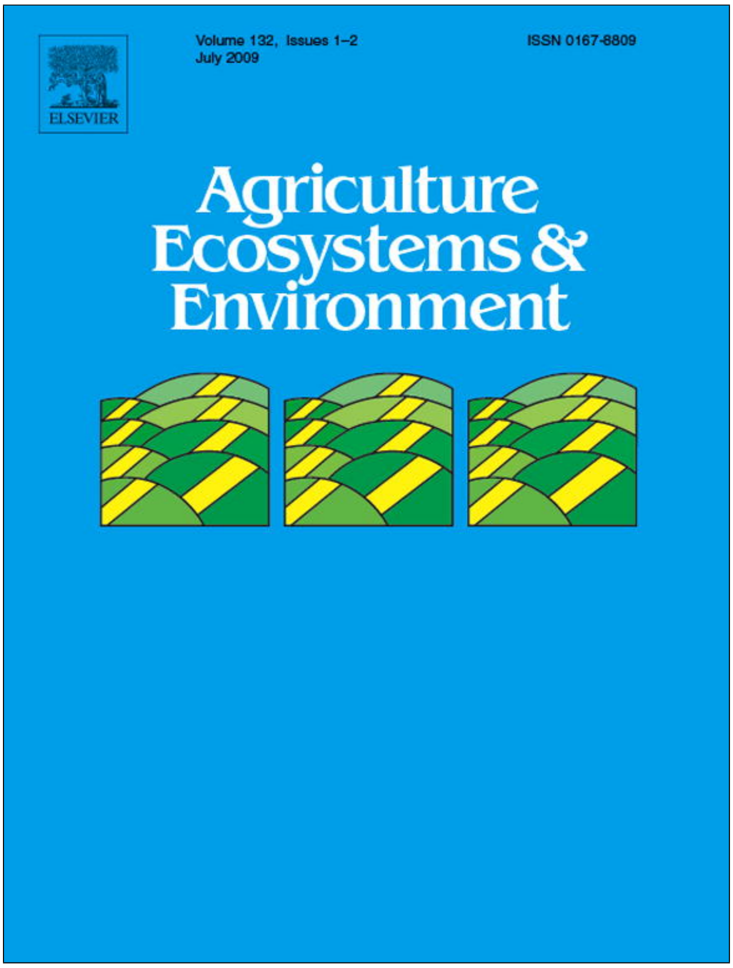
Volume 132, Issues 1–2
July 2009
ISSN 0167-8809
ELSEVIER
Agriculture Ecosystems & Environment

Agriculture, Ecosystems and Environment 132 (2009) 48–56

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Expansion of sugarcane production in São Paulo, Brazil: Implications for fire occurrence and respiratory health

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ARTICLE INFO

Article history:
Received 22 September 2008
Received in revised form 18 February 2009
Accepted 24 February 2009
Available online 31 March 2009

Keywords:
Agro-energy
Sustainability
Cerrado
Ethanol

ABSTRACT

Recent increases in the price of oil have generated much interest in biofuel development but the social and environmental impacts of large scale adoption of biofuels at both regional and national scales remain understudied, especially in developing economies. Although the recent swings in prices for oil may slow down these surges in supply and demand, production of biofuels from food remain profitable above $50/barrel making the biofuel market viable. Here we use municipality-level data for the state of São Paulo in Brazil to explore the effects of fires associated with sugarcane cultivation on respiratory health of elderly and children. We examined the effects of fires occurring in the same year in which respiratory cases were reported as well as chronic effects associated with long-term cultivation of sugarcane. Across the state, respiratory morbidity attributable to fires accounted for 113 elderly and 317 child cases, approximately 1.8% of total cases in each group. Although no chronic effects of fire were detected for the elderly group, an additional 650 child cases can be ascribed to the long-term cultivation of sugar cane increasing to 5.4% the percent of children cases that can be attributed to fire. For municipalities with greater than 50% of the land in sugarcane the percentage increased to 15% and 12%, respectively, for elderly and children. An additional 209 child cases could also be attributed to past exposure to fires associated with sugarcane, suggesting that in total 38% of children respiratory cases could be attributed to current or chronic exposure to fires in these municipalities. The harmful effects of cane-associated fires on health are not only a burden for the public health system but also for household economies. This type of information should be incorporated into land use decisions and discussions of biofuel sustainability.

Sustainable land management must balance environmental, economic, and social concerns at multiple scales (Daily and Ellison, 2002). Many developing countries are expanding biofuel production as a strategy to reduce their dependence on petroleum, increase opportunities for the agricultural sector, and mitigate global warming (Dufey, 2006; WWI, 2007). The area planted to biofuel crops has been growing rapidly but the environmental and social consequences of a widespread adoption of biofuel production remain largely unexplored: There are questions about the potential effect of expanding biofuel crop areas on the world's food production and food security (Muller et al., 2007); the feasibility of basing agricultural development plans on agro-energy as opposed to food and fiber production (Charles et al., 2007); the impacts of land use change on the natural resource base and on biodiversity (Hill et al., 2006; Raghu et al., 2006; Fargione et al., 2008); and the potential effect of biofuel crop expansion on land tenure and the livelihoods of small farmers (Mol, 2007). These issues are currently being viewed as opportunities by some and as threats by others throughout the developing world. Although the recent swings in prices for oil may slow down these recent increases in supply and demand, production of biofuels from food remain profitable above $50/barrel making the biofuel market viable.

From a global perspective, there is little support for biofuel cultivation as a strategy to either mitigate anthropogenic carbon emissions or meet predicted world energy demand (Giampietro et al., 1997; Dias de Oliverira et al., 2005; Righelato and Spracklen, 2007; Crutzen et al., 2007; Fargione et al., 2008). However, political and economic considerations at a regional and national level have generated a considerable amount of enthusiasm for the use of biofuels as a short- to mid-term solution (Goldemberg, 2007; Nass et al., 2007). Typically, studies undertaken at this scale have analyzed the potential of particular energy policies to reduce dependency on foreign oil, or have explored the implications of biofuel expansion on job and income generation (e.g., Moreira and Goldemberg, 1999; Kivronos and Olarreaga, 2006; WWI, 2007; Goldemberg, 2007). Comprehensive analyses of the social and

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doi:10.1016/j.agee.2009.02.018

environmental consequences of bio-energy expansion at a regional or national scale are generally lacking (but see Hill et al., 2006; Martinelli and Filoso, 2008). Yet, this type of analysis is essential to fully evaluate the actual costs of biofuel programs and to inform decision making.

Labor costs, land prices, and the amount of solar radiation all suggest that developing countries in the tropics would have much to gain from an increase in worldwide biofuel consumption. Moreover, tropical or subtropical countries with fast-growing economies depend critically on cheap energy and can also benefit from reducing their dependency on oil imports. Current trends in biofuel expansion support these assertions. For instance, ethanol production in India increased from 665 million liters in 2005 to 823 million in 2007 (WWI, 2007). In addition, large areas are being planted with oilseed crops. Clearly, cheap biofuel can foster economic development in these growing economies, but at what social and environmental costs? One potential consequence of biofuel expansion is that agricultural productivity increases at the expense of environmental health and fair labor practices. Incorporating these and other externalities into existing analysis is particularly crucial for developing countries with high indices of social inequality, vulnerable populations, and either weak or unenforceable environmental and labor regulations.

