AN EMPIRICAL EXPLORATION OF THE POPULATION-ENVIRONMENT NEXUS IN INDIA

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This article presents an empirical study of population growth and environmental change using cross-section district-level data from South, Central, and West India. Environmental change is measured using a satellite-based vegetation index. Unlike prior work, the analysis treats population growth and environmental change as jointly determined, distinguishes between rural and urban populations, and distinguishes between two components of population growth, natural growth and migration. Among key findings are that environmental decline spurs rural population growth and net rural in-migration, which prompt further environmental decline; environmental improvement spurs urban population growth and net urban in-migration; and environmental scarcity spurs environmental improvement.

Key words: environmental degradation, population growth, satellite data.

Links between population growth and the environment are debated in many realms of social science. In the long run, opposing views of "Malthusians" (Meadows 1972; Ehrlich, Ehrlich, and Daily 1993) and "Boserupians" (Boserup 1965; Simon 1996) conjecture, alternately, that unchecked population growth will ultimately lead to a complete collapse of the natural environment or, in contrast, that the combination of population growth and natural resource scarcity will spur innovation that conserves natural resources and increases the material services that the resources deliver.

However, there appears to be general agreement that population growth and the natural environment both affect one another (Dasgupta 1995). Population growth can increase the exploitation of open-access environmental resources (Brander and Taylor 1998). In turn, environmental deterioration can increase rural families' demand for children to manage livestock or to fetch water and fuelwood (Nerlove 1991; Dasgupta 1995) or, by worsening individual and public health (and thus raising child and adult mortality), to provide economic support to the household (Rosenzweig and Stark 1997). Fusing these forces is a "vicious cycle" theory—modern Malthusianism—that conjectures a reinforcing downward spiral wherein population growth depletes the environment, spurring yet more population growth, and so on.[1] Intermediating forces may operate to break or lessen this cycle, including rural out-migration and/or government and community action to stem environmental decline.

In this article, we test for these bi-directional links between population growth and environmental change using cross-section district-level data from South, West, and Central India. In doing so, we account for the joint determination of population and environmental change; distinguish between rural and urban populations that can affect the environment—and be affected by it—in different ways; and distinguish between two components of population growth, natural growth (births minus deaths) and migration. To measure environmental health, we use two satellite-based (remote-sensing) indices, one an index of overall vegetation (or "greenness") and the other a measure of the proportion of land that has a high level of "greenness." The former index incorporates both forest biomass and impacts of soil productivity on cropland vegetation, while the latter is constructed as a measure of forest

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[1] Modern formalizations of the Malthusian hypothesis and its implications for the environment are studied in Brander and Taylor (1998), and Reuveny and Decker (2000).

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cover. Both indices are measures of *rural* environmental health that are correlated with fuelwood availability, water and soil resources, and "amenities" such as scenery and wildlife.

Distinguishing between rural and urban population growth is important for a number of reasons. While rural populations *produce* goods from natural resources (including food, water, and fuel), urban populations *demand* these goods. Urban population growth, by fueling increased demand for rural products, can spur increased depletion of open-access natural resources. Rural population growth can fuel extraction of open-access resources due to effects on both the demand side *and* the supply side (increased availability of extractive labor). Hence, there are reasons to expect rural (vs. urban) population growth to have larger negative effects on the rural environment.

In the opposite direction—environmental effects on fertility—household production theory generally implies a *negative* relationship between environmental health and the *rural* demand for children (Nerlove 1991; Dasgupta 1995). However, in *urban* households, environmental amenities and children can be complements in consumption (the "demand side" of fertility), and a better environment can lower costs of food, wood, and water that are borne in the support of children (the "supply side" of fertility). Hence, a better environment can be expected to *increase* urban fertility.

Environmental improvement can have competing effects on incentives for rural-to-urban migration. A better environment can not only increase the productivity of rural labor in resource extraction, but also lead to an increased supply—and hence, lower prices—of the goods derived from these activities. While increased rural labor productivity will dampen incentives for rural out-migration, lower prices of "environmental goods" will raise them. If the latter price effects dominate, then rather than operating to mitigate the "vicious cycle" of environmental degradation, migration will tend to reinforce it: environmental deterioration will dampen incentives for rural out-migration, fueling further environmental decline.

These arguments—which we formalize using a simple conceptual model—imply several hypotheses that we test using data from 178 districts in India over the period 1991–4. The data include birth and death numbers, overall population growth rates, average per-capita consumption expenditures, and a variety of other socioeconomic indicators, all by sector (rural and urban). We estimate a simultaneous equation model for five endogenous outcomes, natural growth rates (births less deaths, rural and urban), in-migration (rural and urban), and the change in "greenness." We are most interested in how the environmental measures (the endogenous change, and the lagged level) affect the population decisions (natural growth and migration, rural and urban), and how the population growth rates (rural and urban) affect the measured environmental change.

Our article builds upon a rather large literature on how population growth affects environmental health, as generally measured by forest stocks.[2] Few studies distinguish effects of rural and urban population pressure or of natural growth and migration.[3] And, to our knowledge, none treats population growth as endogenous. A smaller literature considers environmental effects on population growth, documenting the importance of the environment as a determinant of birth rates in developing countries and the distinct effects of environmental health on birth rates and migration as components of regional population growth.[4]

Theory and Hypotheses

We begin with an illustrative conceptual model.[5] The model focuses on several key attributes of the environment-population nexus in developing countries such as India. While it abstracts from private ownership, endogenous property rights, and dynamics (for example), it captures the heavy dependence of rural households on open access forestlands and common property resources (CPR) that characterizes our study region. Based on survey

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[2] Cross-national studies include Cropper and Griffiths (1994), Deacon (1994), and Ehrhardt-Martinez, Crenshaw, and Jenkins (2002). Within-nation cross-section studies focus on Brazil (Pfaff 1999), the Philippines (Kummer and Sham 1994), Uganda (Place and Otsuka 2000), Cambodia and Lao PDR (Dasgupta et al. 2003), Ecuador (Southgate, Sierra, and Brown 1991), and China (Rozelle, Huang, and Zhang 1997). Three papers study panel data from Thailand (Panayotou and Sungsuwan 1994; Cropper, Griffiths, and Mani 1999) and India (Foster and Rosenzweig 2003). See Panayotou (2000) for further references. This literature identifies deleterious effects of population pressure on deforestation, with one exception (to our knowledge); Foster and Rosenzweig (2003) find a positive link between population and forest stocks.

[3] Cropper and Griffiths (1994) consider effects of rural population density, and Ehrhardt-Martinez, Crenshaw, and Jenkins (2002) consider rural-urban migration. Cropper, Griffiths, and Mani (1999) distinguish effects of agricultural (vs. nonagricultural) population density.

[4] For links between the environment and fertility, see Aggarwal, Netanyahu, and Romano (2001), Filmer and Pritchett (2002), and Loughran and Pritchett (1997). For environmental effects on migration, see Amacher et al. (1998) and Chopra and Gulati (1997).

[5] Our model builds generally on the household production literature (e.g., Renkow 1990; Singh, Squire, and Strauss 1986).

evidence (NSSO 1999), the ratio of CPR land-to-land privately owned by households is approximately 0.46 across our study region, and the average CPR land per household is 0.32 hectares.[6] Sixty-nine percent of rural households in the region have forests within reach or access to proximate CPR lands that are at least 0.1 hectare per household. The households use the common lands and forests for a variety of purposes. Approximately 67% use fuelwood and over 47% collect this wood from common lands, yielding collections of over 490 kilograms per household per year. Adding woodchips to this accounting almost doubles the collections. In addition, 20% of the households graze livestock on common lands. And in India overall, 23% of rural households use common water resources for irrigation, and 30% use them for livestock rearing. Many of these activities deplete the commons (Rao 1994).

In view of this evidence, we assume (for our model) that rural households use child and adult labor to exploit an open-access environmental resource in order to produce goods that are both consumed in the household and sold to the urban sector.[7] The households make decisions on child bearing and migration, as well as labor allocation and marketing, in view of anticipated environmental and market conditions. In doing so, they trade off benefits of children in household/resource-good production against costs of birthing and child maintenance; and they trade off benefits of migrant family labor in remittances against costs in lost adult labor in household production and leisure. More intensive rural household production comes at the cost of greater degradation in the environmental resource.

