio during the latter half of the 20th century. This increase is, however, due mainly to the Green Revolution and fertilizer use, rather than to fallow intensification. Further, evidence from the developing world, including agricultural frontiers, has shown how population density can both induce agricultural intensification *and* environmental degradation.

Still, population effects on the frontier are complex, change over time and space, and appear to be more dependent on timing and location of migration, and cohort, age, and period effects than on sheer population size. For example, one common process during the middle and later stages of frontier development reverses the anticipated population growth–deforestation trend: settler out-migration following land consolidation by large farmers contributes to overall population decrease while deforestation may accelerate, particularly when the large farmers adopt cattle as has happened widely in Latin America (e.g., Hecht, 1983; Heckadon & McKay, 1984; Wood et al., 1996). Further, deforestation on the frontier occurs in pulses—not continuously—relating more to the frontier life cycle, such as initial settlement clearing and later clearing for conversion to pasture than to population growth *per se*.

Though they did not explicitly advance this theme, Malthus, Boserup, and their more contemporary legacies offer substantial insight to be applied to a root cause of migration to the rural frontier—a process that is driving LUCC to a far greater magnitude than *in situ* demographic processes. Research on farmer responses to population pressure and other demands, may further our understanding of frontier deforestation, not merely by examining where and why farmers are intensifying agriculture where they are currently, but rather by investigating where and why out-migration to the frontier may follow the exhaustion of (or take place in lieu of) intensification, off-farm labor, family planning, or other alternative responses (Davis, 1963; Bilsborrow & Carr, 2001).

Malthusian and Boserupian theories, nonetheless, incompletely apprehend key contemporary population–LUCC processes emerging at the human–forest penumbra. The great diversity of human systems inscribe landscape change on the face of the earth in widely varied signatures over time and across space (Rudel & Roper, 1997; Bilsborrow & Carr, 2001; Carr, 2002a). In many instances, changing the scale of analysis will reveal examples in which population growth declined yet deforestation accelerated (Hecht & Cockburn, 1989), population growth was accompanied by reforestation (Tiffen et al., 1994), or population growth was followed by a host of human–environment responses (Schelhas, 1996; Kalipeni, 1999).[10]

The role of the Malthus–Boserup debate in relation to frontier deforestation may be somewhat reconciled when temporal and spatial scales are given their due. Population growth has been associated with—and, again, evidence suggests that it has induced—both agricultural expansion and agricultural intensification. The former is more likely in areas of great land availability and scarce labor, the latter in more population-dense, market-oriented economies (Boserup, 1965; Brush & Turner, 1987). Within the frontier, the former is more likely at early and late stages of frontier settlement (during farm establishment and later if cattle is adopted), the latter as growing children contribute to labor on the farm and/or farm households respond to intensification demands from local markets or shrinking land availability (Brondizio et al., 2002; McCracken et al., 2002). Such research is not inconsistent with Boserup: her theory allows that population–land-use change interactions are reciprocal, i.e., that decreasing population density should lead to agricultural disintensification (Boserup, 1965).

Population dynamics are but one of several sets of factors determining human impacts on the environment (Carr, 2004). Yet population theories are incomplete when they fail to fully consider structural issues of inequitable resource access and accompanying policies. Political and economic factors are largely responsible for engendering the very population pressures and poverty that exacerbate environmental degradation in marginalized rural communities around the globe, that spawn movements of landless peasants to tropical frontiers, and that fan the destructive farming initiated at the frontier. Whether or not population growth induces agricultural intensification, off-farm employment, fertility reduction, or out-migration—on the frontier or elsewhere—will be related to a host of scale- and place-contingent economic, social, political, and ecological factors. Under these complex realities, Malthus is geographically relative, and Boserupian stages of land use are not so much evolutionary as circumstantial.

CONCLUSION

Malthusian, Boserupian, and other theories of population change must be examined within spatial and temporal contexts and in relation to political, economic, and ecological processes. The formulation of proximate and underlying causes is a positive step toward conceptualizing these nested causal links. When seen this way, demographic processes are among the essential drivers of frontier deforestation. In-migration is the major demographic factor behind frontier deforestation. However, frontier regions also tend to have extraordinarily high fertility, further encouraging forest conversion on the farm, and the formation of new farms on current (following farm fragmentation) and future (following out-migration) frontiers.

Current research on proximate population links to frontier forest conversion is limited to small fragmented case studies or to disconnected macro-scale studies, both of which generally suffer from inadequate demographic data. Research has been limited by estimations based on incongruous resolutions and measurements. Further, the scale of outcome variables are frequently not examined at commensurate scales as the hypothesized drivers; this is due to the commission of the ecological fallacy at the conceptual level or to data limitations at the empirical level.

Further investigation is necessary to understand under what conditions and at which spatial scales population or other socioeconomic and political inducements will lead to agricultural intensification and whether or not this intensification will accompany more or less forest clearing. Research could fruitfully be applied in *recently* settled frontiers where virtually none of the studies on frontier land use is actually conducted yet where a large proportion of forests are cleared and will continue to be cleared in the humid tropics.

