Energy and health transitions in development: fuel use, stove technology, and morbidity in Jarácuaro, México

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The ''energy ladder'' relating improvements in socioeconomic status with transitions to more sophisticated stoves and to higher quality, less polluting fuels is often invoked as a theoretical model for analyzing household energy management practices. We report here on an integrated study of the energy, health and economic implications of fuel switching in the small village of Jarácuaro, Michoacán State, México, that challenges and extends the traditional energy ladder model. We monitored fuel and stove use, economic status, exposure to respirable suspended particulates (RSP) and trace gases (CO, CO_2, NO_x, SO_2), and morbidity during both wet and dry seasons for a sample of 141 persons living in 21 homes. The families surveyed utilized simple ''three stone'' fires, traditional enclosed or improved stoves, and gas ranges or a combination of these technologies. In Jarácuaro, people who cook regularly are twice as likely as non-cooks to exhibit acute respiratory infection (ARI), (relative risk = 2.0, 95% CI = 1.3 - 2.7). The use of improved stoves correlates with reductions in indoor concentrations of RSPs and CO, and decreases in reported cases of ARI, eye infections, and intestinal disorders. These changes are consistent with the technology component of the energy ladder, relating improvements in stove and fuel type to emissions and then to respiratory ailments. This suggests an associated ''health ladder'' for families adopting improved stoves or kitchen designs. We find that the energy ladder framework, while useful, is also an oversimplification that masks some of the strategies used in household decision-making. This is reflected in Jarácuaro where the socioeconomic correlate of stove ''quality'' and income breaks down: the more affluent families do not necessarily use cleaner fuel and stove combinations or invest in kitchens that are more healthy or energy efficient. Some of the most affluent households even exhibited the highest RSP and CO concentrations. These findings lead to a more eclectic model of fuel and stove adoption and use that has implications for integrated health and development policies. One direct conclusion from this study is the need and the opportunity for educational programs to facilitate transitions to more efficient stoves and cleaner fuels for the rich and poor alike.

1. Introduction

Recent policy and academic interest in promoting sustainable development has led to efforts to facilitate communities in adopting more efficient cooking stoves, thus mitigating the environmental impacts of fuelwood collection and charcoal production, reducing the concentration of indoor air pollution, and reducing the burden of disease. This normative chain is based largely on the belief in an ''energy ladder'' (see Figure 1) as a theoretically and functionally useful framework to explain the dynamics of fuel and stove adoption and use [Reddy, 1982; Baldwin, 1986; Hosier and Dowd, 1987; Smith, et al., 1994; Masera, 1994; Kammen, 1995a,b]. The ladder model suggests that with increasing affluence, a progression may be expected from traditional biomass fuels (e.g., dung, agricultural residues, and wood) to more advanced and less polluting fuels (e.g., from wood to charcoal, kerosene, propane, and then to gas). Advancing up the energy ladder is also associated with increasing commercialization and cost of both the stoves and the fuel.

The relationship between energy use and health has been the focus of a growing number of studies investigating a variety of fuel and stove technology combinations. Important examples include those exploring the relationship between woodfuel burning and malaria [Snow, et al., 1987], biomass fuel use, stoves, and

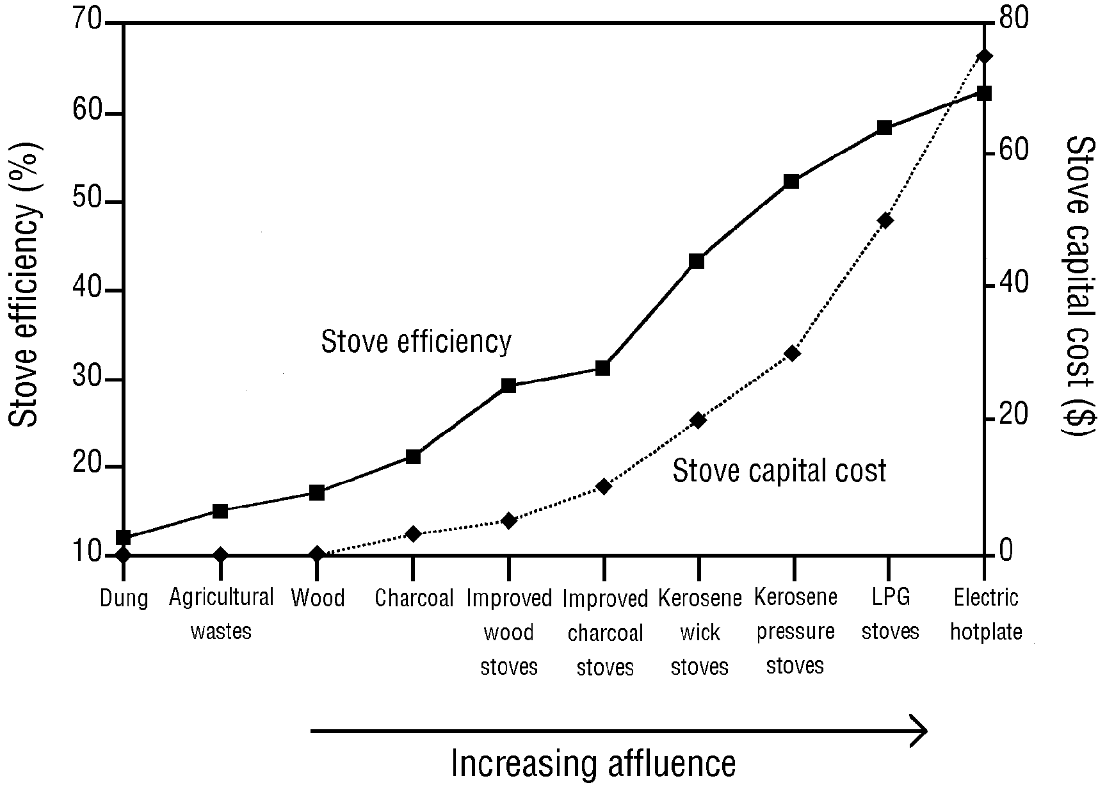

Figure 1. The energy ladder characterizing the general movement towards increased stove and fuel cost as a function of affluence. Modified from [OTA, 1991]

respiratory infections [Smith, 1993], domestic coal use and health [Ellegård, 1993], and the health effects of particulate and SO_2 pollution from power plants [Wells, et al., 1994; Florig, 1996]. Despite this growing body of epidemiological and analytic work, there are still comparatively few efforts to systematize and act on the observed interactions between the sources and use of energy and the resulting implications for human health. (For two recent bibliographic studies of the health impacts of biofuel combustion, see McCracken and Smith, 1998; and Kammen, et al., 1999.)