Formally, we consider a two-period model. In Period 2, a representative rural household obtains utility from environmental/forest products X_c, other (numeraire) goods Z, leisure Q, and children c_R,

$$(1) \qquad U^R(X_c, Q, c_R) + Z.$$

The number of children (c_R) and labor that migrates to the urban sector (m) are chosen in Period 1. Migrant labor earns an exogenous net wage in the urban sector in Period 2, w.[8] Children c_R are available for production of forest products X in Period 2, but also cost $v_{1R}c_R$ in Period 1 (in numeraire goods) and consume environmental/forest goods in the amount $v_{2R}c_R$ in Period 2. Forest goods are produced according to the function,

$$(2) \qquad X = X(E, L = l + c_R - m)$$

where l = total adult labor allocated to production and migration, and E = initial state of the environment/forest in Period 2.[9] Note that, consistent with evidence that markets for child labor in India are thin at best, child labor is assumed to be available only within the household. Out of production, the household markets X_m of forest products to the urban sector at price P (that households take as given). Consumption of X_c is:

$$(3) \qquad X_c = X(\cdot) - X_m - v_{2R}c_R.$$

Leisure satisfies the identity, $Q = \underline{L} - l$, where $\underline{L}$ is total available adult labor. Hence, in Period 2, rural households solve the problem:

$$(4) \qquad U^{R*}(E, c_R, m, P) = \max_{l, X_m} U^R(X(E, l - m + c_R) - X_m - v_{2R}c_R, \underline{L} - l) + PX_m + wm$$

which yields the optimal labor and marketed surplus decisions, $l^*(E, c_R, m, P)$ and $X_m^*(E, c_R, m, P)$. Normalizing v_{1R} to account for intertemporal discounting, the optimal $c_R^*(E, P)$ and $m^*(E,P)$ are chosen to solve

$$(5) \qquad \max_{c_R, m} U^{R0} = U^{R*}(\cdot) - v_{1R}c_R.$$

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[6] This figure excludes Rajasthan, where average CPR land per household is 4.77 hectares. The ratio of common (to private) property varies across our study States, from a low of 20.3% to a high of 92.3% . There are also differences in the nature of the lands (due to different agro-climatic conditions) and management regimes; for example, in the early 1990s, the proportion of public forestland in the Joint Forest Management program—which aims to vest communities with an ownership stake in public forests—ranged from 9% to 35% in our study States, averaging 20.5%. Despite these differences, all of the States have rural sectors that depend heavily on common lands.

[7] In India, urban households demand products from local rural forests and commons, as posited here. For example, the NSSO (1999) reports that, in sampled villages with over 5,000 population, 56% of households use fuelwood from the local rural environment; in our sample states, this figure varies from 29% (Kerala) to 73% (Karnataka).

[8] We abstract from an urban labor market that may have (*a*) an endogenous wage w that affects urban income Y and rural-urban migration incentives, and (*b*) urban child workers. Such a market could dampen both increases and decreases in incentives for rural out-migration (due to resulting changes in the urban wage), but are unlikely to alter directions of effect. Urban child workers would complicate the calculus for urban child bearing, but are also unlikely to alter the qualitative rural-urban links identified here.

[9] A number of studies document the importance of environmental factors for household production (see, for example, Kohlin and Amacher 2005).

Period 2 environmental change depends on the initial state of the environment E, the extraction X, and natural factors W (e.g., rainfall and temperature):

$$(6) \qquad \Delta E = f(E, X, W), \text{ where } \partial f / \partial X < 0.$$

Thus, rural production activities deplete the environmental resource.

In the urban sector, children and the state of the environment are consumption goods.[10] Formally, a representative urban household obtains utility from the environmental amenity (E), children (c_U), forest products (X_U), and other (numeraire) goods (Z),

$$(7) \qquad U^U(E, c_U, X_U) + Z.$$

Children c_U bear the numeraire cost $v1UcU$ in Period 1 and consume $v_{2U}c_U$ in forest goods in Period 2. With exogenous household income of Y, the time 2 urban choice problem is

$$(8) \qquad U^{U*}(E, c_U, P) = \max_{X_d} U^U(E, c_U, X_d - v_{2U}c_U) + Y - PX_d$$

which yields the demand for forest goods, $X_d^*(E, c_U, P)$. Stepping back to Period 1, children $c_U^*(E, P)$ are chosen to solve

$$(9) \qquad \max_{c_U} U^{U*}(E, c_U, P) - v_{1U}c_U.$$

The market price for forest goods equates supply and demand:

$$(10) \qquad P(E, c_R, c_U, m) : X_m^*(E, c_R, m, P) = X_d^*(E, c_U, P)$$

where X_m^* and X_d^* are marketed supply and urban demand from equations (4) and (8).

Implicitly, we assume that local economic conditions have price effects in local markets for environmental goods.[11] For India, this premise is plausible for forest products that are costly to transport long distances and for which international trade is essentially nonexistent (Foster and Rosenzweig 2003). To a lesser extent, this premise is plausible for food products that are also costly to transport inter-regionally.

We are first interested in the effects of the population decisions (c_R, m, and c_U) on environmental change (ΔE). Sequentially substituting $P(\cdot)$ (from (10)) into $l^*(\cdot)$ (from (4)); the resulting $l^*(\cdot)$ into $X(\cdot)$ (from (2)); and the resulting $X(\cdot)$ into $f(\cdot)$ (from (6)), yields the reduced form for environmental change that we will seek to estimate:

$$(11) \qquad \Delta E = \Delta E(E, c_R, c_U, m, W).$$

Differentiating (11) gives us:[12]

Hypothesis 1. Higher rural birth rates and lower rates of rural out-migration lead to increased deterioration of open-access land and forest resources: $d\Delta E/dc_R < 0$ and $d\Delta E/dm > 0$.

Hypothesis 2. Higher urban birth rates lead to increased deterioration of open-access land and forest resources: $d\Delta E/dc_U < 0$.

Hypothesis 1 gives us a well-known implication of open-access resource models (Brander and Taylor 1998, Proposition 2). In our model, rural population growth (in the form of more children and less out-migration) increases the supply of rural labor available for household production of environmental/forest goods, thereby leading to more resource exploitation in equilibrium. Greater urban population growth raises the demand for the products from the rural environment, leading to a higher equilibrium price for these products and thereby spurring more (resource-degrading) rural production. We can test these hypotheses by estimating effects of rural and urban population growth rates on our measures of environmental change.

If forest resources are protected by property law, effects of population growth can be very different, with increased populations potentially spurring an increased equilibrium supply of these resources (Foster and Rosenzweig 2003). In testing Hypotheses 1 and 2, we will thus be distinguishing between dominance of open-access resource effects and potential impacts on private forest resources.

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[10] Urban households benefit from rural forests and open space, both for recreation and due to the families' rural roots.

[11] Although we assume that rural households are net suppliers of forest products to the urban sector, the analysis is robust to a setting in which rural households use these products only for their own (household) consumption and transient migrants (or others) collect the products for sale. In this case, there are two sets of rural residents, our households and another set of resource extractors who supply X_s^* (E, P); the market equilibrium then equates net supply, $X_s^* + X_m^*$ (where X_m^* may be negative) with the urban demand, X_d^*. Nothing in what follows is qualitatively altered by this change. We thank a referee for this observation.

[12] Derivation of results in this section are available in Bhattacharya and Innes (2008).

Equation (11) also implies effects of initial resource scarcity (the "state of the environment" E) on environmental change. In our simple model, a worsened environment reduces the productivity of exploitive activities and thereby spurs less of them. Additional forces may also be at work. As open-access environmental resources become increasingly scarce—and hence increasingly valuable and costly to exploit—governmental incentives to protect the resources grow, whether in terms of improved property law (Demsetz 1967; Libecap and Smith 2002) or increased enforcement of environmental protection laws. For privately owned environmental resources, scarcity spurs higher prices for environmental products and, hence, heightened incentives for the private supply of these resources. For all of these reasons, we have the Boserup/Simon conjecture:

Hypothesis 3. Poorer environmental health will promote environmental improvement: $d\Delta E/dE < 0$.

Next we are interested in the effects of first period environmental change (as captured by the end-of-period environmental stock, E) on the three population decisions, c_U, c_R, and m. Formally, substituting $P(\cdot)$ (from (10)) into $c_R^*(\cdot)$, $c_U^*(\cdot)$ and $m^*(\cdot)$ (defined in equations (5) and (9)), and solving simultaneously yields:

$$(12) \quad c_R = c_R^{**}(E), \quad c_U = c_U^{**}(E),$$
$$m = m^{**}(E).$$

In (12), E equals the initial environmental stock, E_0, plus its Period 1 change, ΔE_1.

The effects of environmental improvement on population decisions can be decomposed into (1) direct effects and (2) indirect effects, due to impacts on the price of environmental/forest goods P. For the rural sector, these two effects are competing. On one hand, a better environment can directly raise the marginal product of child and adult labor in household resource extraction, thus increasing the demand for children and reducing incentives for out-migration. However, a better environment also enables more rural production, which in turn depresses the equilibrium price for the product sold by rural households. The lower output price in turn depresses the demand for child and adult labor in household production. The latter price effects will dominate if environmental improvement has a small effect on marginal labor productivity, as implied by the prevailing view that children are substitutes for natural resource health in household production (e.g., Nerlove 1991). In this case, we have:

Hypothesis 4. Environmental improvement (*a*) reduces the rural demand for children and (*b*) raises incentives for rural out-migration: $dc_R^{**}/dE < 0$ and $dm^{**}/dE > 0$.[13]

For urban households, we assume that environmental health and children are complements in consumption; hence, an improved environment directly raises child demand. In addition, by lowering the equilibrium price of resource-based goods (including food and fuel), environmental improvement lowers the costs of child maintenance. Both effects favor more children.