Brazil, the world's leader in ethanol production from sugarcane (*Saccharum* L.), stands to profit greatly from the recent boom in biofuel markets (Martines-Filho et al., 2006). In 2007 alone, it produced 19 billion liters of ethanol from sugarcane, a quantity similar to that of corn ethanol in the United States. Over 50% of the sugarcane harvest is exported. The history of sugarcane in Brazil has been documented extensively (Moreira and Goldemberg, 1999). In brief, the sugarcane boom occurred in the late 1970s, a response by the military government to the oil crisis of 1973. The aim was to replace a significant percentage of fossil-fuel consumption with ethanol produced from sugarcane. Initial price subsidies from oil revenues, mandatory regulations determining the amount of ethanol to be mixed with gasoline, and funding for an aggressive research and development program led to wide adoption of ethanol as a fuel source and lowered production costs. By 2004, ethanol subsidies had been removed and ethanol became competitive with gasoline in the market (Moreira and Goldemberg, 1999). In recent years, renewed interest in alternative energy sources has fostered an expansion in the area planted to biofuels, especially to sugarcane. From 2006 to 2007 alone, the area planted in sugarcane increased by 10.6% relative to the previous year with concomitant decreases in the area of pastures and other crops (IBGE). Brazil's unique position in the biofuel market and the availability of extensive social and environmental data provides us with a unique opportunity to evaluate some of the social and environmental consequences of biofuel production, particularly in the light of the growing global interest in biofuels.

Sugarcane can be harvested mechanically or manually, though the majority of global harvesting is currently done by hand. Manual harvesting begins with burning of the field to remove dry and dead growth. The cane is then cut with machetes. Mechanical harvesting utilizes a specialized chopping machine, a combine. The machine cuts the stalks and removes the leaves. However, mechanical harvesting is a low-efficiency procedure, which results in greater levels of sugar loss from cut cane, and therefore lower revenues than from manually harvested cane. In Brazil, most of the sugarcane is produced in the northeast or south central regions. The State of São Paulo accounts for 60% of production of both sugar and ethanol and for 70% of exports. Cane is harvested continuously from May to October (the dry season). Almost 80% of the Brazilian harvest is manual (UNICA, 2008).

Sugarcane production in Brazil has been associated with a number of unsustainable environmental and social outcomes. These include atmospheric pollution from fires used to facilitate harvest (Martinelli et al., 2002; Santos et al., 2002; Allen et al., 2004; Lara et al., 2005), soil degradation (Cerri et al., 1991; Ceddia et al., 1999; Oliveira et al., 1995, 2000; Pereira-Netto et al., 2004), pollution of aquatic ecosystems (Ballester et al., 1999; Martinelli et al., 1999; Oliveira et al., 2002; Filoso et al., 2003; Gunkel et al., 2007), loss of biodiversity (Ometto et al., 2000; Dotta, 2005; Gheler-Costa, 2006), and exploitation of cane cutters, mostly migrant workers from northeastern Brazil (Costa and das Neves, 2005; Rodrigues, 2006; Alves, 2006; see Martinelli and Filoso, 2008, for a comprehensive review).

Pre-harvest burning of sugarcane also affects human health in areas where it is the major land use. In addition to the particles produced as byproducts of biomass burning, pre-harvest fires have been related to increased levels of carbon monoxide and ozone in the agricultural region and cities where sugarcane is produced (Kirchhoff et al., 1991). Epidemiological studies in two municipalities in São Paulo concluded that sugarcane burning led to low air quality and increased incidence of respiratory morbidity (Arbex et al., 2000, 2007; Cançado et al., 2006). These two studies were conducted in municipalities where sugarcane accounts for over 50% of land cover, so it remains unclear to what degree sugarcane burning contributes to respiratory illness at the state level. Here, we collect state-wide data for São Paulo to determine the magnitude of sugarcane expansion in the state. Using this data, we examine the spatial and temporal links between current and long-term sugarcane cultivation, occurrence of fires, and respiratory health. Finally, we take our analysis one step further to make predictions about the effects of recent expansion of sugarcane cultivation on fire occurrence and respiratory health outcomes.

1. Methods

1.1. Study area and data collection

We focused our analyses in the state of São Paulo, Brazil. Agricultural land use in the state is dominated by sugarcane plantations (Fig. 1) and pastures, with the former being more prevalent in the northwestern part of the state and the latter on the eastern region. To understand spatial variation in sugarcane cultivation across the state and its overall importance in total agricultural production, we collected annual data on the area in cultivation for each major crop as well as production statistics for each municipality (1990–2006) from the Brazilian Institute of Geography and Statistics (IBGE).

We obtained fire occurrence data for 2003 from INPE, the Brazilian National Space Agency (http://www.dpi.inpe.br/proarco/bdqueimadas). These data are derived from images collected by polar orbit satellites that can detect fires $>30 \times 1$ m under clear conditions (consult INPE website for a detailed description of the limitations of the fire data used in the analyses). The number of fires observed was standardized by the area of each municipality. For a subset of the municipalities (46 out of 645), we also collected monthly air quality data, namely concentration (in $\mu g/m^3$) of smoke, inhalable particles ($PM_{2.5}$), SO_2, and total suspended particles (<50 μm in diameter). These data are available from the São Paulo Environmental Agency (CETESB accessed January 2008). Smoke, inhalable, and suspended particles all affect respiratory health directly. In the sugarcane cultivation region, the main source of suspended particles is sugarcane burning (Martinelli et al., 2002; Lara et al., 2005).

To investigate the effects of fire and air quality on respiratory health, we first extracted disease data for 2003 from the government health agency DATASUS accessed January 2008, Brasilia, Brazil. We considered only hospital admissions, and excluded patients who did

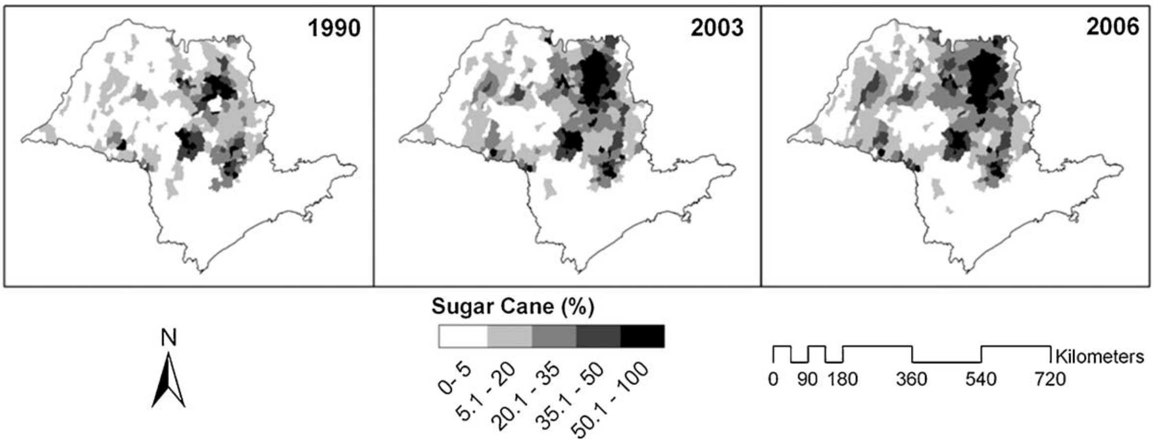

Fig. 1. Percent of total land area in São Paulo municipalities cultivated for sugarcane in 1990 and 2005. GIS municipality data were downloaded from IBGE (www.ibge.gov.br).

not reside within the municipality that housed the attending facility. We selected respiratory disease cases for children ($\leq$10 years of age) and the elderly ($\geq$60 years of age) using standard codes from World Health Organization International Classification of Diseases 10th revision (Codes J00–J99) (WHO, 2007). Probabilities of respiratory disease were standardized in our statistical model (see below) by population numbers in these same demographic classes from the 2000 census (IBGE, 2005).