Inefficient combustion of traditional fuels is linked to respiratory infections, the leading health hazard to children in developing countries. It is now widely recognized that among all endemic diseases, acute respiratory infection (ARI) is the most pervasive cause of chronic illness, resulting in an estimated 4.3 million deaths per year [Smith, 1988, 1993]. Response and management strategies to prevent ARI have become a primary focus of national health programs in a number of nations, including the Integrated Management of the Sick Child Initiative of the World Health Organization [WHO, 1997a]. International efforts are under way to change the focus of health policy from one of diagnosis and treatment of individual ailments, to holistic approaches that address the environmental and socioeconomic factors contributing to disease. Thus, many WHO activities now focus on the fact that not only do five diseases – pneumonia, diarrhea, measles, malaria and malnutrition – cause 70% of worldwide childhood deaths, but that these illnesses are negatively synergistic [WHO, 1997b]. The difficult next step is to develop practical integrated programs that address health, environmental, and economic problems associated with stove and fuel combinations at various points along the energy ladder. Particularly efficient avenues to reduce childhood morbidity, not only from ARI, but from associated opportunistic diseases as well, may come from programs that encourage the adoption of new cookstove designs, or from the implementation of building standards that promote ‘‘healthy homes’’.

The goal of this study was to test the applicability of the energy ladder model in an environmentally homogeneous but socioeconomically stratified village. In Jarácuaro, México, access to modern fuels (liquid petroleum gas; LPG) and a variety of stove technologies is available through the local market. However, economic and other constraints and cultural preferences result in households utilizing a diverse range of fuels and combustion technologies. In the next section (Section 2) we describe the experimental site and the sampling methods, and then in Section 3 present the results of 12 months of health interviews, and trace gas and particulate sampling studies to monitor the concentrations of indoor air pollutants. The sample of 21 households and 144 individuals is sufficient to contrast and examine the energy decisions by several important sub-groups in the population, but is not sufficient to definitively preclude debate on the statistical significance of each finding. Nevertheless, we find that the weight of both quantitative and more qualitative sociological data provides a compelling argument for a set

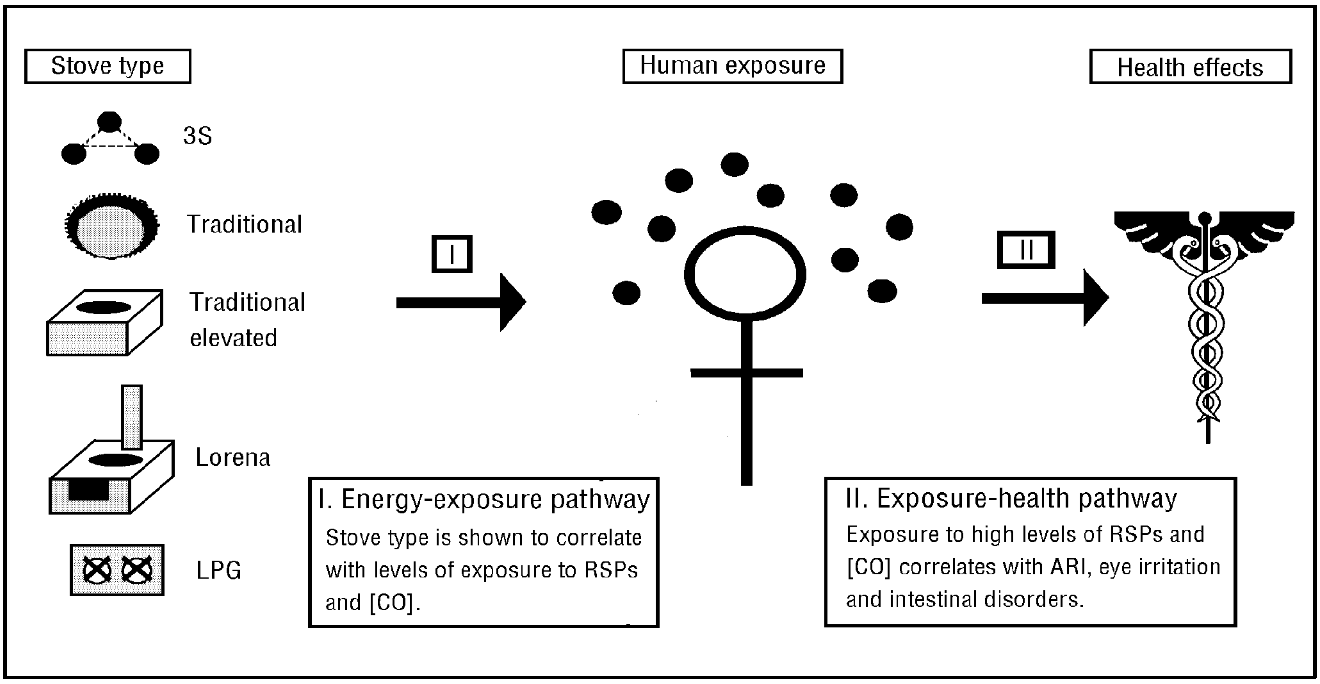

Figure 2. Schematic presentation of hypothesis testing in the energy-health ladder model

of conclusions on the decisions made within households on the energy supplies and stove technologies that work best for the inhabitants of this small rural community. We show that families adopting cleaner fuel and stove combinations do realize environmental health benefits. However, the socioeconomic component of the energy ladder hypothesis, between increasing affluence and the adoption of cleaner cooking practices, is not realized in Jarácuaro. In Section 4 and in the conclusions we outline an expanded model of household energy, health, and environmental management and development based not on simple, linear, transitions between stove types, but a model instead based on education and eclectic decisions by households to maintain multiple cooking technologies and fuel options.

2. Methods

This investigation examines the interaction between energy use and health based on a two-stage model linking: (1) levels of emissions from different stoves, fuel types and combustion processes; and (2) a dose-response assessment of morbidity based on local epidemiology. This model is presented schematically in Figure 2, and builds on a number of previous efforts to illuminate the environmental health pathway [e.g., WHO, 1987; Nyström, 1988; OTA, 1991; Smith, et al., 1994; Ellegård, 1996]. The study takes place in Jarácuaro, Michoacán, a small community in the *Sierra Purépecha* highlands of central México. The Purépecha region covers an area of over 6,000 km^2 between 101º30′ and 102º30′ W and 19º20′ and 19º05′N and has a population of roughly 250,000 with an annual growth rate of 2%. The precipitation varies from 700 mm per year to over 1600 mm per year [Bello, 1993, quoted in Masera, 1994].