Hypothesis 5. Environmental improvement raises the urban demand for children: $dc_U^{**}/dE > 0$.

The Empirical Model

We estimate a system of five simultaneous equations, one each for rural natural growth rates (births minus deaths, G_R), urban natural growth rates (G_U), net rural in-migration (M_R), net urban in-migration (M_U), and the change in our environmental/"greenness" index (ΔE):

$$(13) \quad G_R = \alpha_1 + \beta_1 \Delta E + \eta_1 E_0 + \gamma_1 X_P + \varepsilon_1$$

$$(14) \quad G_U = \alpha_2 + \beta_2 \Delta E + \eta_2 E_0 + \gamma_2 X_P + \varepsilon_2$$

$$(15) \quad M_R = \alpha_3 + \beta_3 \Delta E + \eta_3 E_0 + \gamma_3 X_P + \varepsilon_3$$

$$(16) \quad M_U = \alpha_4 + \beta_4 \Delta E + \eta_4 E_0 + \gamma_4 X_P + \varepsilon_4$$

$$(17) \quad \Delta E = \alpha_5 + \delta_1 G_R + \delta_2 M_R + \delta_3 G_U + \delta_4 M_U + \eta_5 E_0 + \gamma_5 X_E + \varepsilon_5$$

where all endogenous variables are measured over our 1991–4 sample period, and the exogenous X variables (X_P and X_E) and

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[13] There are other mechanisms for Hypothesis 4. An improved environment, by improving child and adult health and productivity, can reduce the demand for children as social insurance and raise the time costs of children (Dasgupta 1995). Potentially confounding Hypothesis 4 are incentives for interdistrict migration that are missed in our simple conceptual model. With such opportunities, resource scarcity can spur distress out-migration (Chopra and Gulati 1997), and environmental gains may attract new migrants (Amacher et al. 1998).

environmental state (E_0) are in initial (1991) levels.[14] Note that our dependent variables represent changes in environmental indicators and population aggregates, thus controlling for unobserved heterogeneity that drives levels.

Natural growth and migration equations. Equations (13)–(16) give empirical counterparts to equation (12), where birth and migration rates depend upon the expected trajectory of environmental quality (future E). We measure this expected trajectory with three regressors: the jointly endogenous contemporaneous environmental change (ΔE), the initial (1991) environmental state (E_0), and environmental change over the prior five years (1986–90). Our theoretical hypotheses imply negative effects of environmental health on both rural birth rates and rates of rural in-migration ($\beta_1 < 0$, $\eta_1 < 0$, $\beta_3 < 0$, $\eta_3 < 0$), and positive effects on both urban birth rates and urban in-migration ($\beta_2 > 0$, $\eta_2 > 0$, $\beta_4 > 0$, $\eta_4 > 0$).

Beyond impacts of the environment, birth and migration rates are influenced by socioeconomic factors left in the background in our theoretical model. These factors include income, literacy, health services, social norms, and religious beliefs (Dasgupta 1995; Rosenzweig and Stark 1997; Martine, Dasgupta, and Chen 1998). To control for these effects, we have explanatory data on per-capita consumption expenditure; female, male and total literacy; female workforce participation; average household size; the sex (female-to-male) ratio; the tribal population proportion and the religious makeup of the population. Because Hindus and Muslims represent over 95% of the Indian population, we use the Muslim population share as our indicator of a district's religious composition. We include three measures of health status: infant death rates, overall population death rates, and life expectancy at birth, all measured at the start of the study period (1991). Potential congestion effects are captured by including population density. All of these explanatory variables are specific to the rural/urban sector of a district. In addition, Dasgupta (1995) observes that the extent of urbanization may affect the outward orientation of a district's population, which may affect birth rates (as well as attitudes toward the environment). We therefore include a district's urban population share. Due to potential rural-urban spillovers, we include all urban regressors in the rural population equations, and vice versa. Finally, the extent of agricultural cultivation may affect economic opportunities, the supply of common lands in rural areas, and hence, rural natural growth and migration rates. We therefore include the district's 1991 percentage net sown area (NSA).

The environment equation. Equation (17) gives the empirical counterpart to equation (11). Equation (11) implies that environmental change is determined in part by the rural availability of child and adult labor for resource-based household production, and urban population growth that drives the demand for rural products. Rural household labor availability depends, in turn, on birth, death, and migration rates, as well as demographic determinants of labor allocations (such as household size, sex ratio, and health status).[15] Our theoretical hypotheses imply negative effects of rural and urban population growth on environmental change ($\delta_i < 0, i = 1, \ldots, 4$), and a positive effect of environmental scarcity—for which the initial environmental state (E_0) is an inverse measure—on environmental improvement ($\eta_5 < 0$).

Other socioeconomic indicators can be important drivers of environmental change, including predetermined (1991) population densities, literacy (that may promote environmental awareness), the urban population share (a measure of "openness"), per- capita consumption expenditures (our income proxy), and the tribal population share. Tribal populations are widely regarded as resource conserving. Rural and urban incomes affect the demand for environmental amenities and products, while rural incomes may also affect rural households' net benefits from the exploitation of open-access resources and their reliance on more environmentally depleting livestock and agricultural production practices. Finally, there are important natural and climatic factors at work. To control for natural processes, we use data on rainfall, temperature, elevation, and prior environmental change (1986–90).

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[14] As in equation (12), the first four (population) equations contain no mutual interactions, but rather only the jointly endogenous environmental change on the right-hand side. Hence, taking these four equations as a unit, we estimate a "quasi"-reduced-form model. We do not aggregate natural growth and migration (into a net population growth variable) because the two components have different structures (both in theory and in our estimations).

[15] For example, lower rural sex ratios and higher rural female workforce participation rates are indicators of the availability of female labor that is traditionally used for resource-gathering activities.

Data

We have district-level data from eight states of the southern (Andhra Pradesh, Tamil Nadu, Karnataka, Kerala), western (Maharashtra, Gujarat, Rajasthan), and central (Madhya Pradesh) regions of India for the 1991–4 period. Adjusting for district redefinitions and missing data, and excluding one all-rural and three all-urban districts, gives us a sample size of 178 districts. Table 1 describes the variables that we use, and table 2 provides sample statistics. In our data, urban (vs. rural) areas are defined, as per the census of India, as (*a*) all places within a defined municipality, and (*b*) all other places that have a minimum population of 5,000, at least 75% of the male working population engaged in nonagricultural pursuits, and a population density of at least 400 persons per square kilometer.

In our sample, district-level rural natural growth rates (births minus deaths) average 2.8% of 1991 populations over the four-year period 1991–94. Corresponding urban natural growth rates are much higher, averaging 10% of 1991 populations. However, there is a great deal of cross-district heterogeneity in these growth statistics. For example, rural population growth rates vary from 4.2% to over 16%. Population densities (1991) are also highly variable, averaging 220 people per square kilometer in rural areas and almost 3,000 people per square kilometer in urban areas. Our sample districts are predominantly rural, with an average rural population percentage of 75%. Incomes are substantially lower in rural areas than in urban areas, with average 1987 monthly consumption expenditures of approximately 383 rupees (US$9) per capita in rural areas and 562 rupees in urban areas. Urban areas also exhibit signs of greater development, with higher

Table 1. Variables Definitions

Demographic Variables (Classified by Rural (R) and Urban (U) areas)	
G_R, G_U	Natural population growth (1991 to 1994) per thousand 1991 population
M_R, M_U	Net in-migration (1991 to 1994) per thousand 1991 population
Environmental Variables	
ΔNDVI	Change in average NDVI from 1990–1 to 1994–5
Δ*z*-NDVI	Change in *z*-NDVI from 1990–1 to 1993–5
NDVI[a]	Average NDVI for 1990 and 1991
z-NDVI[a]	Average *z*-NDVI of NDVI for 1990 and 1991
LagΔNDVI	Change in average NDVI from 1986 to 1990
LagΔ*z*-NDVI	Change in *z*-NDVI of NDVI from 1986 to 1990
Rainfall	District-level computed average rainfall in centimeters (1991 to 1994)
Rain dev (+)	Sum of positive deviations in rainfall from historical average (1991 to 1994)
Rain dev (−)	Sum of negative deviations in rainfall from historical average (1991 to 1994)
Elevation	Average elevation of the district (meters)
Temperature	Average temperature during 1991–4 (centigrade)
Socioeconomic Variables (Classified by Rural (R) and Urban (U) areas)	
Popn dens	Population per square kilometer (1991)
Cons exp	Per household average monthly consumption expenditure in Rupees (1987–8)
Inf death	Infant deaths per thousand live births (1991)
Death rate	Deaths (1991) per thousand 1991 population
Life exp	Life expectancy at birth (1991)
AHS	Average Household Size (1991)
Fem lit	Literacy rate (%) in female population (1991)
Male lit	Literacy rate (%) in male population (1991)
Total lit	Literacy rate (%) in total population (1991)
Sex ratio	Females per thousand males (1991)
Fem work	Working-age females participating in the workforce % (1991)
Muslims	Muslim population percentage (1991)
Tribals	Tribal population percentage (1991)
Other Variables	
Urban popn	Urban population percentage (1991)
NSA	Proportion of district land area cultivated (1991)

[a] NDVI is the normalized difference vegetation index, a satellite-based measure of terrestrial vegetation. *z*-NDVI is an index measuring the extent to which a district has high NDVI land (see footnote 17).