São Paulo has subtropical weather; it is humid with dry winters and low temperatures are rare. Since respiratory health is linked to weather, meteorological data were obtained from the state of São Paulo network of agro-meteorological stations (CIIAGRO accessed January 2008). Low temperatures may foster respiratory disease directly by increasing crowding and reducing indoor ventilation (Hajat et al., 2004). However, heat can also result in respiratory distress (Shek and Lee, 2003). High relative humidity has also been positively correlated to greater respiratory morbidity, particularly at high temperatures, but the relationship may be reversed at low temperatures (Viegas et al., 2004). Lower humidity and temperature may also impair dispersion of air pollutants, affecting respiratory health indirectly (Tanner and Law, 2002). For our analyses, we used total monthly precipitation and average monthly maximum temperature for 2003. Data were collected from agro-meteorological stations evenly spread throughout the state. Depending on the month, data were available for 98–101 of the 645 municipalities in the state. In cases for which data were not available, we used an ordinary kriging procedure to estimate missing values. Kriging was performed using a Gaussian random field model fit to centroids of municipalities for which we had data (Ribeiro and Diggle, 2001).

Respiratory health is also affected by urban pollution (e.g., Gonçalves et al., 2005) and social and economic status (Roseiro, 2002). Urban development and socioeconomic development indices are highly correlated in the state of São Paulo, with rural areas having lower GDP per capita, a higher percentage of people living in poverty, and lower development indicators (e.g., Human Development Index, GINI economic inequality index) (data not shown). To account for these effects, we included the percent of inhabitants considered rural as a predictor of respiratory disease in our statistical model. Data were obtained from IBGE.

1.2. Statistical analyses

Admissions for children and elderly were modeled separately for all of 2003. We used a mixed effects logistic regression model to understand the dependence of respiratory health on air quality and meteorological variables as well as selected demographic and economic indicators.

The likelihood of a respiratory admission in municipality i in month j for the full respiratory health data set across all M municipalities in the state over 12 months for a given age class is:

$$p(w|s)\prod_{i=1}^{M}\prod_{i=1}^{12_p}\mathrm{Binomial}(w_{ij}|s_{ij}) \tag{1}$$

where the population counts (s) in the demographic class (i.e. elderly/young) was the number of "trials" and the number of admittances (w) were considered "successes".

The probability of a patient being admitted to a health facility is the logit:

$$\mathrm{logit}(s_{ij}) = X_{ij}\beta \tag{2}$$

where X_{ij} is the design vector of factors and covariates, and β is the corresponding vector of parameters. Since weather patterns can affect fire detection, we smoothed the number of fires in each month by averaging values from the previous and current months. Precipitation and temperature are known to have a delayed effect on respiratory morbidity, so we lagged these variables for the analyses by averaging values for previous and current months (Braga et al., 2002). For each municipality, we included as fixed covariates fires per hectare, total precipitation, mean maximum temperature, and percent of inhabitants who live in rural areas. Humidity may affect respiratory health directly, with greater respiratory distress under dry conditions (Gonçalves et al., 2005), and indirectly, through the transport of pollutants (Tanner and Law, 2002). To account for these effects, we included interactions between precipitation and temperature (a proxy for humidity), and the three-way interaction between weather variables and fire occurrence. We expect that the effect of fires on respiratory health will be greater at low humidity. Beyond the effects of the focal year fires on respiratory health, repeated annual burnings can have chronic effects on respiratory morbidity. We also included the amount of land in sugar cane in 1995 to our regressions in an effort to account for the potential effects of past fires associated with sugar cane cultivation on chronic respiratory problems. Municipality was included as a random effect to account for differences amongst these administrative units that are not captured by the fixed covariates (e.g., quality of care). To facilitate interpretation, all estimated parameters were standardized by centering them on their mean and dividing by two standard deviations. We tested model residuals for spatial autocorrelation using a variogram fitting procedure and calculating Moran's I using the centroids of the municipalities. We found no significant spatial autocorrelation in the data (Young: Moran's $I = -0.01$, z-score = -0.16, p-value = 0.56; Elderly: Moran's $I = 0.03$, z-score = 0.36, p-value = 0.359).

Ultimately, our intent is to predict the effect that expansion of sugarcane production will have on respiratory morbidity. However, we encountered two problems. First, fire data for 2003 and later periods were collected using different satellites so they were not directly comparable. Second, a complete respiratory health dataset was not available for 2004–2007. To circumvent these limitations, we modeled the occurrence of fires in the 2003 data using a zero-inflated negative binomial process and used this model to generate predictions of fire occurrence in 2007 as a result of actual expansion in sugarcane cultivation area. The probability of observing ψ fires in municipality i in month j was calculated as:

$$p(\psi_{ij}) \sim z_{ij} + (1 - z_{ij}) \times \mathrm{NegBin}(0|\lambda_{ij}, k) \quad \text{for } \psi = 0 \tag{3a}$$

$$p(\psi_{ij}) \sim (1 - z_{ij}) \times \mathrm{NegBin}(\psi_{ij}|\lambda_{ij}, k) \quad \text{for } \psi > 0 \tag{3b}$$

where z, the zero-inflated part of the probability function is linked to predictors through a logit link as in Eq. (2), and λ and k, the mean and clustering parameter of the negative binomial part of the probability model is linked to predictors in Eq. (2) through a log link. We then used actual data for municipality-level expansion in sugarcane area from 2003 to 2007 to quantify the expected increase in the number of respiratory cases for the two vulnerable populations. All analyses were conducted using R statistical software (R Development Core Team, 2008).

2. Results

2.1. Sugarcane cultivation

The spatial extent of sugarcane cultivation in São Paulo increased from 1.8 Mha in 1990 to 3.28 million in 2006 (Fig. 1). This increase reflects both an expansion in cultivated area in the traditional sugarcane region (e.g., Ribeirão Preto and Piracicaba) and the replacement of pastures with new sugarcane fields in the western, less developed region. Sugarcane accounted for nearly 60% of total agricultural production value in 1990 increasing to 75% by 2006 (IBGE). Total value of sugarcane production was negatively correlated with that of soybeans, reflecting fluctuations in world market prices for these two commodities.

2.2. Fire

Both the spatial and temporal patterns of fire occurrence indicate that sugarcane cultivation is the major cause of burning in the state (Figs. 2 and 3). Air quality data collected at selected monitoring stations further suggest that burning of sugarcane fields leads to greater concentrations of pollutants associated with fires such as smoke, inhalable particulate matter, and total level of suspended particulates (Fig. 3). The marked seasonal fluctuations in the concentrations of these pollutants, which align with the cane harvesting seasonal, stands in stark contrast to the largely aseasonal concentrations of air quality indicators associated with fossil-fuel emissions (e.g., SO_2, Fig. 3).

2.3. Respiratory morbidity

During 2003, there were 5196 admissions due to respiratory disease for the elderly group and 18,052 admissions for children under 10. The average number of cases per month for both groups combined was 2040 for the burning season (May–October) but only 780 for months outside of the cane harvest period (January–April, November–December). Over the course of the year, the mean number of respiratory admissions per thousand individuals was 2.83 for children in contrast to 1.83 for the elderly group, reflecting the high vulnerability of children to respiratory disease.

