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Effect of Air Pollution Control on Mortality and Hospital Admissions in Ireland

Douglas W. Dockery, David Q. Rich,
Patrick G. Goodman, Luke Clancy,
Pamela Ohman-Strickland, Prethibha George,
and Tania Kotlov

Includes a Commentary by the Institute's Health Review Committee

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ABOUT HEI

The Health Effects Institute is a nonprofit corporation chartered in 1980 as an independent research organization to provide high-quality, impartial, and relevant science on the effects of air pollution on health. To accomplish its mission, the institute

- Identifies the highest-priority areas for health effects research;
- Competitively funds and oversees research projects;
- Provides intensive independent review of HEI-supported studies and related research;
- Integrates HEI's research results with those of other institutions into broader evaluations; and
- Communicates the results of HEI's research and analyses to public and private decision makers.

HEI typically receives half of its core funds from the U.S. Environmental Protection Agency and half from the worldwide motor vehicle industry. Frequently, other public and private organizations in the United States and around the world also support major projects or research programs. HEI has funded more than 280 research projects in North America, Europe, Asia, and Latin America, the results of which have informed decisions regarding carbon monoxide, air toxics, nitrogen oxides, diesel exhaust, ozone, particulate matter, and other pollutants. These results have appeared in the peer-reviewed literature and in more than 200 comprehensive reports published by HEI.

HEI's independent Board of Directors consists of leaders in science and policy who are committed to fostering the public–private partnership that is central to the organization. The Health Research Committee solicits input from HEI sponsors and other stakeholders and works with scientific staff to develop a Five-Year Strategic Plan, select research projects for funding, and oversee their conduct. The Health Review Committee, which has no role in selecting or overseeing studies, works with staff to evaluate and interpret the results of funded studies and related research.

All project results and accompanying comments by the Health Review Committee are widely disseminated through HEI's Web site (*www.healtheffects.org*), printed reports, newsletters and other publications, annual conferences, and presentations to legislative bodies and public agencies.

ABOUT THIS REPORT

Research Report 176, *Effect of Air Pollution Control on Mortality and Hospital Admissions in Ireland,* presents a research project funded by the Health Effects Institute and conducted by Dr. Douglas W. Dockery of the Harvard School of Public Health, Boston, Massachusetts, and his colleagues. This report contains three main sections.

The HEI Statement, prepared by staff at HEI, is a brief, nontechnical summary of the study and its findings; it also briefly describes the Health Review Committee's comments on the study.

The Investigators' Report, prepared by Dockery and colleagues, describes the scientific background, aims, methods, results, and conclusions of the study.

The Commentary is prepared by members of the Health Review Committee with the assistance of HEI staff; it places the study in a broader scientific context, points out its strengths and limitations, and discusses remaining uncertainties and implications of the study's findings for public health and future research.

This report has gone through HEI's rigorous review process. When an HEI-funded study is completed, the investigators submit a draft final report presenting the background and results of the study. This draft report is first examined by outside technical reviewers and a biostatistician. The report and the reviewers' comments are then evaluated by members of the Health Review Committee, an independent panel of distinguished scientists who have no involvement in selecting or overseeing HEI studies. During the review process, the investigators have an opportunity to exchange comments with the Review Committee and, as necessary, to revise their report. The Commentary reflects the information provided in the final version of the report.

PREFACE

HEI's Outcomes Research Program

The goal of most air quality regulations is to protect the public's health by implementing regulatory actions or providing economic incentives that help reduce the public's exposure to air pollutants. If this goal is met, air pollution should be reduced, and indicators of public health should improve or at least not deteriorate. Evaluating the extent to which air quality regulations succeed in protecting public health is part of a broader effort — variously termed *outcomes research*, *accountability research*, or *research on regulatory effectiveness* — designed to assess the performance of environmental regulatory policies in general. In recent decades, air quality in the United States and Western Europe has improved substantially, and this improvement is attributable to a number of factors, including increasingly stringent air quality regulations. However, the cost of the pollution-control technologies and mechanisms needed to implement and enforce these regulations is often high. It is therefore prudent to ask whether the regulations have in fact yielded demonstrable improvements in public health, which will provide useful feedback to inform future efforts.

Several U.S. government agencies have concluded that direct evidence about the extent to which air quality regulations have improved health (measured as a decrease in premature mortality and excess morbidity) is lacking. This finding is well documented by the National Research Council (NRC) in its report *Estimating the Public Health Benefits of Proposed Air Pollution Regulations* (NRC 2002), as well as by the California Air Resources Board, the U.S. Environmental Protection Agency (EPA), the U.S. Centers for Disease Control and Prevention (CDC), and other agencies.