Jarácuaro village was once an island, but is now located on a peninsula due to the decline in the level of Lake Pátzcuaro. The population is ~3,000 and the village includes ~220 hectares of land which is held communally. Extensive data exists on the patterns of energy use and household economics in the Pátzcuaro region, and in Jarácuaro in particular because it is one of three regional villages under long-term study by the energy and development scholar Omar Masera and his colleagues [Masera et al., 1989; Masera, 1994].

Jarácuaro is well suited for an integrated assessment of the impact of fuel and stove substitution on intra- and inter-household dynamics, health, and economic development. Commercial markets exist for a variety of stoves and fuels. The region around the village is heavily deforested, and a fuelwood market is well established. Fuelwood costs 0.2 pesos (P)/kg (US$0.07/kg), a price that has risen roughly 200% over the past three years. (As of August 1996, the exchange rate was 7.5P = $1, which is used throughout this paper.) Over 90% of the families in Jarácuaro purchase wood weekly. Average fuelwood consumption in Jarácuaro has been estimated at 2 kg/capita/day, and thus a total consumption of 1,400 tonnes/year. The use of timber and fuelwood is extensive in the region. In neighboring communities, fuelwood is also used in small pottery, brick-making, and baking industries [Fernandez, et al., 1997; Hibbert, 1997]. The total demand in the region is estimated at 1,300,000 m^3/year (600,000 tonnes/year) of which ~437,000 m^3/ year is for fuel while 267,000 m^3/ year is for other household uses, and 170,000 m^3/ year is for small-scale industrial activities [Masera, 1994].

A wide range of stove types are used in Jarácuaro. The simple ‘‘three stone’’ fire is found in many households, although used most frequently as the everyday technology primarily among the poorest segments of the community. Traditional stoves are used by many families as well, and range from a ring of stones reinforced and shielded by a

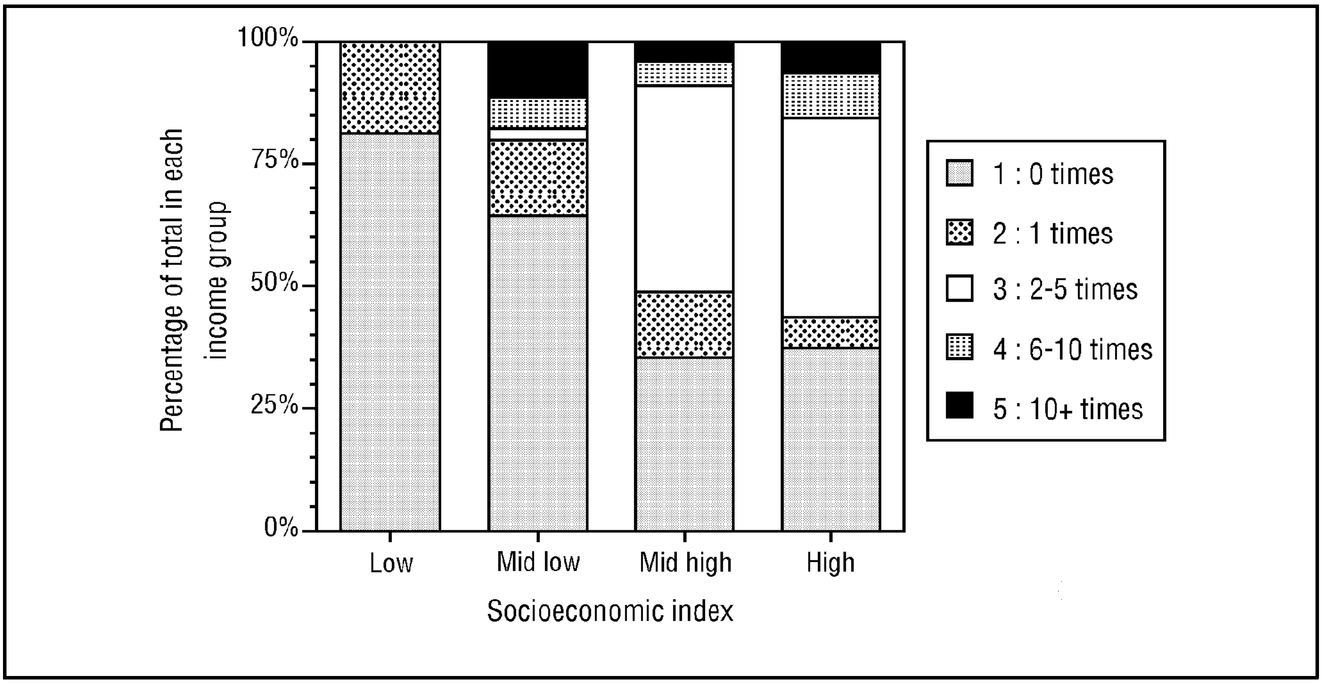

Figure 3. Socioeconomic level versus reported doctor visits over a 12-month period.
The number of reported visits to the doctor is plotted against the socioeconomic level assigned to each individual and family as per Table 1. Data was collected for 138 of the 141 people in the sample group, with 32 responses from (or about, in the case of children) members of the highest socioeconomic group, 45 from the mid-high and mid-low groups, and 16 from members of the lowest group.

Table 1. Socioeconomic ranking of families in the Jarácuaro survey

Socio economic ranking	Typical land holding (ha)	Typical family employment	Typical resources
High (I)	> 5	Large commercial activities	Vehicles, livestock
Mid-high (II)	3-5	Wage income, professionals	Livestock
Mid-low (III)	1-2	Artisans, skilled laborers	Few animals
Low (IV)	< 1	Underemployed, subsistence	Minimal to none

Notes

The 21 families were selected as a representative sample of local socioeconomic groups, categorized as low (IV), mid-low (III), mid-high (II), and high (I). The categories are distinguished primarily on the basis of access to animal and mechanical resources, and are in accordance with the earlier work by O. Masera [1994].

wall of clay or earth, to more elaborate masonry enclosures with one or more fireboxes and separate openings for pots and the *comal*. A common improvement is a *traditional elevated* stove on a block base. A number of local research and development organizations have been involved in ''appropriate technology'' programs in Jarácuaro to disseminate improved efficiency *lorena* woodstoves with chimneys that can substitute for the use of three-stone fires, traditional clay and earth stoves (either built directly on the ground or elevated), and even gas stoves. From a health perspective, the most important single feature of these stoves is that they have chimneys. Liquefied petroleum gas (LPG) is used throughout the region, primarily by the more affluent households. In Jarácuaro, roughly 37% of the families use some LPG, which is supplied to local distributors regularly by truck. Economic factors influence the use of LPG, which is generally sold in 30 kg tanks which sell for ~35 P/tank, or about 1.2P/kg ($ 0.16/kg). The initial cost of the LPG stove and tank is 500-2,000P, depending on the model. Beyond the cost, a significant impediment to the use and complete substitution of fuelwood by gas is a strong local preference for the taste of tortillas prepared on the wood-burning stoves, and the need for fuelwood for frequent traditional feasts and ceremonies.