Overall, our statistical model provided an excellent fit to the data (Elderly: $R^2 = 0.90$, $F = 1$, 6683, $p < 0.00001$; Children: $R^2 = 0.92$, $F = 1$, 6683, $p < 0.00001$). Table 1 presents detailed results of the statistical analyses. Monthly variation in fire occurrence was positively associated with respiratory morbidity for both age groups even after controlling for precipitation and temperature. Fire incidence had stronger effects on respiratory health of the elderly relative to the children group. Fig. 4 presents the estimated number of hospital admissions for both children and elderly, as derived from the results of the regression that can be attributed to cane burning practices. Across the state, respiratory morbidity attributable to fires accounted for 113 elderly and 317 child cases, each ~1.8% of total elderly and child cases. Although no chronic effects of fire were detected for the elderly group, an additional 650 child cases can be attributed to the long-term

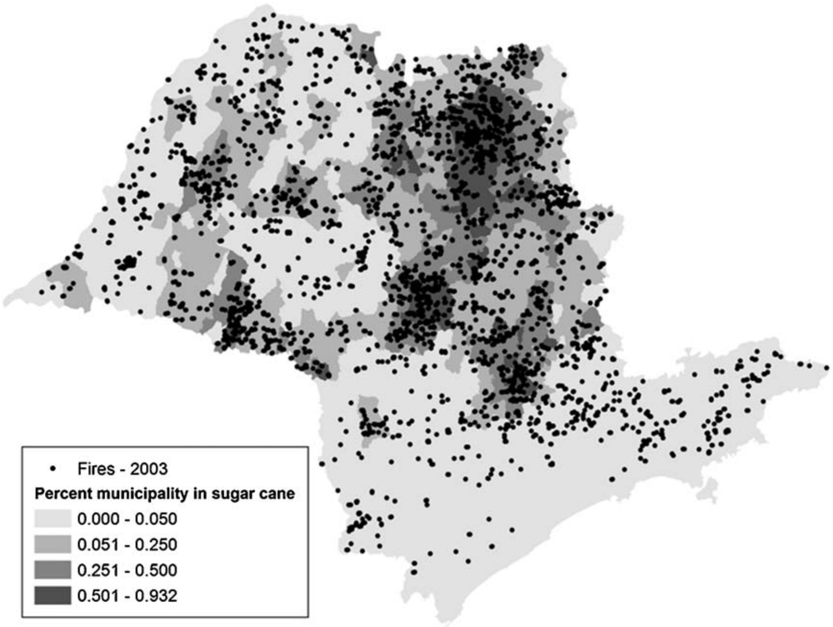

Fig. 2. Percent of total land area in São Paulo municipalities cultivated for sugarcane and number of fires detected in 2003, $R^2 = 0.42$.

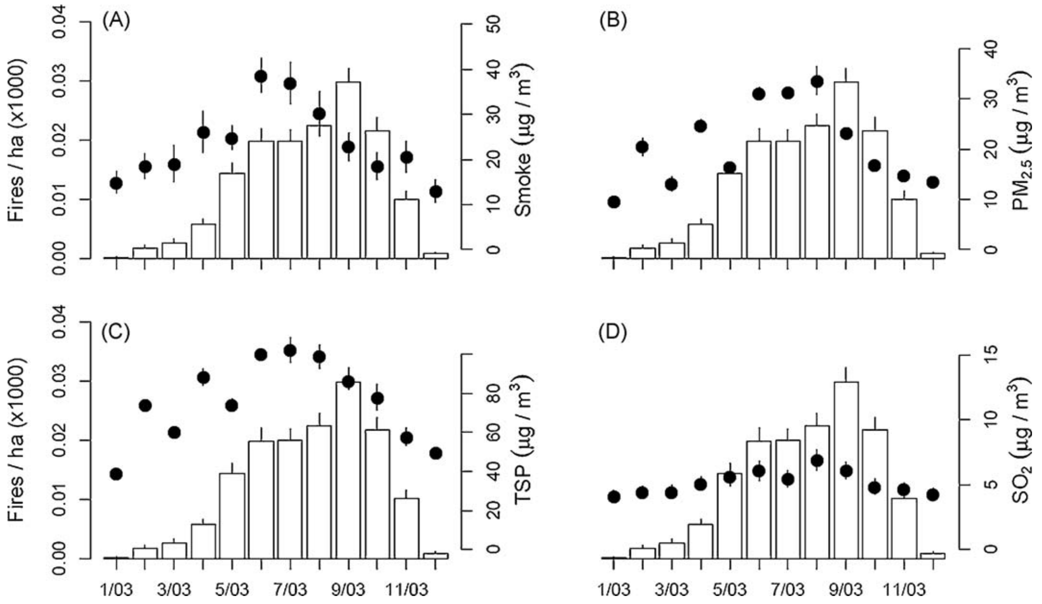

Fig. 3. Monthly occurrence of fires (open bars indicate total for 1999–2005) on concentrations (black dots) (in µg/m^3) of (A) smoke, (B) inhalable particles (<2.5 µm in diameter), (C) total suspended particles (<50 µm in diameter), and (D) sulfur dioxide. Sugarcane is burned from May to October.

cultivation of sugar cane raising to 5.4% the percent of cases of respiratory disease in children that can be attributed to fire. Furthermore, for municipalities with >50% of the land allocated to sugarcane the percentage of cases attributable to current fire increased to 15% and 12%, respectively, for elderly and children (elderly: 16 out of 109 cases, children: 93 out of 768 cases). An additional 209 child cases could also be attributed to past exposure to fires associated with sugarcane, suggesting that in total 38% of children respiratory cases could be attributed to current or chronic exposure to fires.

Lower precipitation was also associated with impaired respiratory health in both groups (Table 1). This effect was particularly marked at high temperatures, possibly representing the negative effects of low air humidity on respiratory health. A closer look at the three-way interactions between precipitation, temperature, and fire suggested that the effects of fires are most marked at high temperatures or low precipitation levels. Finally, municipalities with a higher percentage of rural inhabitants tended to have a lower probability of respiratory morbidity, with this covariate possibly acting as a proxy for lower levels of air pollutants associated with urban centers (e.g., industrial and automotive emissions).

2.4. *Effects of sugarcane expansion on respiratory disease*

We used data on sugarcane area (IBGE see above) expansion by municipality from 2003 to 2007 to simulate the increase in fires from 2003 levels. Results of simulated fire events overlaid on actual fires for 2003 are shown in Fig. 5 and parameter estimates are provided in Table 2. We estimate that the expansion in area of sugarcane from 2.82 Mha to 3.66 Mha from 2003 to 2007 would lead to 672 additional fires assuming similar weather patterns. This represents an increase of 19% relative to the 2003 numbers. Although the predicted total number of fires for 2003–2007 is not directly comparable to observed increases because the satellites collecting the data have changed, our method estimate is still within the range observed by the new satellites. As we stated in above, we then used the simulated fire data to predict the increase in occurrence of respiratory hospital admissions that can be attributed to fire. Results are shown in Fig. 6 and based on the mean

Table 1
Results of binomial model applied to respiratory data for children and elderly group. Covariates were standardized by centering them on their mean and dividing by two standard deviations.

Parameter	Estimate	S.E.	*z*-Value	Pr(>|*z*|)
(A) Children (<10 years of age)				
Intercept	−8.97	0.048	−185.6	<2e−16
Fires/km^2	0.195	0.026	7.65	2.0e−14
Maximum temperature	−0.022	0.032	−0.69	0.49
Precipitation (PPT)	−0.072	0.024	−3.03	0.0025
Percentage of rural	−0.72	0.11	−5.80	6.6e−09
PPT × maximum temperature	−0.56	0.053	−10.49	<2e−16
Maximum temperature × PPT × fires/km^2	−0.83	0.14	−5.86	4.7e−09
Sugarcane in 1995 (km^2)	0.23	0.08	2.76	0.0057
(B) Elderly (>60 years of age)				
Intercept	−10.1514	0.0772	−131.6	<2e−16
Fires/km^2	0.2944	0.0544	5.4	6.2e−08
Maximum temperature	−0.1869	0.0594	−3.1	0.0017
Precipitation	−0.3113	0.0473	−6.6	4.7e−11
Percentage of rural	−0.8842	0.1765	−5.0	5.4e−07
PPT × maximum temperature	−1.0864	0.1143	−9.5	<2e−16
Maximum temperature × PPT × fires/km^2	−0.9994	0.3226	−3.1	0.0020