In 2003, the Health Effects Institute published a monograph on outcomes research, Communication 11, *Assessing Health Impact of Air Quality Regulations: Concepts and Methods for Accountability Research* (HEI 2003).This monograph was written by the members of HEI's multidisciplinary Accountability Working Group after a 2001 workshop on the topic. Communication 11 set out a conceptual framework for outcomes research and identified the types of evidence required and the methods by which the evidence should be obtained. It has also guided the development of the HEI Health Outcomes Research program, which is discussed below.

Between 2002 and 2005, HEI issued requests for applications (RFAs) for its Outcomes Research program, under which 8 studies were funded (see Table). A ninth study was funded under the preliminary application process. The study by Dockery and colleagues described in this Research Report (Dockery et al. 2013) was funded under Request for Preliminary Applications (RFPA) 02-1, "Measuring the Health Impact of Actions that Improve Air Quality."

This preface describes both the framework of outcomes research as it relates to air quality regulations and HEI's Outcomes Research program.

BACKGROUND

The first step in assessing the effectiveness of air quality regulations is to measure emissions of the targeted pollutants to see whether they have in fact decreased as intended. A series of intermediate assessments, described in detail below, are needed in order to accurately measure the adverse health effects associated with air pollution to see whether they, too, decreased in incidence or severity relative to emissions. Some outcomes studies to date have used hypothetical scenarios (comparing estimated outcomes under existing and more stringent regulations) and risk estimates obtained from epidemiologic studies in an attempt to quantify past effects on health and to predict future effects (U.S. EPA 1999). However, more extensive validation of these estimates with data on actual outcomes would be helpful.

The long-term improvements in U.S. air quality have been associated with improved health in retrospective epidemiologic studies (Chay and Greenstone 2003; Laden et al. 2006; Pope et al. 2009). Considerable

HEI's Outcomes Research Program: First-Wave Studies[a]

RFA / Investigator (Institution)	Study or Report Title	Intervention
RFA 02-1		
Douglas Dockery (Harvard School of Public Health, Boston, MA)	Effect of Air Pollution Control on Mortality and Hospital Admissions in Ireland (published as Research Report 176, 2013)	Coal ban in Irish cities
Annette Peters (GSF–National Research Center for Environment and Health, Neuherberg, Germany[b])	The Influence of Improved Air Quality on Mortality Risks in Erfurt, Germany (published as Research Report 137, 2009)	Switch from brown coal to natural gas for home heating and power plants, changes in motor vehicle fleet after reunification of Germany
RFA 04-1		
Frank Kelly (King's College London, London, U.K.)	The Impact of the Congestion Charging Scheme on Air Quality in London: Part 1. Emissions Modeling and Analysis of Air Pollution Measurements. Part 2. Analysis of the Oxidative Potential of Particulate Matter (published as Research Report 155, 2011)	Measures to reduce traffic congestion in the inner city of London
RFA 04-4		
Frank Kelly (King's College London, London, U.K.)	The London Low Emission Zone Baseline Study (published as Research Report 163, 2011)	Measures to exclude most polluting vehicles from entering greater London
Richard Morgenstern (Resources for the Future, Washington, D.C.)	Accountability Analysis of Title IV Phase 2 of the 1990 Clean Air Act Amendments (published as Research Report 168, 2012)	Measures to reduce sulfur emissions from power plants east of the Mississippi River
Curtis Noonan (University of Montana, Missoula, MT)	Assessing the Impact of a Wood Stove Replacement Program on Air Quality and Children's Health (published as Research Report 162, 2011)	Wood stove change-out program
Jennifer Peel (Colorado State University, Fort Collins, CO	Impact of Improved Air Quality During the 1996 Summer Olympic Games in Atlanta on Multiple Cardiovascular and Respiratory Outcomes (published as Research Report 148, 2010)	Measures to reduce traffic congestion during the Atlanta Olympics
Chit-Ming Wong (University of Hong Kong, Hong Kong)	Impact of the 1990 Hong Kong Legislation for Restriction on Sulfur Content in Fuel (published as Research Report 170, 2012)	Measures to reduce sulfur content in fuel for motor vehicles and power plants
RFPA 05-3		
Junfeng (Jim) Zhang (University of Medicine and Dentistry of New Jersey, Piscataway, NJ)	Cardiorespiratory Biomarker Responses in Healthy Young Adults to Drastic Air Quality Changes Surrounding the 2008 Beijing Olympics (published as Research Report 174, 2013)	Measures to improve air quality during the Beijing Olympics

[a] Abbreviations: RFA, Request for Applications; RFPA, Request for Preliminary Applications.