Table 2. Sample Statistics

Variable	Mean	Std. Dev	Min	Max
Environmental Variables				
ΔNDVI	5.66	3.55	−4.15	28.62
NDVI	168.32	11.36	133.33	193.72
LagΔNDVI	4.51	3.47	−1.83	14.09
Δz-NDVI	0.48	0.35	−0.22	2.95
z-NDVI	−0.77	1.18	−7.99	1.25
LagΔz-NDVI	0.89	2.08	−2.78	13.89
Rainfall	107.97	80.63	19.42	343.21
Rain dev(+)	410.64	288.12	0	1101.24
Rain dev(−)	−228.25	140.61	−630.22	−43.74
Elevation	353.08	219.06	5.67	1,460.85
Temperature	26.36	1.04	23.45	29.16
NSA	0.52	0.16	0.05	0.83
Endogenous Demographic Change Variables				
G_R	27.62	24.72	−5.13	109.62
G_U	100.32	51.82	7.62	309.25
M_R	17.11	35.19	−95.84	161.85
M_U	−27.06	63.37	−236.81	247.67
Rural Socioeconomic Variables				
Cons exp	383.05	96.05	183.78	810.39
Popn dens	219.71	193.21	7	1,236
Death rate	4.48	2.34	0.48	11.24
Female lit	31.73	20.17	4.2	93.96
Male lit	59.40	15.24	20.53	97.39
Total lit	45.94	17.14	13.74	95.67
Sex ratio	958.55	56.78	786	1,230
Fem work	28.71	13.87	2.18	59.5
Tribals	13.28	17.89	0.04	91.14
Inf death	23.24	17.43	0.91	88.60
Hh size	5.44	0.69	3.74	7.07
Muslims	5.85	6.83	0.10	67.07
Life exp	60.49	7.06	39.5	74.9
Urban Socioeconomic Variables				
Cons exp	562.30	156.44	221.78	1,226.32
Popn dens	2,947.05	2,465.17	267.35	27,490.64
Death rate	5.75	2.23	0.21	15.45
Female lit	61.26	12.41	32.54	94.16
Male lit	82.11	6.47	66.87	97.66
Total lit	72.14	9.01	51.05	95.91
Sex ratio	929.75	75.71	764	1,685
Fem work	9.51	3.91	1.98	26.61
Tribals	3.29	4.17	0.01	28.02
Inf death	17.84	12.53	0.23	86.21
Hh size	5.38	0.58	4.12	7.47
Muslims	16.97	9.12	0.68	70.37
Life exp	67.22	6.98	47	87.1
Urban popn	24.74	13.18	4.73	79.97

Number of observations = 178.

literacy rates and lower infant death rates than their rural counterparts. Average household sizes are about 5.4 people in both urban and rural areas. However, female workforce participation is much higher in rural areas (averaging 28.7%) than in urban areas (at 9.5%). Climatically, districts in our sample are quite heterogeneous, with normal annual rainfall varying from less than one-third of a meter to 3.5 meters.

The environment. The satellite-based normalized difference vegetation index (NDVI) provides a measure of vegetation or "greenness" that is available throughout our study period. The NDVI is measured on a ten-day composite basis, at fine resolution (with each pixel eight square kilometers in size), and takes on values between zero and 256.

These remote-sensing data are used to construct two measures of the state of the environment. The first is the average district-level NDVI, a measure of overall vegetation (including crop cover). The second represents an index of forest cover, measuring the extent to which a district has "high NDVI" land—land in the top 20% of NDVI values.[16] We focus on the "top 20%" because, in 1995, approximately 19.1% of our study region was in forest, and in 1990–1, 21% of India was forested. To construct the "high NDVI" measure, we find the critical NDVI level such that approximately 20% of the study region's month-pixel NDVI values are higher than this level; we then construct a z-score, "z-NDVI," for each district that is monotonically related to the proportion of time pixels that are above this critical NDVI index value.[17] To obtain more precise measures of environmental change, we construct two-year average values for our indices at both the beginning and end of our 1991–94 study period, and take differences.[18]

Population. Our study is made possible by data recently released by the Registrar General's Office of India, revealing district-level births and deaths (total, rural, and urban), as well as birth rates and death rates (districtwide), for the four years 1991–94. Using these data, as well as district-level rural and urban population levels from the 1991 Census of India, we derive district-level birth rates (rural and urban), death rates (rural and urban), and net migration rates (rural and urban), for the four-year period 1991–1994, as fractions of relevant (rural and urban) 1991 district populations. Our calculated migration rates represent net district-level in-migration (rural and urban), as point-to-point migration numbers are not available.[19]

Rainfall, temperature and elevation. Annual rainfall data are available for meteorological subdivisions of India, each of which is defined according to climatic features and contains several districts. Because there are only 19 subdivisions—and "greener" districts are likely to have higher rainfall—we obtain approximations to district-level actual rainfall by combining subdivision rainfall and district-level NDVI data as follows:

$$Rain_{ij} = Rain_j * (NDVI_i/NDVI_j)$$

where $Rain_{ij}$ = "rainfall" for district i in subdivision j, $Rain_j$ = annualized 1991–4 rainfall of subdivision j, $NDVI_i$ = average NDVI level of district i for 1990–91, $NDVI_j$ = average $NDVI$ level of subdivision j for 1990–91. Average (1991–94) district temperatures and elevations are obtained from the International Research Institute for Climate and Society.

Income. District-level rural and urban average per-capita consumption expenditure data are available from the National Sample Survey Organization for 1987. Per-capita consumption expenditures are generally thought to be good indicators of permanent incomes.

Other socioeconomic data. Other socioeconomic data are obtained from Human Development Reports published by the National Council for Applied Economic Research (NCAER); reports of the International Institute for Population Sciences (IIPS); and the statistical web site, www.indiastat.com.

Identification Strategy

Table 3 describes the X_P and X_E exogenous variables included in the empirical model described in equations (13)–(17), revealing

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[16] Monthly composite images downloaded from NASA are reprojected into Geographic format and stacked to calculate pixel-level averages and standard deviations for one- or two-year timeframes. Using the political map of India, district-level NDVI averages and standard deviations are extracted from the pixel-level data. A substantial literature documents that the NDVI is highly correlated with plant matter and takes on higher values when forest vegetation is present. See, for example, Somanathan, Pabhakar, and Mehta (2002), and Zhou et al. (2003).

[17] Formally (following Yool 2001), we calculate the average NDVI value (μ_s) and standard deviation (σ_s) for all monthly pixels in our study area for the two-year (24-month) interval, 1990–91. We then construct the critical index:

$$N = \mu_s + n_{.20}\sigma_s$$

where $n_{.20}$ = critical value of a standard normal random variable such that the upper tail has a 20% probability ≈0.84. In our sample, the calculated critical N index is 177. For any given time interval of interest (one- or the two-year period 1990–91, for example), we then construct the z-score:

$$z\text{-}NDVI_i = z\text{-score for district } i = (\mu_i - N)/\sigma_i$$

where μ_i = district i average of time-pixel NDVI and σ_i = district i standard deviation of time-pixel NDVI.

[18] We use the 1990–91 period to measure the initial environmental state. Because NDVI data are not available for the last four months of 1994, our end-of-study-period environmental state is measured using the last four months of 1993, the first eight months of 1994, and the calendar year 1995. Environmental change variables are determined by differences between average NDVI/z-NDVI in 1993–95 and 1990–91.

[19] Lacking primary migration data, we estimate rural and urban net migration as follows: Using data from the Census and Registrar, we determine estimated district-level 1994 rural and urban populations. From the 1994 population estimates we subtract the 1991 populations and natural growth over 1991–94 to determine net migration, which we then normalize (as with our natural growth measures) to be per thousand 1991 population.