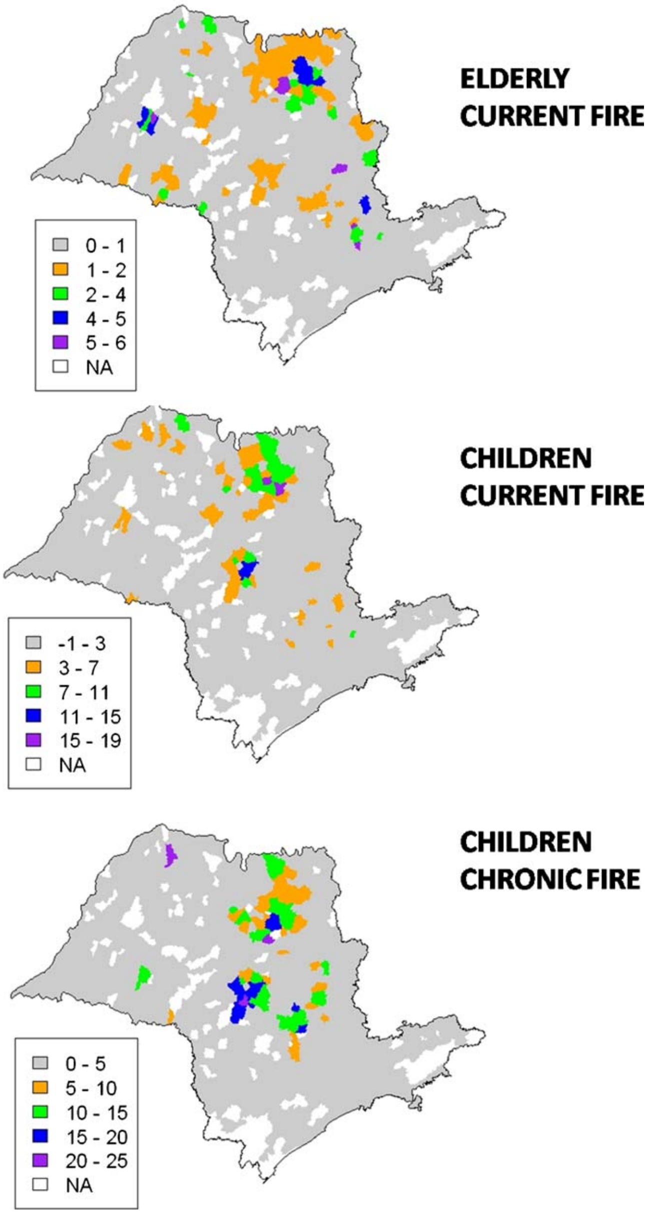

Fig. 4. Estimated hospital respiratory admissions directly attributable to fires by municipality for elderly and children (units = number of cases per 10,000 individuals). Effects include both current (2003 for elderly and children) and chronic effects (for children) of fires associated with sugar cane.

of 1000 simulations. The recent expansion of sugarcane led to an average of 253 additional cases for the elderly group and 561 additional respiratory cases for the children group (on top of the cases attributed to current fire in 2003 and not including any increase in chronic effects). At the state scale, these increases account for 4.8% and 3.0% increases in total cases; however, these cases represent 224% and 177% increases in the number of cases attributable to fire between 2003 and 2006.

3. Discussion

The rise in oil prices worldwide has boosted the competitiveness of renewable energy and resulted in unprecedented expansion in total biofuel production. Unlike previous periods of high oil prices, which were generally driven by short-term political or military conflict, this latest spike is demand-driven, fueled primarily by rapidly growing middle-income economies (Dufey, 2006; US DOE, 2006; Coyle, 2007). Although the recent swings in prices for oil and agricultural commodities call projections of any kind into question, one authoritative, near-term outlook for oil prices suggests a period of continued high prices relative to the 1990s, even if not at the unprecedented 2007–2008 levels (World Bank, 2009). The report states that at oil prices above $50 a barrel, production of biofuels from food crops—even without subsidies—will remain profitable. Given the likely increase in biofuel demand, it is essential to understand the full social and environmental costs of biofuel production and to impose sustainability goals to this fast-growing industry.

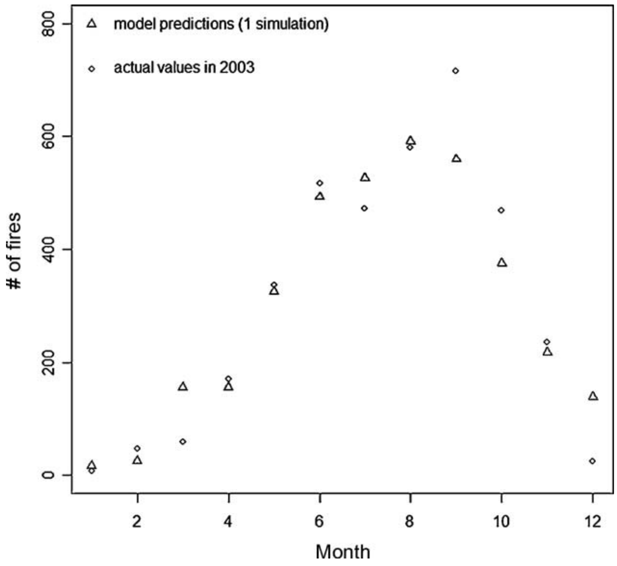

Fig. 5. Simulated and observed fire events in 2003 by month. Fires were simulated using a zero-inflated negative binomial process with total area, area in a sugarcane cultivation, and precipitation ($R^2 = 0.72$, $F = 1610$, d.f. = 1, 641, $p < 0.00001$).

The sugarcane-based ethanol program in Brazil with its positive energy balances and low production costs has been touted as an example for other developing economies (Goldemberg, 2007). Yet, a full accounting of the social and environmental costs of ethanol production is lacking (but see Martinelli and Filoso, 2008). One of these unaccounted effects is that of sugarcane burning prior to harvest, a common practice in Brazil. In 2006, 3.4 Mha were harvested to produce both sugar and alcohol. Only 900,000 were harvested mechanically and, despite regulations to reduce the extent of burning, the number of fires in São Paulo state increased by almost 25% in 2006 relative to 2005 (www.inpe.br).

Like previous studies, our analyses have shown that biomass burning in cane fields is detrimental to respiratory health of two vulnerable populations, children and the elderly (Arbex et al., 2000; Cançado et al., 2006). The added value from our study is that

Table 2
Parameter estimates for zero-inflated negative binomial model developed to predict fire occurrence. Covariates were standardized by centering them on their mean and dividing by two standard deviations, see Eq. (3).

Parameter	Estimate	S.E.	z-Value	Pr(>|z|)
(A) Coefficients for negative binomial model with log link portion of model				
Intercept	0.1680	0.0762	2.21	0.027
Area in sugarcane	0.4567	0.0400	11.43	<2e−16
Precipitation	−0.7699	0.1321	−5.83	5.7e−09
(B) Coefficients for binomial with logit link portion of model				
Intercept	1.4582	0.0943	15.46	<2e−16
Precipitation	2.5434	0.1654	15.38	<2e−16
Area not in sugarcane	−1.1434	0.1154	−9.91	<2e−16
Area in sugarcane	−1.9110	0.1540	−12.41	<2e−16