The data collection methodology employed in Jarácuaro was designed to provide concurrent information on the management of cooking fuels, health outcomes, and socioeconomic status and change. The study sample consists of 21 households (inhabited by 141 individuals) where indoor air pollution levels were monitored and health surveys were conducted during both the wet and dry seasons. The strength of this study does not lie in the quantitative data alone, but also in the agreement between the analytic and more qualitative findings on energy use and health in Jarácuaro. Further, a recent survey by Masera and colleagues of 420 households in three regions of Mexico, including more than 100 homes in the Purépecha region, serves to confirm the findings presented here.

The household sample we gathered is stratified socioeconomically because extensive kinship and exchange networks preclude a simple univariate income ranking. A four-tier ranking (low, mid-low, mid-high, and high) is used to maintain consistency and build on previous research in the region [Masera, 1993]. Households were assigned to one of the four categories based on survey information and the preliminary interviews, and on concordance with the local community perception of family wealth and status. The ranking is in accordance with a variety of local assessments, both subjective and based on resource inventories. The 21 families were selected as

Table 2. Comparison of per capita costs and energy use to prepare a meal

Stove type	Fuel	Fuel cost (US¢/kg)	Usage (kg/meal/cap)	Sample size (#)	Energy content (MJ/kg)	Cost/meal (¢/meal/cap)	Energy use (MJ/meal/cap)
TSF	Wood	7	0.5-1.0	> 100	16	3-7	8-16
Traditional	Wood	7	0.7	3	16	5	11
Elevated	Wood	7	0.3-0.8	38	16	2-6	5-13
Lorena	Wood	7	0.6	2	16	4	10
LPG	Gas	18	0.4-1.0	> 40	51	7-18	20-50

Notes

The table compares estimates of the energy use and the cost of the fuel used to prepare meals with the stove/fuel combinations most common in Jarácuaro. Wood use in a three-stone fire (TSF) is based on two separate estimates: (1) the regional per capita daily range of 1.0-2.0 kg/wood/day, assuming two cooked meals/day (Masera, et al., 1993; Masera, 1994, p. 269); and (2) our data set of 10 three-stone stoves (used for the preparation of *nixtamal, tortillas,* and *comida)* that used an average of 0.55 kg/capita/meal. Among the houses we surveyed, the traditional stove and the improved *lorena* stoves were used only for *tortillas;* the wood use levels are given as single average values due to the small sample size. Data for the elevated, but otherwise unimproved, stove is from homes we surveyed, and is for the same cooking pattern as the three-stone fire: preparation of *nixtamal* to be subsequently made into *tortillas,* and an aggregate number for *comida* (main, mid-day, meal). Masera (personal communication) estimates that the standard 30-kg LPG tank lasts for about 45 days (for mixed fuelwood-LPG users). This is used to prepare two meals/day, a light breakfast and a large lunch, which suggests a reasonable lower bound on the gas required to prepare a meal to be 0.2-0.5 kg. Based on a 50:50 wood/LPG split for actual fuel use, we estimate 0.4-1.0 kg/meal of fuel used per idealized ''LPG'' meal. Monitoring of individual homes is consistent with this range. Family size is based on that of the Jarácuaro sample, (141 persons/21 families) = 6.7 persons per household. Both wood and gas are purchased commodities in Jarácuaro. Note: ''Energy use'' is not a measure of efficiency, it is instead based on total fuel consumption, and thus reflects the energy usefully consumed and wasted heat.

representative of the local socioeconomic groups, categorized as low (group IV), mid-low (III), mid-high (II), and high (I). The categories are distinguished on multiple grounds[1], with the most direct measures based primarily on land ownership, the type of family employment, and by level of access to animal and mechanical resources, as show in Table 1.

Surveys were also used to collect data on the purchases of fuelwood or gas for each household, while in-depth interviews were used to detail the health history of each individual. The survey was developed in collaboration with an indigenous community development organization, a regional doctor (MD), and local energy and health researchers. The survey forms are in Spanish, with translation to Purépecha when necessary. Data on individual morbidity was based on interview responses without a medical practitioner present, and later discussed and/or spot-checked with a collaborating MD from the Centro de Estudios Sociales y Ecológias, A.C., for consistency with records from out-patient clinic visits in the region. Data was collected from over 200 individuals, but some houses were not revisited for pollutant data during both the wet and dry seasons and these have been excluded from this study. Interviews in 21 households with or (in the case of children) about 141 individuals, are included in this data set. 65% of the people interviewed were girls and women.

The RSP data were collected by a drawn air filter calibrated to a flow rate of 1.9 l/ min (SKC Inc., Eighty Four, PA). Samples were collected via an SKC cyclone, which removes particles larger than 7.1 μm. The resulting collected particulate matter is roughly comparable to PM_{10}. The exposed filter and a control (matched to within 25 μg) were handled and weighed according to NIOSH [1994] protocol 0600 on a 5-digit accuracy electronic balance at the University of Morelia, Mexico (pilot study) and at Texas A&M University. The resulting uncertainty in airborne particulate concentrations is < 30 $\mu g/m^3$. These data consist of readings of 37 ambient control measurements, 24 during the preparation of *nixtamal* (corn base for tortillas), 37 measurements during tortilla preparation, and 7 while the main meal, *comida,* is prepared. The measurements lasted for 30-180 minutes, spanning the period of active food cooking. The air was sampled continuously at a flow rate of 1.9 l/min as per the SKC cyclone pump. The pump and filter assembly were worn by the cook, with the air intake valve placed near the collar bone. To generate a representative concentration parameter for each household, RSP measurements were averaged across food types and data collected during the wet and dry seasons [Saatkamp, Masera and Kammen, 1998].