Table 3. Model Structure: Explanatory Variables for the Empirical Model

Dependent Variable:	G_R,G_U,M_R,M_U	ΔE
Equation number:	(13)–(16)	(17)
Explanatory variables	X_P	X_E
Environmental Variables		
NDVI/z-NDVI	✓	✓
LagΔNDVI/LagΔz-NDVI	✓	✓
Rainfall^{a+}		✓
Elevation^{a}		✓
Average temperature^{a}		✓
Rain deviation(+)	✓	✓
Rain deviation(−)	✓	✓
Socioeconomic Variables (Rural and Urban)		
Popn dens	✓	✓
Cons exp	✓	✓
Inf death^{b+}	✓	
Death rate^{b+}	✓	
Hh size^{b}	✓	
Life exp	✓	✓
Fem lit	✓	✓
Male lit	✓	✓
Total lit	✓	✓
Sex ratio	✓	✓
Fem work	✓	✓
Muslims	✓	✓
Tribals	✓	✓
Other Variables		
Urban popn	✓	✓
NSA	✓	✓

Notes: X_P denotes explanatory variables in all four population change regressions of equations (13)–(16) (G_R,G_U,M_R,M_U). X_E denotes explanatory variables in the vegetation change regression of equation (17) (ΔE). See text for discussion of identifying instruments. ^{a}denotes identifying instrument for vegetation change; ^{b}denotes identifying instrument for population change; $^{+}$denotes "core" identifying instrument; ✓denotes inclusion of variable in model.

the identification strategies that we discuss next.

Identifying environmental change in the population equations. To identify environmental change in the natural growth and migration rate regressions, we use a "core" instrument, district-level rainfall (1991–94), and two additional natural/climatic variables: average district temperatures (1991–94), and average district elevation. In judging the merits of these instruments, several issues arise. First, are the instruments highly correlated with environmental change? Following standard practice (Bound, Jaeger, and Baker 1995), we assess the instruments' strength from their performance in first-stage regressions of environmental change on all exogenous variables. The instruments perform very well in these regressions, with all three estimated to have a significant and positive impact on our two environmental measures (see tables 4–6).

Second, does our "core" rainfall variable identify transitory environmental changes,

Table 4. First-Stage Results for Vegetation Change

	ΔNDVI (1)	Δz-NDVI (2)
Rain	0.0181***	0.0011***
	(0.006)	(0.003)
Elevation	0.0057**	0.0004***
	(0.030)	(0.003)
Temperature	1.1580**	0.0635***
	(0.044)	(0.045)
F-test for Instrument(s)	4.08 (0.0082)	7.41 (0.0001)

Note: The table gives selected results from the first-stage estimations used for the population growth estimations of tables 7 and 8.
Double asterisk ($**$) denote significance at 5%; triple asterisks ($***$) denote significance at 1%; p- values in parentheses; Number of observations = 178.

Table 5. First-Stage Results for Population Change Equations with NDVI

	(1) G_R	(2) G_U	(3) M_R	(4) M_U
Death rate(R)	6.55***	−6.07***	−8.08***	7.6879*
	(0.000)	(0.000)	(0.000)	(0.053)
Death rate(U)	2.24***	10.69***	−5.14***	−0.13
	(0.002)	(0.000)	(0.001)	(0.979)
Inf death(R)	0.07	0.11	−0.12	0.21
	(0.514)	(0.669)	(0.503)	(0.628)
Inf death(U)	0.03	−1.05***	0.18	0.84**
	(0.695)	(0.000)	(0.413)	(0.016)
AHS(R)	21.60***	10.49	−24.18***	−7.47
	(0.000)	(0.126)	(0.003)	(0.582)
AHS(U)	−11.77**	−26.39***	23.58**	37.32
	(0.017)	(0.003)	(0.044)	(0.028)
F- test for Death rate(R,U), Inf death(R,U)	33.06	27.51	16.56	4.14
	(0.0000)	(0.0000)	(0.0000)	(0.0033)
F- test for Death rate(R,U), Inf death(R,U), AHS(R,U)	27.64	20.74	12.08	3.62
	(0.0000)	(0.0000)	(0.0000)	(0.0023)

Note: The table gives selected results from the first-stage estimations used for the vegetation change estimations of table 9.
Single asterisk (∗) denotes significance at 10%; double asterisk (∗∗) denotes significance at 5%; triple asterisks (∗∗∗) denotes significance at 1%; *p*-values in parentheses; number of observations = 178.

Table 6. First-Stage Results for Population Change Equations with *z*-NDVI

	(1) G_R	(2) G_U	(3) M_R	(4) M_U
Death rate(R)	6.59***	−6.42***	−8.17***	8.73**
	(0.000)	(0.000)	(0.000)	(0.027)
Death rate(U)	1.98***	10.60***	−4.96***	−0.80
	(0.006)	(0.000)	(0.001)	(0.863)
Inf death(R)	0.02	0.08	−0.05	0.12
	(0.833)	(0.747)	(0.796)	(0.770)
Inf death(U)	0.05	−1.02***	0.17	0.80**
	(0.583)	(0.000)	(0.457)	(0.016)
AHS(R)	21.63***	8.62	−24.44***	−4.06
	(0.000)	(0.198)	(0.003)	(0.761)
AHS(U)	−11.60**	−25.50***	22.20*	36.33**
	(0.018)	(0.003)	(0.051)	(0.033)
F- test for Death rate(R,U), Inf death(R,U)	31.69	25.23	16.19	4.16
	(0.0000)	(0.0000)	(0.0000)	(0.0032)
F- test for Death rate(R,U), Inf death(R,U), AHS(R,U)	25.89	19.87	12.22	3.64
	(0.0000)	(0.0000)	(0.0000)	(0.0022)

Note: This table gives selected results from the first-stage estimations used for the vegetation change estimations of table 9.
Single asterisk (∗) denotes significance at 10%; double asterisks (∗∗) denote significance at 5%; triple asterisks (∗∗∗) denote significance at 1%; *p*- values in parentheses; number of observations = 178.

rather than longer-run environmental changes that are more likely to drive births or migration decisions? While this is an empirical question as much as a conceptual one, we note that subdivision-level rainfalls are highly correlated over time in our study region. For example, the correlation coefficient between rainfall in the period 1986–1990 and 1991–94 is over 0.9.[20] Hence, contemporaneous rainfall is likely to capture systemic weather differences

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[20] This high correlation is partly due to two factors: (*a*) cross-sectional variation in rainfall is relatively large (with average annual rainfalls over twenty years varying from a low of 0.26 meters to a high of 2.88 meters), and (*b*) time-series variation is dampened when averaging over a five-year interval. Despite the high correlation between five-year averages, we note that our rainfall

across districts in our sample and thus identify more than transitory environmental change.

Third, are our instruments exogenous to natural growth and migration decisions? In principle, rainfall may affect agricultural productivity, which in turn affects natural growth and migration.[21] Agronomic research indicates that agricultural productivity is affected by deviations of rainfall outside of normal bands (see Azzam and Sekkat 2003). We therefore control for potential effects of rainfall on agricultural productivity by constructing two rainfall deviation variables that we include in our population equations (see table 3); specifically, we sum positive and negative deviations of annual rainfalls, over the period 1991 to 1994, from average annual rainfall (calculated over the twenty-year period, 1981 to 2000).[22]

Beyond improving identification, adding the temperature and elevation instruments enables us to provide some statistical evidence on all three instruments' irrelevance to population decisions. When estimating the population equations with one of the instruments included as an explanatory variable and the other two used to identify environmental change, we find that none of our posited instruments is ever a statistically significant explanator (even at rather high levels of significance). In addition, we can perform standard tests of the overidentifying restrictions (the null of no correlation with the error); in all eight population equations (four each with the NDVI and z-NDVI), we do not reject the restrictions at reasonable levels of significance (20% or lower).

Identifying Natural Growth and Migration in the Environment Equation. We have four jointly endogenous variables in the environment equation, two natural growth rates (rural and urban) and two net migration rates (rural and urban). We use four "core" instruments to jointly identify these four variables: raw 1991 death rates (rural and urban) and 1991 infant death rates (rural and urban). These four instruments are inverse indicators of health status.

The core instruments are clearly important for natural growth. Higher infant death rates can deter birthing by increasing the costs of having children (*ceteris paribus*). Conversely, from the population literature (e.g., see Dreze and Murthy 2001), we know that higher raw death rates, by raising the risks that children will not live to help support parents in later life, can increase net birth rates. These instruments are also potentially important for migration behavior. Poorer health status is likely to deter in-migration (and promote out-migration). In addition, however, in-migration is a likely substitute for natural growth in supplying labor; if a higher infant death rate tends to reduce birth rates (by raising the costs of children), then in-migration may rise to provide substitute labor. In the case of raw death rates, these two forces operate in tandem; hence, we expect negative effects of raw (sector-specific) death rates on net (sector-specific) in-migration. However, for infant death rates, if the second effect dominates, we expect positive effects on in-migration. Our empirical results are consistent with these relationships (see tables 7 and 8). Following standard practice (Bound, Jaeger, and Baker 1995), we test the strength of our instruments by evaluating their joint significance in first-stage regressions; for all instrument combinations that we consider, we find strong evidence of joint significance (see F-statistics in table 5 and 6).