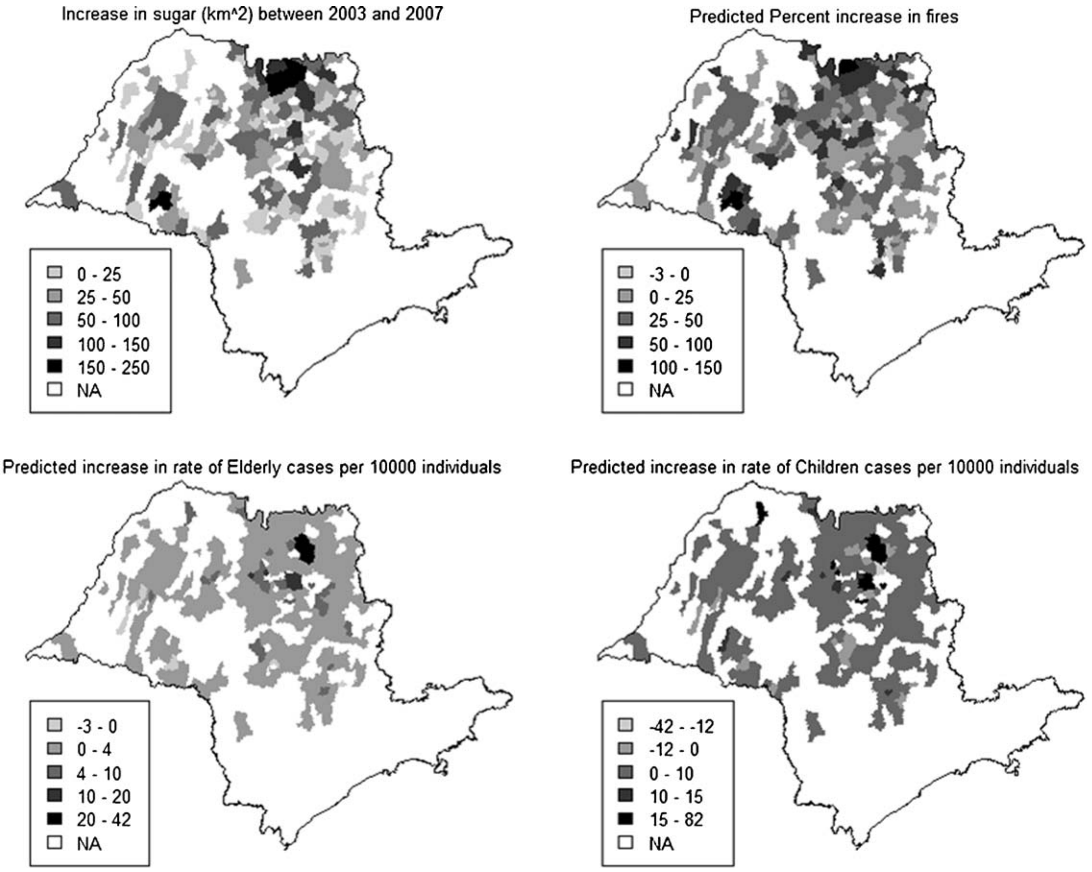

Fig. 6. Predicted additional occurrence of fires, elderly, and children respiratory admissions for 2004–2007 that can be attributed to increases in sugarcane area during the same time period. Units are number of cases per 10,000 individuals in the relevant age group.

it provides quantitative and municipality-specific predictions for the total number of cases (and associated uncertainty) that can be attributed to cane fires rather than meteorological or municipality-level variables. For instance, a quick look at Fig. 4 points to municipalities that should be prioritized for mechanization. Production of sugarcane is highly concentrated spatially because the limiting factor is transport to the mill. Therefore, we expect that for municipalities that have a high percentage of their land in sugarcane and the adequate infrastructure (i.e., mills) to process the cane, it makes economic sense to continue the expansion leading to more severe effects on respiratory health. However, economic analyses should include the increases in public health expenditures associated with incremental respiratory morbidity generated by these fires and compare them to potential profit losses (e.g., Rittmaster et al., 2006). The harmful effects of fires on health are not only a burden for the public health system but also for household economies. This type of information should be incorporated into land use decisions and discussions of sustainability. Without a thorough assessment of pros and cons, a scenario in which biofuels provide a solution to one specific problem while creating others becomes a very real possibility (Dufey, 2006).

Law 11,241 adopted in the state of Sao Paulo in 2002 requires a gradual mechanization of areas currently harvested manually. The law is poorly respected and its implementation has been pushed back repeatedly (Moreira and Goldemberg, 1999). In response to recent public pressure, municipalities have been pressing sugarcane producers to stop the burning. According to the law, mechanizable areas ($<$12% slope and $>$150 ha) must be converted by 2020. Non-mechanizable areas are expected to be phased out of production by 2030. Additional environmental legislation requires that riparian vegetation on both margins of a river must be preserved at a minimum of 10 m for streams and a maximum 500 m for rivers. We used 2005 cane GIS maps from INPE together with geo-referenced river maps (WWF, 2008) and digital elevation maps (Farr et al., 2007) to calculate the total area that would need to be abandoned based on these criteria. It amounts to approximately 28% of total area in cultivation in the state with a 500 m river buffer (976,301 ha) and 4% with a 50 m buffer (127,302 ha). Whether it will be abandoned remains to be seen. If so, the costs of restoring abandoned riparian buffer areas have recently been estimated at $3350/ha (Silva et al., 2007). Judging by recent increases in the number of fires, expansion of manual sugarcane cultivation is proceeding faster than mechanization. Moreover, the introduction of mechanized harvesting *per se* does not guarantee the end of fires in the cane fields, because the yield can be up to 30% greater with burnt cane and burning also reduces the cost of transport to the mill (Scopinho et al., 1999; Alves, 2006). There are other issues associated with the abandonment of manual harvest including an estimated loss of 300,000 jobs, primarily of low-skilled laborers (Conab, 2008). Enforcement of mechanization should be complemented with programs of agrarian reform to settle at least part of these workers.

Our model examines the importance of specific drivers on the incidence of respiratory disease at the municipality level and allows for the implementation of adequate healthcare strategies and practice guidelines. The analyses point to low relative humidity as a strong driver of respiratory disease. Both low precipitation and high temperatures led to greater respiratory morbidity (Table 1). The positive effect of temperature on respiratory disease contradicts results from previous studies which attributed the higher rate of respiratory disease in winter months to overcrowding conditions of susceptible individuals (e.g., Viegas et al., 2004; Hajat et al., 2004). However, the negative effects of temperature on respiratory morbidity may be primarily relevant to temperate regions. In São Paulo, a region with subtropical weather, air humidity may be a more important determinant of respiratory disease (Gonçalves et al., 2005). Indeed, a number of studies, including one in the São Paulo metropolitan region, have found associations between high temperature, atmospheric pollution, and health (Kalkstein, 1991; Chestnut et al., 1998; Braga et al., 2000). Low humidity has also been linked with high rates of respiratory disease in milder climates (Panagiotis and Matzarakis, 2006).

Current fire policies in the region lend support to our analysis. The government of São Paulo has forbidden diurnal fires from July until the middle of October. This measure is intended to avoid degradation in air quality during the winter, when relative humidity is at its lowest and respiratory stress at its highest. The resolution also stipulates that fires will be forbidden altogether if the relative humidity goes below 20%. These policies must be carefully managed because cane is typically harvested in dry periods to maximize yield (Aguiar et al., 2007). Balancing profit and potential health effects of cane harvest will depend on meteorological parameters that vary between municipalities.

As the biofuel market continues to expand, the Brazilian government is working on zoning that would prevent sugarcane cultivation in ecologically sensitive areas like Amazonia and the Pantanal. Priority for planting in Brazil is in degraded pastures although there is concern among conservationists that this will lead to degradation of the *cerrado*, a highly valuable and endangered ecosystem. These plans for expansion are consistent with an economic development model that fosters agricultural development of monocultures, primarily for export. Land use policies should consider the consequences of this model for environmental degradation, social welfare, employment, and concentration of wealth. A recent World Bank study found that a 10% increase in sugar world prices would lead to reduction in poverty of 1% in sugarcane growing regions of Brazil and an increase in labor wages (Kivronos and Olarreaga, 2006). Given the instability of the energy markets, potential effects of decreases in sugar prices must also be considered. Furthermore, short-term reliance on biofuels may potentially inhibit the development and maturation of long-term technologies that have greater potential to correct the harmful effects of fossil-fuel dependence. In this light, policy instruments currently employed or proposed by governments in developing nations to promote biofuels in the short-term appear questionable (Charles et al., 2007).