Trace gas emissions (CO, CO_2, NO_x, SO_2)) were recorded at a set of points around the stove during food preparation: at the location of the stove (x = 0.0m distance, y = 0.0m height above the stove), in the effluent gas column (0.0m, 1.0m), at the average location of the cook (0.5m, 0.5m), as well as at grid points extending up to 1.0m in radius along three cardinal directions. The [CO] data, which is featured in this analysis, and the other trace gas measurements, were recorded by an electrochemical sensor manufactured by Energy Efficiency Systems (Westbury, NY). The individual [CO] measurements are accurate to within ± 5 ppm (at standard conditions of 1 atm pressure and 25ºC temperature, 1.145 ppm = $1 mg/m^3$). Measurements were taken every 15 minutes during the cooking of each of the primary foods (*nixtamal,* tortillas, *comida).* The [CO] cited in this paper is the concentration at the location of the cook (as with the RSP data, averaged over food types, and season). The sample consisted of measurements for three households using ''three stone'' fires, four traditional adobe and brick stoves directly on the floor, 13 traditional stoves with the combustion chamber elevated 0.5m off the floor, two improved efficiency biomass *(lorenas)* stoves with an enclosed combustion chamber and a chimney to vent

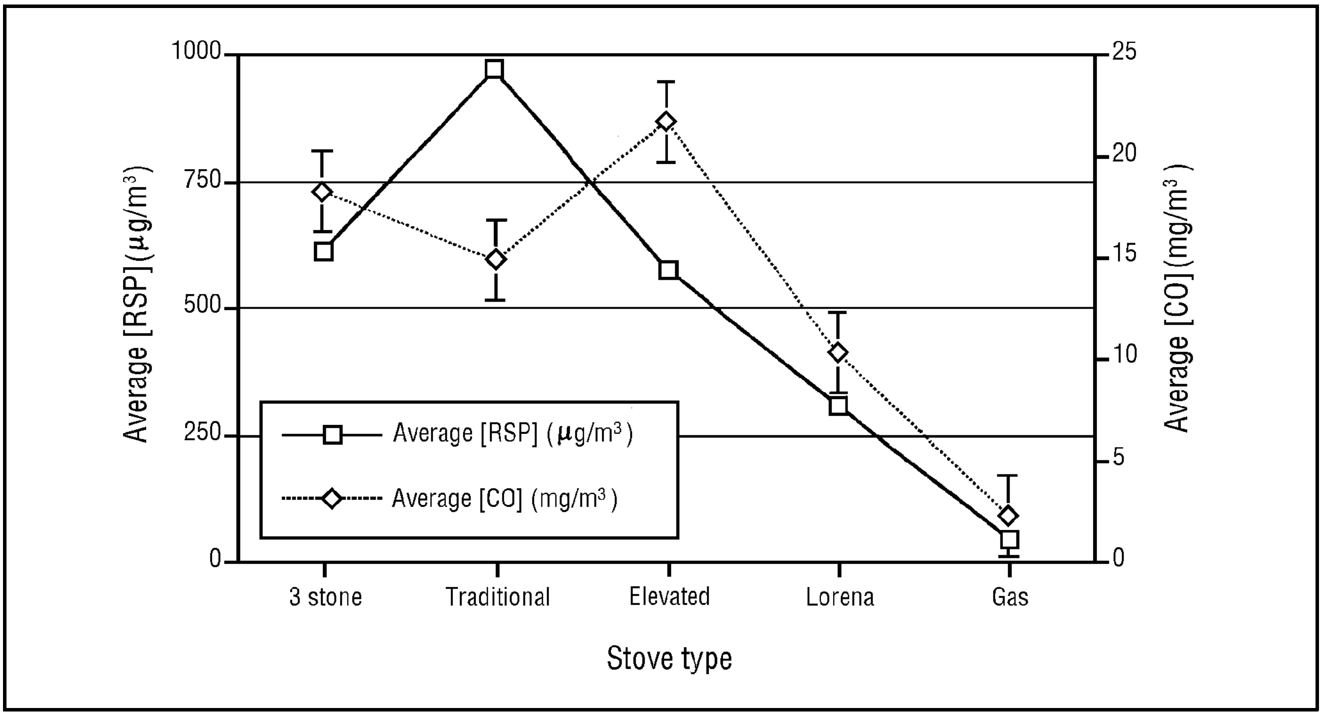

Figure 4. The technological energy ladder
Average airborne concentrations of both respirable particulate matter [RSP] and [CO] for a variety of cookstove varieties utilized in Jarácuaro, México are presented. Both the RSP and CO data were taken at the location of the primary cook, with hand-held sampling equipment (for CO) or personal monitors worn at shoulder height in the case of RSP data. The data shown are the averages of wet and dry season measurements and during the preparation of each of the local staple foods. The RSP data is based on over 230 individual filter exposures, while over 400 [CO] measurements were used. The three-stone fires and some of the traditional stoves are placed outdoors, diluting the concentrations and lowering the RSP and CO levels; all other measurements are for indoor kitchens.

pollutants outside the home, and one gas stove[2].

3. Results

Households in Jarácuaro all have at least some access to a range of fuels, primarily wood and gas, and even some of the poorest families on occasion use improved stoves, or gas ranges. The fuel cost per meal prepared on three-stone fires, traditional stoves, traditional but elevated stoves, or improved *"lorena"* stoves is roughly US$ 0.02-0.07 per person per meal, which is less than half the cost of gas (Table 2). The price of the stoves themselves varies greatly, from nothing for the simplest models, to over US$ 200 for the most expensive gas ranges. A simple breakdown of stove and fuel use by home is impossible because the combination is not constant within a home. This variation is due to a number of factors: the relative prices of wood and gas; seasonal variations; employment and earning power; and because different stove/fuel combinations are preferred for different foods. Nevertheless, a survey of the stoves in use during our visits to conduct household surveys and pollutant measurements provides one rough measure. Over 80% of cooking observed in the highest ranked homes (Type I; n = 30 observing sessions) was on gas stoves, with 60% in Type II (n = 26). The proportions fell to only 30% gas use in Type III (n = 29) and 15% in the poorest (Type IV; n = 15) households. The bulk of the cooking (>80%) in the less affluent homes was on three-stone and traditional stoves.

The survey data listed above suggests that LPG use generally increases with affluence. Fuelwood, however, is more complex. Even in homes that purchase LPG, wood is preferred as a fuel for making tortillas, and for *nixtamal* as well as several other traditional dishes. In addition, families using both fuelwood and LPG (the dominant trend in Jarácuaro) spend more money on all fuel purchases than families that rely exclusively on wood. Thus, the combination of fuelwood and LPG is not simply a strategy to minimize costs or maximize convenience. Instead, the use of both fuels can be viewed as a strategy designed to maintain the benefits of the suite of fuels (wood for tortilla preparation and LPG for morning meals). Relying on both fuelwood and LPG is also a logical insurance against shortages in one or both fuels.

The average airborne concentrations of both respirable particulate matter [RSP] and [CO] in the cooking area for a variety of stoves is shown in Figure 4. The data are the averages of wet and dry season measurements. The three-stone fires, and some of the traditional stoves are placed outdoors, often in shielded alcoves or alleys. This arrangement dilutes the concentrations of RSPs and CO; all other measurements are for indoor kitchens. The strong correlation of reduced pollutant concentration with improvement in stove type from three-stone, to traditional, to improved traditional, to *lorena*, to LPG stove is consistent with the findings of a number of other studies [c.f. Smith, 1993], and what may be called the ''technological component'' of the standard energy ladder hypothesis.