Are our instruments exogenous to measured environmental change? We can imagine two potential channels for health status to affect the environment, other than via the population impacts that we seek to identify and income effects for which we control. First, because improved health enhances life expectancy and longer-lived peoples potentially have greater incentives for conservation, improved health may conceivably promote environmental improvement directly. Beyond statistical tests that belie such conjectured effects, we control for them directly by including measures of district-level (rural and urban)

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data exhibit a high degree of year-on-year variation. For example, over the twenty years 1980–2000, year-on-year correlations (within subdivision) average −0.03 (ranging from −0.35 to 0.19), and mean-normalized standard deviations average 0.24 (ranging from 0.13 to 0.48).

[21] An additional potential criticism of the rainfall instrument is that rainfall may be correlated with disease (such as malaria), which in turn may affect population decisions. However, there are two components to such potential effects, and we control for both. The two components are (*a*) systematic (cross-district) differences in rainfall, and (*b*) exceptional rainfall, within the sample period, that causes (for example) floods or droughts. Our rainfall deviation measures (discussed below) control for the second set of effects. To control for systematic effects of health status, whether due to rainfall or other factors, we include relevant health measures (infant death rates, overall death rates, and life expectancy) in our population equations.

[22] Formally, with μ_j representing twenty-year average rainfall for subdivision j, district i (of subdivision j) has the raw rainfall deviation for year t,

$$R_{it} = (NDVI_i/NDVI_j)(Rain_j - \mu_j).$$

Our district-level rainfall deviations sum (respectively) the positive and negative R_{it} deviations over 1991–94.

Table 7. Natural Population Growth Rate (G_R & G_U) Regressions

	(1) G_R	(2) G_R	(3) G_U	(4) G_U
Environmental variables:				
ΔNDVI	−3.208***		4.243*	
	(0.009)		(0.075)	
NDVI	−0.238		−0.464	
	(0.250)		(0.231)	
LagΔNDVI	0.157		2.008*	
	(0.781)		(0.068)	
Δz-NDVI		−35.703**		69.801**
		(0.015)		(0.035)
z-NDVI		−5.968		13.871
		(0.209)		(0.125)
LagΔz-NDVI		2.563*		1.567
		(0.070)		(0.571)
Rural Variables:				
Popn dens(R)	−0.023	−0.031***	−0.036	−0.031
	(0.139)	(0.010)	(0.343)	(0.292)
Death rate(R)	7.225***	7.774***	−7.072***	−8.941***
	(0.000)	(0.000)	(0.001)	(0.000)
Inf death(R)	0.032	−0.090	0.114	0.286
	(0.801)	(0.485)	(0.679)	(0.243)
AHS(R)	20.865***	20.118***	10.365	12.615
	(0.000)	(0.000)	(0.176)	(0.100)
Urban Variables:				
Urban popn	−0.092	−0.114	−1.337***	−1.294***
	(0.475)	(0.356)	(0.000)	(0.000)
Popn dens(U)	0.001	−0.000	−0.001	0.001
	(0.385)	(0.730)	(0.641)	(0.462)
Death rate(U)	3.356***	2.278***	9.083***	10.363***
	(0.000)	(0.004)	(0.000)	(0.000)
Inf death(U)	−0.083	−0.093	−0.910***	−0.788***
	(0.473)	(0.532)	(0.000)	(0.006)
AHS(U)	−10.637**	−13.603**	−29.928***	−23.478**
	(0.046)	(0.013)	(0.001)	(0.024)
Constant	454.252***	285.551***	133.228	234.374
	(0.000)	(0.003)	(0.505)	(0.236)
Hansen J-test	1.307	3.091	3.074	1.010
	(0.5201)	(0.2132)	(0.2150)	(0.6036)
Pagan-Hall test	19.918	19.096	22.339	32.378
	(0.9809)	(0.9868)	(0.9521)	(0.5953)

Notes: Single asterisk (*) denotes significance at 10%; double asterisks (**) denote significance at 5%; triple asterisks (***) denote significance at 1%; p-values in parentheses.

Two-step GMM estimates using rainfall, elevation, and temperature to identify ΔNDVI and Δz-NDVI.

All models also include the regressors Raindev(+), Raindev(−), NSA, rural and urban Cons exp, Life exp, literacies (male, female, total), sex ratio, Fem work, Muslims, and Tribals.

life expectancies as regressors in our environmental change equations. Second, there is the potential for joint endogeneity between death rates and environmental change; environmental degradation may worsen the climate for disease (including the spread of malaria and gastro-intestinal parasites). However, this link is not possible between environmental change (our endogenous variable) and past death rates (our instruments). Moreover, we control for prior period environmental change, thus vitiating any potential link due to serial correlation.

In order to improve our predictions of the population variables, we consider two additional identifying instruments: rural and urban household size. We expect (and find in our data) that household size is an important determinant of natural population growth (see table 7). Larger households may enjoy economies of child care/management, lowering costs of children and thus favoring higher birth rates. On the other hand, larger households may enjoy economies of household production and social security, lowering the demand

Table 8. Net In-Migration Rate (M_R and M_U) Regressions

	(1) M_R	(2) M_R	(3) M_U	(4) M_U
Environmental Variables:				
ΔNDVI	−1.812		6.015	
	(0.195)		(0.134)	
NDVI	0.638**		−0.233	
	(0.039)		(0.672)	
LagΔNDVI	−1.003		−1.555	
	(0.145)		(0.259)	
Δz-NDVI		−38.734*		68.058
		(0.070)		(0.201)
z-NDVI		−10.432		22.415
		(0.191)		(0.115)
LagΔz-NDVI		−2.815		4.323
		(0.165)		(0.345)
Rural Variables:				
Popn dens(R)	0.037*	0.034*	0.041	0.063
	(0.082)	(0.075)	(0.283)	(0.109)
Death rate(R)	−7.420***	−6.591***	7.453*	6.554
	(0.000)	(0.000)	(0.058)	(0.141)
Inf death(R)	−0.186	−0.172	0.177	0.268
	(0.304)	(0.371)	(0.685)	(0.572)
AHS(R)	−25.558***	−27.214***	−5.528	−1.274
	(0.003)	(0.002)	(0.700)	(0.929)
Urban Variables:				
Urban popn	−0.420**	−0.447**	1.303***	1.266***
	(0.021)	(0.014)	(0.000)	(0.001)
Popn dens(U)	0.000	−0.001	−0.002	−0.000
	(0.998)	(0.431)	(0.228)	(0.715)
Death rate(U)	−4.317***	−4.690***	−4.833	−1.964
	(0.007)	(0.001)	(0.337)	(0.645)
Inf death(U)	0.046	0.025	1.149***	1.087**
	(0.837)	(0.911)	(0.005)	(0.014)
AHS(U)	20.729*	21.004*	32.542*	37.108**
	(0.064)	(0.066)	(0.052)	(0.037)
Constant	−519.005***	−509.972***	78.348	219.956
	(0.003)	(0.003)	(0.797)	(0.459)
Hansen J-test	1.664	0.926	1.273	0.649
	(0.4351)	(0.6293)	(0.5292)	(0.7228)
Pagan-Hall test	31.775	24.007	22.156	23.174
	(0.6246)	(0.9195)	(0.9550)	(0.9372)

Notes: Single asterisk (∗) significant at 10%; double asterisks (∗∗) significant at 5%; three asterisks (∗∗∗) significant at 1%; p values in parentheses.
Two-step GMM estimates using rainfall, elevation, and temperature to identify ΔNDVI and Δz-NDVI.
All models also include the regressors Raindev(+), Raindev(−), NSA, rural and urban Cons Exp, Life exp, literacies (male, female, total), sex ratio, Fem work, Muslims, and Tribals.

for children. Either effect may dominate in practice.