More research is needed to better understand the effects on fertility and household life cycles on *in situ* frontier forest conversion and to link these to meso-and macro-scale processes. Theories of household formation and family size are still largely based on rural agrarian studies from traditional peasant societies, and not in dynamic, land-abundant, labor-scarce frontier environments. Investigations are needed to test to what extent theories of household labor and consumption demand contribute to family planning and birth spacing in such environments. The scarcity of child and maternal health care and contraception in remote rural villages surely contributes to the relatively high fertility of frontier environments. Since some evidence from rural Amazonia points to rapidly falling fertility, research could fruitfully probe what factors are contributing to this decline and how the frontier fertility transition differs from the western demographic transition of the, 19th century and the 21st century transition of the urban developing world.

Since migration is a prerequisite to frontier forest conversion, the potential for future deforestation lies not where farms already are but where they may yet be. Future research is needed to document both the distal, yet fundamental, link between migration and frontier deforestation (*out-migration* to the frontier from areas of origin), as well as the potential effects of migration *from* frontier farms on farm land use. Several intriguing questions emerge relating to the potential effect of out-migration on frontier farm LUCC. Who are the very small minority of the world's migrants who choose the frontier as their destination? To what extent are political–economic, demographic, ecological, and historical conditions spatially homogenous and to what degree are they place-specific? Moreover, following frontier settlement, how might potential out-migration flows *from* the frontier contribute to land-use processes there and in future agricultural frontiers? Our understanding of *future* frontier deforestation would be advanced considerably by understanding not only how farmers are managing land on frontier farms today, but also how and why out-migration to the frontier occurs in the first place. Pioneers of this *terra incognita* could blaze a potentially rich trail in further connecting demography and human–environment research.

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ENDNOTES

1. The proportion of global deforestation attributed to small farmers engaging in shifting cultivation ranges from low estimates of 45% (UNEP, 1992) and 60% (World Bank, 1991; Myers, 1992) to estimates ranging as high as 80% (Amelung & Diehl, 1992). Virtually all old-growth forests cleared by small farmers must be located along agricultural frontiers where such forests still remain.
2. He was influenced, not only by ancient philosophers, but also by more immediate predecessors, including Condorcet (1955), Smith (1863), and Ricardo (1887).
3. More recently, neo-Malthusian arguments (those based on the belief that improving people's standard of living is impossible without limiting population growth) remain predicated on the assumption of a fixed resource base and, therefore, of an ultimate ''carrying capacity'', the maximum number of people that an area can support given resource endowments, resource use, and consumption levels (Pimentel, 1998).
4. Nations of high population growth tend to be those which are experiencing a lagged fertility decline in response to recently, or currently, declining mortality rates (particularly infant and child rates) as theorized in late stage II or early stage III of the demographic transition (Teitelbaum, 1975; Van de Walle & Knodel, 1980).
5. I use ''frontier'' as an area that has ''experienced rapid increase in population and land appropriation…[and the] geographical boundary between 'directly productive' and 'usury-mercantile' capital…[that]…lasts as long as landed property does not consolidate.'' The frontier in this sense is not a fixed place but is ''a brief transitional process'' (Almeida, 1992).
6. The effect of adult mortality on forest cover change is less prominent than fertility in frontier environments where high in-migration and fertility more than compensates for relatively high adult mortality rates to yield a rapid net population growth rate. However, high infant mortality typical in such environments may be a factor encouraging high fertility.
7. Induced innovation theory posits that the adoption of intensification technologies is a result of scarcity in land and labor relative to capital.
8. Further, the increased education and literacy help women to acquire, and take advantage of, information about family planning facilities and contraceptives. A large literature exists on the topic (Bongaarts, 1978; Caldwell, 1980; United Nations, 1995).
9. This is particularly the case in Latin America where a host of studies document such processes (Hecht & Cockburn, 1989; Southgate, 1990; Moran, 1993; Schmink & Wood, 1993; Stonich, 1993; Browder, 1995; Pichón, 1997a, b; Rudel & Roper, 1997; Fearnside, 2001; Turner et al., 2001). The preponderance of cases from Latin America linked to agricultural colonization is contrasted by the literature form other world regions where colonization is sometimes not as important as timber extraction or farm expansion in Asia and Africa: (Smil, 1983; French, 1986; Cruz, 1992; Kummer, 1992; Barbier, 1993; Brechin, et al., 1993; Jarosz, 1993; Kummer & Turner, 1994; Panayotou & Sungsuwan 1994; Paulson, 1994; Sussman et al., 1994; Angelsen, 1995; Shapiro, 1995; Brookfield et al., 1996; Mertens & Lambdin, 1997; Fairi-lead & Leach, 1998; Indrabudi et al., 1998; Cropper et al., 1999; Kalipeni, 1999; Dak & Wessman, 2000).
10. Such relationships were recently described in detail by Carr (2002a, b).

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