The relationship between elevated pollutant exposure and morbidity was statistically significant, and can be demonstrated through both quantitative and qualitative measures. People in Jarácuaro possess a large and often specific vocabulary when it comes to illnesses. There is some variation by socioeconomic level, but most people interviewed were quite precise when identifying typhoid fever, asthma, cholera, diarrhea, *gripa* (general pulmonary disorder), and hepatitis. The interviews were all based on local terminology for each condition, and the conditions reported were cross-checked with community members and the local MD. An independent validation was also performed by asking individuals reporting these conditions to describe the symptoms associated with each illness as a test of their ability to discern morbidity outcomes.

Eighteen of 141 people surveyed reported pneumonia, bronchitis, bronchial pain, chronic cold, and severe asthma/breathing disorder associated with pollutant exposure. These symptoms are characteristic of, and were recorded as, acute respiratory infection (ARI). As seen in Figure 5, women who cook regularly presented a relative risk (RR) for ARI of 2.0 (95% confidence interval 1.3 < RR < 2.7)[3]. This result is particularly telling, with the real RR probably even higher because women were far less likely to report illness of any kind than were men.

Measurement of RSP levels revealed a further set of correlations with morbidity. The average [RSP] exposure for individuals reporting ARI was 655 $\mu g/m^3$ while it averaged 574 $\mu g/m^3$ for non-reporting individuals ($p < 0.02$). Similarly, the RSP exposure for those reporting eye infections was 644 mg/m^3 compared with 574 $\mu g/m^3$ for non-reporting persons. Intestinal illness also correlated with increased domestic RSP exposure. These results are presented in Table 3. The significant linkage between intestinal disorders and higher RSP levels is probably due to the correlation between cooking practices that lead to indoor air pollution and reduced availability of either potable water, or of kitchens with adequate sanitary or cleanup facilities. In total, these measures make a compelling case for broad linkages between morbidity and lower quality energy supplies, and specific food technologies and management practices.

The connection between stove type and pollutant exposure, and the correlation between human exposure and health risks argues for the need for integrated energy and health research, and indicates the presence of avoidable health risks. Policy-makers often look to economic advancement as a clear avenue to shift families up the energy ladder and thus to reduce the morbidity in developing nations [WHO, 1987; Hosier and Dowd, 1987; World Bank, 1993]. Jarácuaro presents a community with all the traditional factors at work: differential economic advancement; market pressures on all fuels and stoves; and multiple options as to which stove to select.

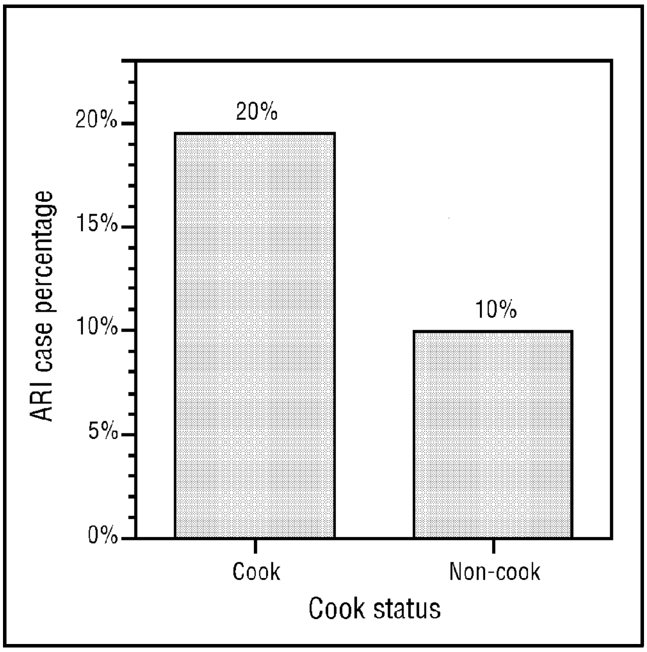

Figure 5. Cooking and the incidence of ARI
Among the study population of 141 individuals, those reporting cooking as a primary occupation were twice as likely to report symptoms of ARI (RR = 2.0, 95% C.I. = 1.3-2.7) as non-cooks. This result, while significant, is likely to be an understatement because women and lower status individuals within households consistently reported fewer illnesses than did men and formal wage earners.

Table 3. Morbidity and RSP exposure

Illness	Mean level in homes reporting illness ($\mu g/m^3$)	Mean level in homes not reporting illness ($\mu g/m^3$)	Number of observations (N)
ARI	655	574	18
Eye infection	644	574	15
Intestinal infirmity	688	534	15

Notes

Summary of illnesses found to be significantly correlated with increased RSP exposure is displayed here. Note that both RSP concentrations in both types of homes are far above the recommended US and Japanese exposure levels of 150-260 $\mu g/m^3$.

4. Broken rungs on the energy ladder?

As we have shown in the previous section, transitions up the energy ladder from one fuel and stove combination to another can reduce the household pollution burden. This result is in agreement with a number of previous studies of the energy ladder [Reddy, 1982; Masera, et al., 1989; Hosier and Dowd, 1987; Smith, 1993; Masera, 1994; Ellegård, 1996]. However, the data from Jarácuaro also reveal a breakdown in the reliance on affluence alone to mitigate health risks. Within our household survey, the average particulate concentration did not decrease consistently as income level rose, as illustrated in Figure 6. The average particulate concentration in the lowest income homes is 449 $\mu g/m^3$, but it is almost twice that, 845 $\mu g/m^3$, in the most affluent households. The absolute comparison of these values is not particularly significant, given the small sample size, and because many of the poorest families cooked outside, which resulted in lower concentrations.