Our empirical results support use of the two household size instruments, in two ways. First, whenever either instrument is included in an environment equation, its estimated impact is statistically insignificant even at rather high levels of significance. Second, we can conduct standard tests of the over-identifying restrictions (the null of no correlation with the environment error). In both cases, we do not reject the restrictions at any reasonable level of significance (30% or lower).[23]

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[23] For robustness purposes, we consider a variety of different instrument combinations. To identify environmental change, we consider the "core" rainfall instrument alone, and all three climatic variables. To identify population change, we consider the "core" death rates; the "core" plus urban household size; and the "core" plus rural and urban household size. (In principle, larger rural households may enjoy economies of natural resource extraction, potentially leading to greater environmental degradation and motivating identifying instrument sets that exclude rural household size.) We report results with the broadest set of identifying

Table 9. Vegetation Change (ΔE) Regressions

	(1) ΔNDVI	(2) Δz-NDVI
Environmental Variables:		
NDVI	0.025 (0.523)	
LagΔNDVI	−0.116 (0.271)	
z-NDVI		−0.230*** (0.000)
LagΔz-NDVI		0.007 (0.777)
Rainfall	0.012 (0.174)	0.000 (0.534)
Endogenous Demographic Variables:		
$G_R + M_R$	−0.059 (0.344)	−0.012** (0.024)
$G_U + M_U$	0.008 (0.669)	−0.003* (0.071)
Selected Other Demographic Variables:		
Urban popn	−0.043 (0.278)	−0.008** (0.020)
Life exp(R)	−0.392* (0.064)	−0.016 (0.348)
Life exp(U)	0.323* (0.083)	0.013 (0.382)
Constant	9.475 (0.654)	−1.886 (0.231)
Hansen J-statistic	3.456 (0.1776)	2.299 (0.3169)
Pagan-Hall statistic	48.729 (0.0382)	3.006 (1.0000)
F-test for equality of coefficients on $(G_R + M_R)$ and $(G_U + M_U)$	1.75 (0.1880)	4.41 (0.0374)
F-test for the validity of constraints	0.24 (0.7834)	0.33 (0.7200)

Notes: Single asterisk (∗) denotes significance at 10%; double asterisks (∗∗) denote significance at 5%; three asterisks (∗∗∗) denote significance at 1%; p-values in parentheses.
To identify G_R, G_U, M_R and M_U, Models (1) and (2) uses Death Rate(R,U), Inf Death(R,U), and AHS(U,R).
Estimations constrain coefficients on G_R and M_R (G_U and M_U) to be equal. The last set of F- statistics support the constraint.
All models also include the regressors Raindev(+), Raindev(−), NSA, rural and urban Cons exp, Popn dens, literacies (male, female, total), sex ratio, Fem work, Muslims, and Tribals.

Results

Tables 7–9 present results from our estimations of rural and urban natural growth equations (table 7 for equations (13)–(14)), rural and urban net migration (table 8 for equations (15)–(16)), and environmental change (table 9 for equation (17)). In all cases, we present two specifications, one using the NDVI (vegetative biomass) to measure environmental health and change, and the other using the z-NDVI (forest cover). We use a consistent two-step generalized method of moment (GMM) estimator that accounts for joint endogeneity.[24]

Three econometric issues bear comment. First, Pagan-Hall test statistics for the null of homoskedasticity are insignificant in all cases.

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instruments. Results using other instrument sets are available in Bhattacharya and Innes (2008) and are qualitatively identical to those we report here.

[24] Three-stage least squares estimations of our empirical model yield qualitatively similar results to those obtained using GMM. Our two-stage GMM estimations yield robust standard errors, accounting for the normal bias associated with two-stage procedures. In table 9, we report estimations that include only the "core" rainfall instrument; similar results are obtained using all three climatic variables.

Second, the Hansen test of the overidentifying restrictions supports the maintained hypothesis of instrument exogeneity in all cases. Third, for efficiency and because we expect overall population growth to affect environmental change, we assume common coefficients for our two components of population growth and test the implied constraint; in all cases, we obtain strongly insignificant *F*-statistics, providing evidence in favor of the maintained constraint.

From the tables, a number of qualitative conclusions are evident.[25]

1) *Rural natural growth rates rise with environmental deterioration*. Environmental change has a statistically significant negative impact on rural natural growth rates (table 7). For example, a contemporaneous increase in the NDVI index by 1% of its initial sample range is associated with a reduction in rural natural growth rates of 7%.[26] Similarly, a contemporaneous increase in the *z*-index by 1% of its sample range is associated with a 12% reduction in rural natural growth. These results broadly support our Hypothesis 4(a).
2) *Urban natural growth rates rise with environmental improvement*. Environmental change has a statistically and quantitatively significant positive effect on urban natural growth rates (table 7), broadly supporting our Hypothesis 5. For example, we find that a 1% (of initial sample range) contemporaneous rise in the NDVI is associated with a 2.5% increase in urban natural growth rates, while a corresponding rise in the *z*-score spurs a 6.4% increase.
3) *Increased rural population growth tends to deplete forest resources*. As indicated in table 9, the coefficient on rural population growth (natural growth plus migration) is negative and statistically significant in the model of *z*-NDVI change, but not statistically significant in the model of NDVI change. Assessing the quantitative significance of these coefficients is not straightforward. However, we note that a one-standard-deviation increase in rural natural growth is associated with a reduction in the *z*-NDVI equal to 85% of the standard deviation for the *z*-score change. Our data thus provide some support for Hypothesis 1 as it relates to forest resources.
   Urban population growth is also estimated to have a negative effect on changes in NDVI and *z*-NDVI. However, these estimated effects are statistically significant (at the 10% level) only in the *z*-NDVI model, and only when we use the most complete set of identifying instruments (as reported in table 9). Hence, our data provide only rather weak evidence for Hypothesis 2. Moreover, we find that the effect of urban population growth on environmental change is significantly less negative than the corresponding effect of rural population growth. For example, in our *z*-NDVI model, the coefficient on urban growth is only one-quarter the magnitude of the coefficient on rural growth, and the *F*-test rejects the null of common coefficients (with *p*-value 0.037).
4) *Net rural in-migration falls with environmental improvement* as measured by changes in the forest-based *z*-NDVI index. Environmental improvement can free up rural labor for migration to urban areas or other districts with employment opportunities. These estimated effects are statistically and quantitatively significant. For example, an improvement in a district's *z*-NDVI equal to 1% of the sample range for the initial *z*-NDVI is estimated to increase rural out-migration by 0.36% of the rural population, which is 1.4% of the sample range for rural migration. We thus find support for Hypothesis 4(b).
5) *Scarcity of forest resources tends to spur increases in forest resource stocks*, with significant negative coefficients on the initial *z*-NDVI in the *z*-change estimation (see table 9). Consistent with Hypothesis 3, we estimate that roughly 23% of prior degradation of the *z*-NDVI is offset by subsequent environmental improvement during our four-year study period.

Taken together, our results provide some evidence of the "vicious cycle" between rural population growth and environmental

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[25] Although they are not the focus of our study, a number of socioeconomic variables also have statistically significant effects in our estimations. As expected, higher raw death rates tend to spur increased natural growth and reduced in-migration. Higher rural consumption expenditures spur lower rural natural growth rates. Higher rural (urban) household sizes are associated with higher (lower) rural (urban) natural growth and lower (higher) rates of rural (urban) in-migration. Higher rural sex ratios and lower rural life expectancies are associated with lower rural natural growth. Higher urban rates of female workforce participation and infant mortality spur lower urban natural growth. More urban districts tend to yield lower rates of urban natural growth and rural in-migration; higher rates of urban in-migration; and more forest depletion.

[26] One percent of the 1990–91 NDVI sample range is 0.6. Multiplied by the coefficient for environmental change (in table 7) and divided by average rural natural growth gives the indicated percentage change.

degradation, particularly as it relates to the forest resources that we attempt to capture using our z-NDVI index. Indeed, our results suggest that the "vicious cycle" may operate by spurring increased natural growth in rural populations, which in turn increases environmentally depleting resource-extraction activities. In addition, environmental depletion may be reinforced by drawing in labor that might otherwise migrate to urban employment opportunities. Moreover, the magnitude of estimated environmental (z-change) effects on rural migration is roughly the same as those on rural natural growth, implying roughly equal roles for the two components of population growth in the "vicious cycle."

However, we also find evidence for two forces that counter the "vicious cycle." First, as forest resources become more scarce (with lower z), heightened incentives for forest preservation lead to improvements in forest health. And second, deforestation is estimated to spur reductions in urban population growth, which in turn are (weakly) found to prompt environmental improvement.

To gain a loose sense of the relative magnitudes of these reinforcing and countering forces, consider how a downward shock to forest resources (i.e., a negative exogenous z-score change) is reinforced or countered by attendant changes in rural populations, urban populations, and "scarcity." In this exercise, we ignore all impacts of lagged z-changes and long-run effects of changes in the initial z on population decisions, and consider three effects: (a) the reinforcing rural population effect, $V_R = (\beta_1 + \beta_3)\delta_1$, where the β and δ coefficients are per equations (13)–(17); (b) the countering urban population effect, $V_U = (\beta_2 + \beta_4)\delta_3$, and ($c$) the countering environmental scarcity effect, $V_S = \gamma_{5z}$ = coefficient on initial z-NDVI in equation (17). Each of these V effects enters the long-run z-change multiplier for the initial z shock.[27] Estimated values for these effects are: $V_R = 1.228$, $V_U = -.532$, and $V_S = -0.23$. Hence, loosely speaking, the urban population effect counters about 44% of the "vicious cycle" effect of the rural population, and the environmental scarcity effect counters 19% more.

Conclusion

In this article, we study bi-directional links between population growth and environmental change using cross-sectional district-level data from South, Central, and West India. Unlike prior work, we account for the joint determination of population and environmental outcomes and, in doing so, find evidence of joint endogeneity. Our results provide some support for the conceptual ingredients to the so-called "vicious cycle" theory. Under this doctrine, population growth spurs environmental degradation; because child labor is in greater demand in environmentally degraded circumstances, the environmental depletion in turn fuels further population growth, and so on. We find evidence in our data that environmental degradation—whether measured in terms of biomass or forest resources—indeed spurs both increased rural natural growth and, perhaps more surprisingly, increased rural in-migration. We also find evidence that increased rural population growth in turn spurs depletion in forest resources. However, our results on the impact of rural natural growth on biomass resources are mixed.