Acknowledgements

We thank all the participants of EEB G6150 (Fall 2007) where these ideas were started and the Earth Institute at Columbia University for providing financial support. We are also grateful to L. Martinelli, for facilitating data collection and A. deSherbinin, M. Jaiteh, M. Pinedo-Vazquez, and two anonymous reviewers for their constructive input.

References

Aguiar, D.A., da Silva, W.F., Feitosa, F.F., Goncalves, F.G., Rizzi, R., Rudorff, B.F.R., 2007. Analise especial da colheita de cana-de-açúcar no estado de São Paulo: a influencia da precipitaçao. Anais XIII Simposio Brasileiro de Sensoramiento Remoto. INPE, pp. 2231–2238

Allen, A.G., Cardoso, A.A., Rocha, G.O., 2004. Influence of sugar cane burning on aerosol soluble ion composition in Southeastern Brazil. Atmos. Environ. 38, 5025–5038.

Alves, F.J.C., 2006. Por que morrem os cortadores de cana? Saúde Soc. 15, 90–98.

Arbex, M.A., Bhon, G.M., Saldiva, P.H.N., Conceiacao, G.M.S., Pope III, A.C., Braga, A.L., 2000. Assessment of the effects of sugarcane plantation burning on daily counts of inhalation therapy. J. Air Waste Manage. Assoc. 50, 1745–1749.

Arbex, M.A., Conceição Martins, L., Carvalho de Oliveira, R., Amador Pereira, L.A., Ferlin Arbex, F., Delfini Cançado, J.E., Nascimento Saldiva, P.H., Ferreira Braga, A.L., 2007. Air pollution from biomass burning and asthma hospital admissions in a sugar cane plantation area in Brazil. J. Epidemiol. Commun. Health 61, 395–400.

Ballester, M.V., Martinelli, L.A., Krusche, A.V., Victoria, R.L., Bernardes, M., Camargo, de.P.B., 1999. Effects of increasing organic matter loading on the dissolved O_2, free dissolved CO_2 and respiration rates in the Piracicaba River Basin, southeast Brazil. Water Res. 33, 2119–2129.

Braga, A.L.F., Conceicao, G.M.S., Pereira, L.A.A., Kishi, H.S., Pereira, J.C.R., Andrade, M.F., 2000. Air pollution and pediatric respiratory hospital admissions in Sao Paulo. Braz. J. Environ. Med. 1, 95–102.

Braga, A.L.F., Zanobetti, A., Schwartz, J., 2002. The effect of weather on respiratory and cardiovascular deaths in 12 U.S. cities. Environ. Health Perspect. 110, 859–863.

Cançado, J.E., Saldiva, P.H.N., Pereira, L.A.A., Lara, L.B.L.S., Artaxo, P., Martinelli, L.A., Arbex, M.A., Zanobetti, A., Braga, A.L.F., 2006. The impact of sugar cane-burning emissions on the respiratory system of children and the elderly. Environ. Health Perspect. 114, 725–729.

Ceddia, M.B., dos Anjos, L.H.C., Lima, E., Ravelli Neto, A., da Silva, L.A., 1999. Sistemas de colheita da cana-de-açúcar e alterações Nas propriedades físicas de um solo podzólico amarelo no Estado do Espírito Santo. Pesqui. Agropecu. Bras. 34, 1467–1473.

Cerri, C.C., Feller, C., Chauvel, A., 1991. Evolução das principais propriedades de um Latossolo Vermelho-Escuro após desmatamento e cultivo por doze e cinqüenta anos com cana-de-açúcar. Cah. ORSTOM Série Pédologie 26, 37–50.

CETESB: Companhia de Tecnologia de Saneamento Ambiental do Estado de Sao Paulo, 2008.

Charles, M.B., Ryan, R., Ryan, N., Oloruntoba, R., 2007. Public policy and biofuels: the way forward? Energy Policy 35, 5737–5746.

Chestnut, L.G., Breffle, W.S., Smith, J.B., Kalkstein, L.S., 1998. Analysis in differences in hot weather related mortality across 44 US metropolitan areas. Environ. Sci. Policy 1, 59–70.

CIIAGRO: Centro Integrados de Informacoes Agrometeorologicas, 2008. Available at http://www.ciiagro.sp.gov.br/.

Conab (Companhia Nacional de Abastecemento), 2008. Perfil do setor do açúcar e do álcool no Brasil.

Costa, C., das Neves, C.S., 2005. Superexploração do trabalho na lavoura de cana-de-açúcar. Relatoria Nacional para o Direito Humano ao Trabalho. 81–87.

Coyle, W., 2007. The Future of Biofuels: A Global Perspective. Economic Research Service, USDA.

Crutzen, P.J., Mosier, A.R., Smith, K.A., Winiwarter, W., 2007. N_2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. Atmos. Chem. Phys. Discuss. 7, 11191–11205.

Daily, G., Ellison, K., 2002. The New Economy of Nature. Island Press.

DATASUS, 2008. Processamento de dados do SUS. Procedimentos hospitalares de SUS. Available at http://tabnet.datasus.gov.br.

Dias de Oliverira, M.E., Vaughan, B.E., Rykiel Jr., E.J., 2005. Ethanol as fuel: energy, carbon dioxide balances, and ecological footprint. Bioscience 55, 593–602.

Dotta, G., 2005. Diversidade de mamíferos de médio e grande porte em função da paisagem na sub-bacia do rio Passa-Cinco, São Paulo. Master Thesis. Ecology of Agroecosistems, Universidade de São Paulo, USP, Brasil.

Dufey, A., 2006. Biofuels Production, Trade and Sustainable Development. International Institute for Environment and Development, London.

Fargione, J., Hill, J., Tilman, D., Polasky, S., Hawthorne, P., 2008. Land clearing and the biofuel carbon debt. Science 319, 1235–1238.

Farr, T.G., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., Rosen, P., Roth, L., Seal, D., Shaffer, S., Shimada, J., Umland, M., Werner, M., Burbank, D., Oskin, M., Alsdorf, D., 2007. The shuttle radar topography mission. Rev. Geophys. 45, RG2004doi:10.1029/2005RG000183.

Filoso, S., Martinelli, L.A., Williams, M.R., Lara, L.B., Krusche, A., Ballester, M.V., Victoria, R.L., Camargo, P.B., 2003. Land use and nitrogen export in the Piraçicaba River Basin, Southeast Brazil. Biogeochemistry 65, 275–294.

Gheler-Costa, C., 2006. Distribuição e Abundância de Pequenos Mamíferos em Relação à Estrutura da Paisagem: A Sub-Bacia do Rio Passa-Cinco como Modelo. PhD Thesis. Ecology Agroecosistems Escola Superior de Agricultura Luiz de Queiroz, ESALQ, Brasil.

Giampietro, M., Ulgiati, S., Pimentel, D., 1997. Feasibility of large-scale biofuel production. Bioscience 47, 587–600.

Goldemberg, J., 2007. Ethanol for a sustainable future. Science 315, 808–810.

Gonçalves, F.L.T., Carvalho, L.M.V., Conde, F.C., Latorre, M.R.D.O., Saldiva, P.H.N., Braga, A.L.F., 2005. The effects of air pollution and meteorological parameters on respiratory morbidity during the summer in São Paulo city. Environ. Int. 31, 343–349.

Gunkel, G.J., Kosmol, M., Sobral, H., Rohn, S., Montenegro, J., Aureliano, 2007. Sugarcane industry as a source of water pollution—case study on the situation in Ipojuca river, Pernambuco. Brazil. Water Air Soil Pollut. 180, 261–269.

Hajat, S., Bird, W., Haines, A., 2004. Cold weather and GP consultations for respiratory conditions by elderly people in 16 locations in the UK. Eur. J. Epidemiol. 19, 959–968.