In Jarácuaro homes, the mean RSP and CO concentrations from gas stoves are measured to be 5-7 times lower than from traditional stoves. This fact, combined with the high pollution levels observed in some of the most affluent homes, paints a very mixed picture that does not

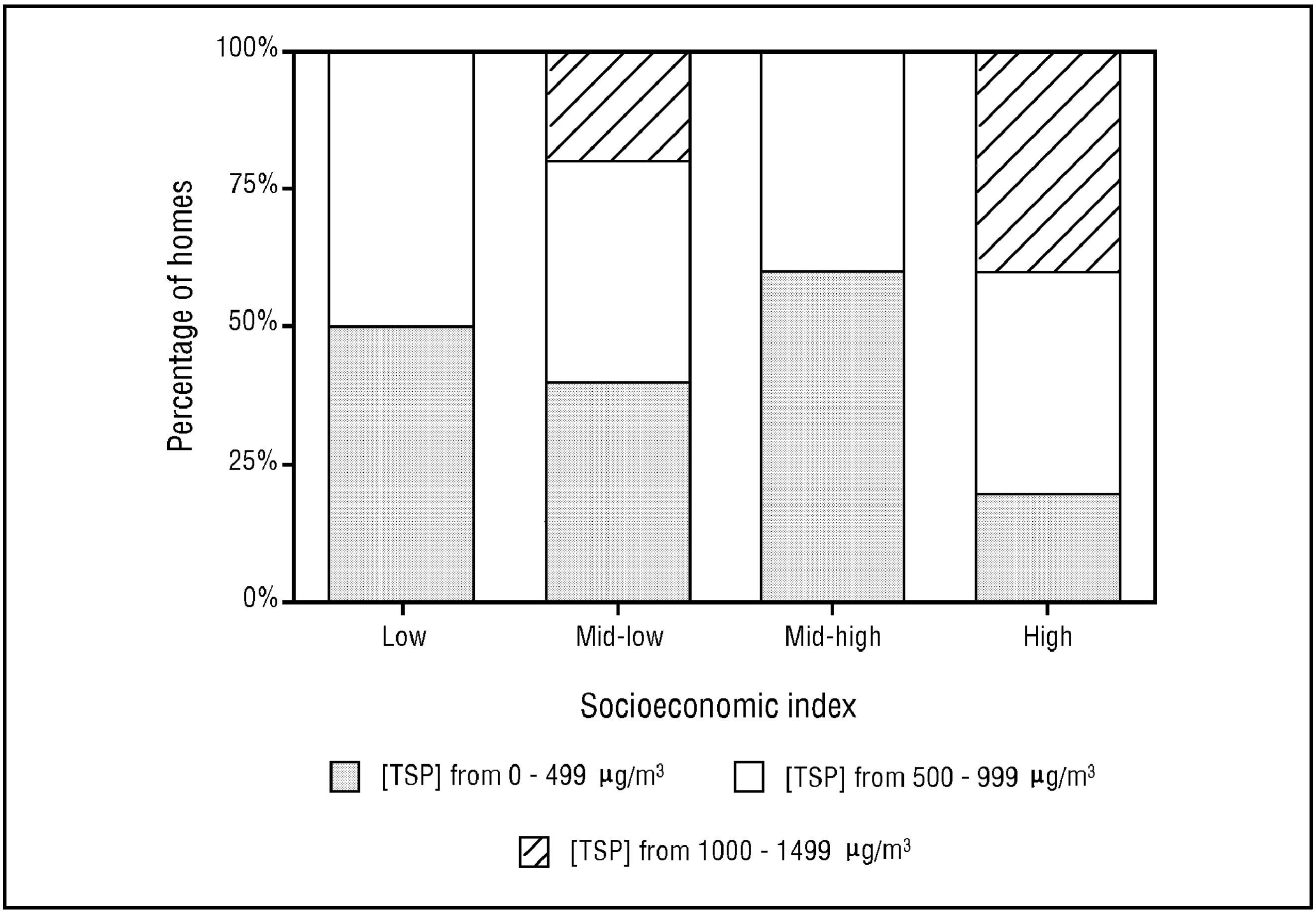

Figure 6. Relationship of indoor air quality to socioeconomic status

In contrast to Figure 2, no significant beneficial relationship is observed between indoor air quality (as measured by RSP concentration) and socioeconomic status. Some of the cleanest and best ventilated kitchens were found among the most affluent (Table 4), but so were some of the most polluted and poorly designed, maintained, or ventilated. The result is particularly striking in that the highest proportions of gas stove usage were from the most affluent, Type I, households. Mean RSP and CO concentrations from gas stoves are 5-7 times lower than from traditional stoves.

conform to the traditional energy ladder. At least in Jarácuaro, and arguably in many other areas as well, cooking practices and attention paid to the environmental quality of the kitchen are the most important determinants of the health impacts of energy and fuel management.

Increases in socioeconomic status do commonly lead to household improvements such as improved access to health care, potable water, and sufficient food supplies. Of direct relevance to our study, increases in socioeconomic status also resulted in the installation of vented tiles and cement floors in the main living spaces of the home. As shown in Table 4, however, a rise in income level does not necessarily lead to an equivalent increase in kitchen quality. Almost every household classified as high or mid-high (Type I or II) invests in cement or improved floors (100%) and vented (''Spanish'') tile roofing (83% for Type I households) for the main dwelling area. By contrast, 33-50% of those same households still have dirt floor kitchens (33%), or poor quality, unventilated kitchen roofs (50%).

In higher quality kitchens vented ceiling tiles, to permit the escape of pollutants, and cement floors also are incorporated in the construction. Kitchens are often overlooked as families make household improvements, and relatively wealthy families choose to invest their income in other areas. When questioned why her kitchen was constructed without any vent for smoke, one woman said, ''We keep meaning to fix the kitchen, but *no one comes in here* anyway, and we just haven't done it.''

5. Conclusions

As we demonstrated in the Results section, and characterized in Figure 4, the technology and the management skills certainly exist to reduce indoor pollution levels. Further, the reductions are not simply between equally unhealthy conditions. Clear benefits for the poor and rural populations, in terms of respiratory, eye, and intestinal disorders, are associated with improvements in the indoor environment. In turn, the indoor environment is determined largely by the management of energy and water resources for cooking. The next stage in the ladder hypothesis predicts a corresponding improvement in the pollutant burden when stove technology is replaced by socioeconomic status as the independent variable. Both Figure 6 and Table 4 document that this has not consistently taken place in Jarácuaro.

In Figure 7 an additional measure, that of self-reported overall health quality, is presented. The use of markers (such as ''Poor health means that you cannot work, or cannot be without pain from a serious illness'') helps to control for the ''wealth-health effect'', which itself can take two, opposite, forms. First, some individuals may see themselves as more/less healthy as a function of greater/lower economic status, and second, it is possible that with increased education as to the potential range of illnesses, some individuals may view themselves as afflicted when a similarly ill but less affluent person would not report any significant morbidity event. Tests of each potential wealth-health effect were statistically insignificant on our sample. This is important given the clear trend of increasing medical access for the more affluent as shown in Figure 3. Overall, we find no clear trend towards greater health simply as a function of increasing socioeconomic status in Jarácuaro.