Despite some confirmation of the "vicious cycle," our analysis suggests the operation of forces that counter the cycle. Whether due to market forces or community/government action, we find that environmental scarcity tends to spur environmental improvement. In addition, for the Indian context that we study, our results suggest that the depletion of forest resources can spur reductions in urban populations; lowered urban population growth may, in turn, operate to offset the original forest depletion. To some extent, identification of these offsetting forces confirms the "Boserupian" conjecture that environmental scarcity breeds creativity, innovation, and policy that conserves natural resources.

Our findings also shed light on the relevant paradigm for thinking about forest policy in countries like India. If forest resources are privately owned and protected, then trends and policies that increase local demand for forest products can potentially spur an increase in the local supply of forests. We loosely term this argument the "market resource" paradigm. Juxtaposed to this logic is the "open-access" paradigm wherein forests are common property resources and an increased demand for forest products prompts increased forest exploitation. We find that rural population growth leads to resource degradation in our sample. These findings do not support the "market resource" perspective and suggest that much of our measured natural resource base is likely to be of the open-access variety; and imply that policy responses to

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[27] Under the indicated premises, the z-change multiplier equals $(1 - V_R - V_U - V_S)^{-1}$.

rural population growth do not compensate for their direct environmental depletion effects. From a policy perspective, these results suggest that programs targeted to reduce rural population growth, even though they reduce the rural demand for forest products, may promote aforestation in India. They also stress the importance of environmental policy to the achievement of aforestation objectives.

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References

Aggarwal, R., S. Netanyahu, and C. Romano. 2001. "Access to Natural Resources and the Fertility Decision of Women: The Case of South Africa." *Environment and Development Economics* 6:209–36.

Amacher, G., W. Cruz, D. Grebner, and W. Hyde. 1998. "Environmental Motivation for Migration: Population Pressure, Poverty and Deforestation in the Philippines." *Land Economics* 74:92–101.

Azzam, A., and K. Sekkat. 2003. "Total Factor Productivity in Moroccan Cereal Agriculture: Accounting for Rainfall, Technical Efficiency, Pricing Policy and Demand Effects?" Working Paper, University of Nebraska, Nebraska.

Bhattacharya, H., and R. Innes. 2008. "AJAE Appendix: An Empirical Exploration of the Population-Environment Nexus in India." Unpublished manuscript. Available at http://agecon.lib.umn.edu/.

Boserup, E. 1965. *The Conditions of Agricultural Growth*. Chicago: Aldine.

Bound, J., D. Jaeger, and R. Baker. 1995. "Problems with Instrumental Variables Estimation when the Correlation Between the Instruments and Endogenous Explanatory Variable Is Weak." *Journal of the American Statistical Association* 90:443–50.

Brander, J., and S. Taylor. 1998. "The Simple Economics of Easter Island: A Ricardo-Malthus Model of Renewable Resource Use." *American Economic Review* 88:119–38.

Chopra, K., and S. Gulati. 1997. "Environmental Degradation and Population Movements: The Role of Property Rights." *Environmental and Resource Economics* 9:383–408.

Cropper, M., and C. Griffiths. 1994. "The Interaction of Population Growth and Environmental Quality." *American Economic Review* 84:250–4.

Cropper, M., C. Griffiths, and M. Mani. 1999. "Roads, Population Pressures, and Deforestation in Thailand, 1976–1989. *Land Economics* 75:58–73.

Dasgupta, P. 1995. "The Population Problem: Theory and Evidence." *Journal of Economic Literature* 33:1879–1902.

Dasgupta, S., U. Deichmann, C. Meisner, and D. Wheeler. 2003. "The Poverty/Environment Nexus in Cambodia and Lao People's Democratic Republic." World Bank Policy Research Working Paper 2960.

Deacon, R. 1994. "Deforestation and the Rule of Law in a Cross-Section of Countries." *Land Economics* 70:414–30.

Demsetz, H. 1967. "Toward a Theory of Property Rights." *American Economic Review* 57:347–59.

Dreze, J. and M. Murthy. "Fertility, Education, and Development: Evidence from India." *Population and Development Review* 27 (2001): 33–63.

Ehrhardt-Martinez, K., E. Crenshaw, and C. Jenkins. 2002. "Deforestation and the Environmental Kuznets Curve: A Cross-National Investigation of Intervening Mechanisms." *Social Science Quarterly* 83:226–43.

Ehrlich, P., A. Ehrlich, and G. Daily. 1993. "Food Security, Population, and Environment." *Population and Development Review* 19:1–32.

Filmer, D., and L. Pritchett. 2002. "Environmental Degradation and the Demand for Children: Searching for the Vicious Circle in Pakistan." *Environment and Development Economics* 7:123–46.

Foster, A., and M. Rosenzweig. 2003. "Economic Growth and the Rise of Forests." *Quarterly Journal of Economics* 118:601–37.

Kohlin, G., and G. Amacher. 2005. "Welfare Implications of Community Forest Plantations in Developing Countries: The Orissa Social Forestry Project." *American Journal of Agricultural Economics* 87:855–69.

Kummer, D., and C. Sham. 1994. "The Causes of Tropical Deforestation: A Quantitative Analysis and Case Study from the Philippines." In K. Brown and D. Pearce, eds. *The Causes of Tropical Deforestation*, pp. 146–158. London: UCL Press.

Libecap, G.D., and J. Smith., 2002. "Economic Evolution of Petroleum Property Rights in the United States." *Journal of Legal Studies* 31:S589–S608.

Loughran, D., and L. Pritchett. 1997. "Environmental Scarcity, Resource Collection, and the Demand for Children in Nepal." World Bank Working Paper, Washington, DC.

Martine, G., M. DasGupta, and L. Chen, eds. 1998. *Reproductive Change in India and Brazil*. New Delhi: Oxford University Press.

Meadows, D. 1972. *The Limits to Growth*. New York: Universe Books.

Nerlove, M. 1991. “Population and the Environment: A Parable of Firewood and Other Tales.” *American Journal of Agricultural Economics* 73:1334–47.

NSSO. 1999. “Common Property Resources in India.” Report Number 452, NSSO Department of Statistics and Program Implementation.

Panayotou, T. “Population and Environment.” CID Working Paper No. 54, July 2000.

Panayotou, T., and S. Sungsuwan. 1994. “An Econometric Analysis of the Causes of Tropical Deforestation: The Case of Northeast Thailand.” In K. Brown and D. Pearce, eds. *The Causes of Tropical Deforestation*, pp. 192–207. London: UCL Press.

Pfaff, A. 1999. “What Drives Deforestation in the Brazilian Amazon? Evidence from Satellite and Socioeconomic Data.” *Journal of Environmental Economics and Management* 37:26–43.

Place, F., and K. Otsuka. 2000. “Population Pressure, Land Tenure and Tree Resource Management in Uganda.” *Land Economics* 76:233–51.

Rao, C.H. 1994. *Agricultural Growth, Rural Poverty and Environmental Degradation in India*. Delhi: Oxford University Press.

Renkow, M. 1990. “Household Inventories and Marketed Surplus in Semisubsistence Agriculture.” *American Journal of Agricultural Economics* 72:664–75.

Reuveny, R., and C. Decker. 2000. “Easter Island: Historical Anecdote or Warning for the Future?” *Ecological Economics* 35:271–87.

Rosenzweig, M., and O. Stark, eds. 1997. *Handbook of Population and Family Economics*. Amsterdam: Elsevier.

Rozelle, S., J. Huang, and L. Zhang. 1997. “Poverty, Population and Environmental Degradation in China.” *Food Policy* 22:229–51.

Simon, J. 1996. *The Ultimate Resource 2*. Princeton: Princeton University Press.

Singh, I., L Squire, and J. Strauss. 1986. *Agricultural Household Models: Extensions, Applications and Policy*. Baltimore: Johns Hopkins University Press.

Somanthan, E., R. Prabhakar, and B. Mehta. 2002. “Collective Action for Forest Conservation: Does Heterogeneity Matter?” Indian Statistical Institute, Mimeo.

Southgate, D., R. Sierra, and L. Brown. 1991. “The Causes of Tropical Deforestation in Ecuador: A Statistical Analysis.” *World Development* 19:1145–51.

Yool, S. 2001. “Enhancing Fire Scar Anomalies in AVHRR NDVI Time-Series Data.” *Geocarto International* 16:5–12.

Zhou, L., R. Kaufmann, Y. Tian, R. Mynemi, and C. Tucker. 2003. “Relation Between Interannual Variations in Satellite Measures of Northern Forest Greenness and Climate Between 1982 and 1999.” *Journal of Geophysical Research* 108:4004.