Hill, J., Nelson, E., Tilman, D., Polasky, S., Tiffany, D., 2006. Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. Proc. Natl. Acad. Sci. 30, 11206–11210.

IBGE: Instituto Brasileiro de Geografia e estatistica, 2005. Producao agricola municipal: Cultural temporaria e permanentes. Available at http://www.ibge.gov.br.

Kalkstein, L.S., 1991. A new approach to evaluate the impact of climate on human mortality. Environ. Health Perspect. 96, 145–150.

Kirchhoff, V.W.J.H., Marinho, E.V., Dias, P.L.S., Pereira, E.B., Calheiros, R., André, R., Volpe, C., 1991. Enhancements of CO and O_3 from burnings in sugar cane fields. J. Atmos. Chem. 12, 87–102.

Kivronos, E., Olarreaga, M., 2006. Sugar Process, Labor Income, and Poverty in Brazil. World Bank Policy Research Working Paper 3874.

Lara, L.L., Artaxo, P., Martinelli, L.A., Camargo, P.B., Victoria, R.L., Ferraz, E.S.B., 2005. Properties of aerosols from sugar-cane burning emissions in Southeastern Brazil. Atmos. Environ. 39, 4627–4637.

Martinelli, L.A., Filoso, S., 2008. Expansion of sugarcane land cover and ethanol production in Brazil: environmental and social challenges. Ecol. Appl. 18, 885–898.

Martinelli, L.A., Ballester, M.V., Krusche, A., Victoria, R.L., de Camargo, P.B., Bernardes, M., Ometto, J.P.H.B., 1999. Land-cover changes and $\delta^{13}C$ composition of riverine particulate organic matter in the Piracicaba River Basin (southeast region of Brazil). Limnol. Oceanogr. 44, 1826–1833.

Martinelli, L.A., Camargo, P.B., Lara, L.B.L.S., Victoria, R.L., Artaxo, P., 2002. Stable carbon and nitrogen isotopic composition of bulk aerosol particles in a C4 plant landscape of southeast Brazil. Atmos. Environ. 36, 2427–2432.

Martines-Filho, J., Burnquist, H.L., Vian, C.E.F., 2006. Bioenergy and the rise of sugarcane-based ethanol in Brazil. Choices 21, 91–96.

Mol, A.P.J., 2007. Boundless biofuels? Between environmental sustainability and vulnerability. Sociol. Ruralis 47, 297–315.

Moreira, J.R., Goldemberg, J., 1999. The alcohol program. Energy Policy 27, 229–245.

Muller, M., Yelden, T., Schoonover, H., 2007. Food versus Fuel in the United States: Can Both Win in the Era of Ethanol? Institute for Agriculture and Trade Policy, Minneapolis, MN, USA.

Nass, L.L., Arraes Pereira, P.A., Ellis, D., 2007. Biofuels in Brazil: an overview. Crop Sci. 47, 2228–2237.

Oliveira, J.C.M.de, Vaz, C.M.P., Reichardt, K., 1995. Efeito do cultivo contínuo da cana-de-açúcar em propriedades físicas de um latossolo vermelho escuro. Sci. Agricola 52, 50–55.

Oliveira, J.C.M.de, Reichardt, K., Bacchi, O.O.S., Timm, L.C., Dourado-Neto, D., Trivelin, P.C.O., Tominaga, T.T., Navarro, R.C., Piccolo, M.C., Cássaro, F.A.M., 2000. Nitrogen dynamics in a soil-sugar cane system. Sci. Agricola 57, 467–472.

Oliveira, M.W., Trivelin, P.C.O., Boaretto, A.E., Muraoka, T., Mortatti, J., 2002. Leaching of nitrogen, potassium, calcium and magnesium in a sandy soil cultivated with sugarcane. Pesqu. Agropecu. Bras. 37, 861–868.

Ometto, J.P.H.B., Martinelli, L.A., Ballester, M.V., Gessner, A., Krusche, A., Victoria, R.L., Williams, M., 2000. Effects of land use on water chemistry and macroinvertebrate in two streams of the Piracicaba River Basin, Southeast Brazil. Freshw. Biol. 44, 327–337.

Panagiotis, N., Matzarakis, A., 2006. Weather impacts on respiratory infections in Athens, Greece. Int. J. Biometeor. 50, 358–369.

Pereira-Netto, A.D., Cunha, I.F., Krauss, T.M., 2004. Persistence of polycyclic aromatic hydrocarbons in the soil of a burned area for agricultural purposes in Brazil. Bull. Environ. Contam. Toxicol. 73, 1072–1077.

Raghu, S., Anderson, R.C., Daehler, C.C., Davis, A.S., Wiedenmann, R.N., Simberloff, D., Mack, R.N., 2006. Adding biofuels to the invasive species fire? Science 313, 1742–11742.

R Development Core Team, 2008. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Ribeiro Jr., P.J., Diggle, P.J., 2001. geoR: a package for geostatistical analysis. R-NEWS 1 (2) ISSN: 1609-3631.

Righelato, R., Spracklen, D.V., 2007. Carbon mitigation by biofuels or by saving and restoring forests? Science 317, 902.

Rittmaster, R., Adamowicz, W.L., Amiro, B., Pelletier, R.T., 2006. Economic analysis of health effects from forest fires. Can. J. For. Res. 36, 868–877.

Rodrigues, A., 2006. O corte: como vivem—e morrem—os migrantes nos canaviais de São Paulo, 72 pp.

Roseiro, M.N.V., 2002. Morbidity by respiratory problems in Riberão Preto, SP, from 1995 to 2001, according to environmental, social, and economic indicators. M.Sc. Thesis. School of Nursing of Riberão Preto, University of São Paulo.

Santos, C.Y.M., Azevedo, D.A., Aquino Neto, F.R., 2002. Selected organic compounds from biomass burning found in the atmospheric particulate matter over a sugar cane plantation areas. Atmos. Environ. 36, 3009–3019.

Scopinho, R.A., Eidi, F., Vian, C.E.F., Silva, P.R.C., 1999. New technologies and workers' health: mechanization of *sugar cane* harvesting. Cad Saúde Pública 15, 147–161.

Shek, L.P., Lee, B.W., 2003. Epidemiology and seasonality of respiratory tract virus infections in the tropics. Paediatr. Respir. Rev. 4, 105–111.

Silva, A.M., Nalon, M.A., Kronka, F.J., Alvares, C.A., Camargo, P.B., Martinellli, L.A., 2007. Historical land-cover/use in different slope and riparian buffer zones in watersheds of the state of São Paulo Brasil. Sci. Agricola 64, 325–335.

Tanner, P.A., Law, P., 2002. Effects of synoptic weather systems upon the air quality in an Asian megacity. Water Air Soil Pollut. 136, 105–124.

UNICA. Accessed January 2008 at http://www.ltid.inpe.br/public/CANA_SP_2005.

US Dept. of Energy, Energy Information Administration, 2006. International Energy Outlook. DOE Publ. No. EIA-0484.

Viegas, M., Barrero, P.R., Maffey, A.F., Mistchenko, A.S., 2004. Respiratory viruses seasonality in children under five years of age in Buenos Aires, Argentina: a five-year analysis. J. Infect. 49, 222–228.

WHO, 2007. International Statistical Classification of Diseases, 10th Revision. World Health Organization, Geneva. Available at http://www.who.int/classifications/apps/icd/icd10online/.

World Bank, 2009. Global economic prospects. Commodities at the crossroads. The International Bank for Reconstruction and Development. The World Bank, Washington, DC, USA.

WWF, 2008. HydroSHEDS: Hydrological Data and Maps Based on SHuttle Elevation Derivatives at Multiple Scales. http://hydrosheds.cr.usgs.gov/.

WWI, 2007. Biofuels for Transport: Global Potential and Implications for Sustainable Energy and Agriculture. Earthscan.