The problems of viewing household development and fuel choice strictly in terms of the energy ladder lead to an obvious but important conclusion: the availability and development of appropriate stove technologies is less critical in combating health risk due to indoor air pollution than is general education regarding these risks. The trend suggests that even if all families possessed the economic resources to purchase less-polluting stove technologies and kitchen refurbishments, the benefits of doing so are either not recognized or devalued in comparison with other investments. In fact, *no* family member interviewed irrespective of socioeconomic level identified the various pulmonary disorders as related to smoke exposure. The result is that even as families move up the energy ladder there is often little attention paid to stove placement, kitchen ventilation, and construction materials.

Improved, *lorena*, stoves present an important and interesting alternative to the energy-ladder socioeconomic advancement model. Lorena stoves present several advantages: their proper use can save 30-40% of the average fuelwood requirements of the traditional (Type-U and TSF) stoves. In addition, the average total suspended particulate and carbon monoxide concentrations associated with the lorena stoves can be half that of the traditional models. These reductions are, however, dependent on careful training, installation, and management education. In communities with active improved cookstove promotion and construction programs, the lorenas have been quite successful and are in considerable demand among

Table 4. Relationship of house and kitchen construction materials to socioeconomic status

	Construction material	High (n=6)	Mid-high (n=6)	Mid-low (n=6)	Low (n=3)
House	Cement floor	67%	67%	17%	0%
	Mixed floor	33%	33%	66%	67%
	Dirt floor	0%	0%	17%	33%
	Vented tile roof	83%	33%	17%	0%
	Mixed roof	17%	67%	83%	33%
	Carton roof	0%	0%	0%	67%
Kitchen	Cement floor	67%	50%	0%	0%
	Mixed floor	0%	0%	0%	33%
	Dirt floor	33%	50%	100%	67%
	Vented tile roof	50%	50%	0%	0%
	Mixed roof	33%	0%	33%	0%
	Carton roof	17%	50%	67%	100%

Notes

This is a comparison of the material investment in the living areas of the homes with that in the kitchens in the surveyed households in Jarácuaro.

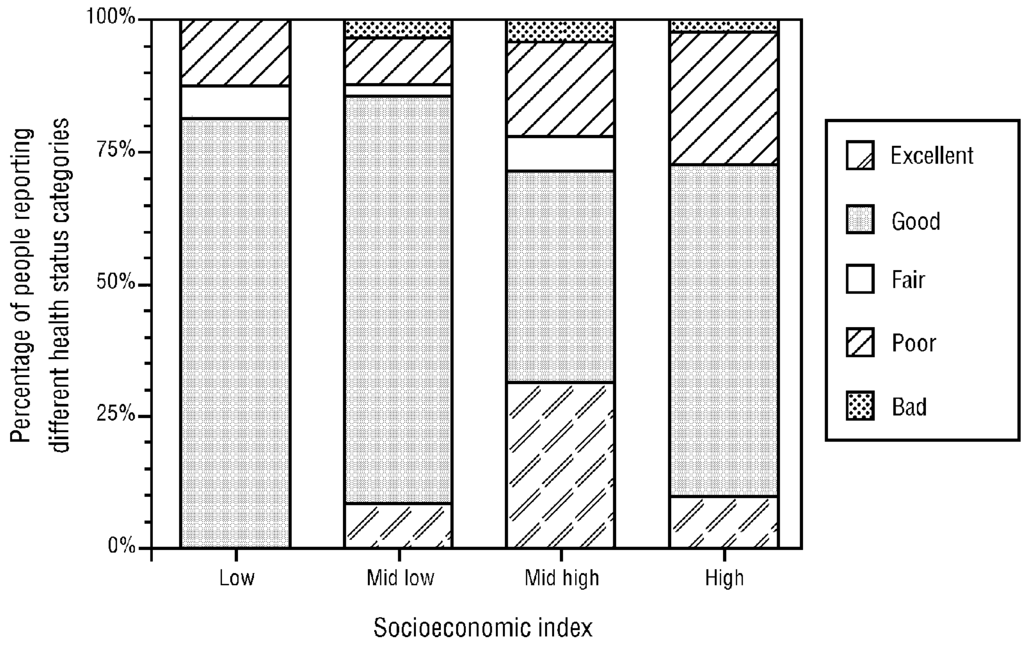

Figure 7. Socioeconomic level versus reported health status
Reported health status as a function of socioeconomic level for 138 of 141 members of the Jarácuaro study group. While this is a subjective indicator, the lack of any clear health-wealth correlation is consistent with the other project findings. Statistical analysis indicates no significant trend correlation between socioeconomic status and ARI, eye or stomach illnesses. In fact, the highest incidence of ARI occurs in the mid-high (II) group (nine of 18 total cases), versus three in Group I, five in Group III, and one in Group IV.

the wealthy and the poor alike.

Development planners have often relied on technical interventions as the catalyst for socioeconomic advancement. This trend is exemplified by the widespread interest in ''inverted-U'' relationships, or Kuznets curves, between pollutant concentrations and per capita GNP as a fundamental means to improve the health and well-being of the poor [World Bank, 1992]. However, the data from Jarácuaro sounds a warning that increasing income level and even improving the quality of energy technology does not guarantee an improvement in household health. Greater affluence naturally has a variety of benefits, but does not replace social and educational programs, nor research and development efforts directed at specific social, economic, and environmental problems. As shown in our analysis, local acceptability, fuelwood savings, and pollution reduction can all be achieved in households across socioeconomic levels. The challenge for policy-makers is to integrate and sustain technology and health education as a primary component of development planning. ■

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Notes

1. A second measure of socioeconomic status, access to health care, is also highly instructive. In Figure 3 we plot the annual doctor visits for members of the four socioeconomic groups. This measure of status is quite robust: a clear drop-off in visitation frequency between the mid-high and mid-low groups can be seen, but this was never a question when members of Jarácuaro were polled on where to assign particular households or individuals. What debate existed at all was almost always between the two lowest or between assignment within the two highest groups; switching ranking between these groups has minimal impact on the results presented here. In addition, the household rankings based on material resources (livestock and vehicle ownership) and employment (Table 1) were generally equally clear and robust against ''mis-assignment''. One interesting, although somewhat subjective, observation is the correlation between access to health care and *actual* health (measured by reported episodes of illness). In particular, is there a ''wealth effect'' in term of greater overall health among the more affluent households? We shall return to this issue in the later part of this paper and the discussion of Figures 6 and 7 as well as in [Masera, Saatkamp, and Kammen, 2000].
2. The variation in the number of stoves reflects the distribution observed in the village. All families in Jarácuaro were included in the study, with the data presented drawn from all households where sufficient data was obtained.
3. The relative risk, RR, indicates the excess risk (RR>1) with the associated 95% confidence interval shown in parenthesis. The RR of 2 indicates that the exposed individual is twice as likely (200%) to develop ARI as a person in the control group.

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