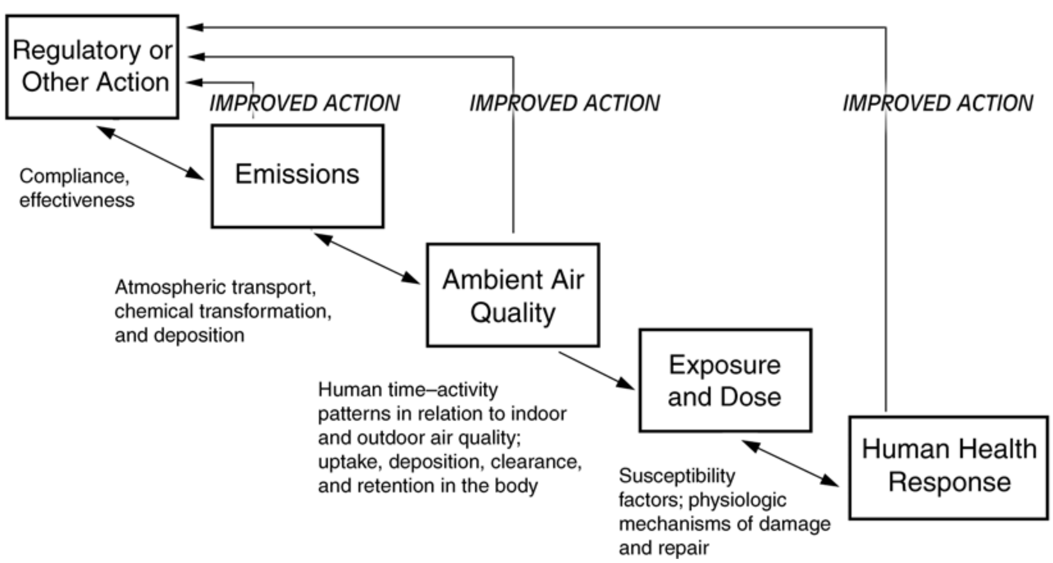
[b] As of 2008, this institution has been called the Helmholtz Zentrum München–German Research Center for Environmental Health.

challenges, however, are inherent in the assessment of the health effects of air quality regulations. Different regulations go into effect at different times, for example, and may be implemented at different levels of government (e.g., national, regional, or local). Their effectiveness therefore needs to be assessed in ways that take into account the varying times of implementation and levels of regulation. In addition, other changes at the same time and place might confound an apparent association between pollution reduction and improved health, such as economic trends (e.g., changes in employment), improvements in health care, and behavioral changes (e.g., staying indoors when government warnings indicate pollution concentrations are high). Moreover, adverse health effects that might have been caused by exposure to air pollution can also be caused by other environmental risk factors (some of which may have changed over the same time periods as the air pollution concentrations). These challenges become more pronounced when regulations are implemented over long periods and when changes in air quality and health outcomes are not seen immediately, thus increasing the chance for confounding by other factors. For these reasons, scenarios in which regulations are expected to have resulted in rapid changes in air quality tend to be among the first, and most likely, targets for investigation, rather than evaluations of complex regulatory programs implemented over multiple years. Studies in Ireland by Clancy and colleagues (2002) and in Hong Kong by Hedley and colleagues (2002) are examples of such scenarios.

These inherent challenges are well documented in Communication 11 (HEI 2003), which was intended to advance the concept of outcomes research and to foster the development of methods and studies throughout the relevant scientific and policy communities. In addition, recent advances in data collection and analytic techniques provide an unprecedented opportunity to improve our assessments of the effects of air quality interventions.

THE OUTCOMES EVALUATION CYCLE

The NRC's Committee on Research Priorities for Airborne Particulate Matter set out a conceptual framework for linking air pollution sources to adverse health effects (NRC 1998). This framework can be used to identify factors along an "outcomes evaluation cycle" (see Figure below), each stage of which affords its own opportunities for making quantitative measurements of the intended improvements.



Outcomes Evaluation Cycle. Each box represents a stage in the process between regulatory action and human health responses to air pollution. Arrows connecting the stages indicate possible directions of influence. The text below the arrows identifies factors affecting the effectiveness of regulatory actions at each stage. At several of the stages, knowledge gained from studies on outcomes can provide valuable feedback for improving regulatory or other actions.

At the first stage (regulatory action), one can assess whether controls on source emissions have in fact been put into place. At the second stage (emissions), one can determine whether controls on sources have indeed reduced emissions, whether emitters have changed their practices, and whether there have been unintended consequences. At the third stage (ambient air quality), one can assess whether controls on sources and reductions in emissions have resulted in improved air quality. At the fourth stage (personal or population exposure), one can assess whether the improvement in air quality has reduced people's actual exposure and whether susceptible subpopulations (those most likely to experience adverse health effects) have benefited. At this stage, it is important to take into account changes in time–activity patterns that could either increase or reduce exposure. The actual dose that an individual's organs may be exposed to should also be considered (i.e., whether reductions in exposure have led to reductions in concentrations in body tissues such as the lung). Finally, at the fifth stage (human health response), one can assess whether risks to health have declined, given the evidence about changes in health outcomes such as morbidity and mortality that have resulted from changes in exposure. The challenge at this stage is to investigate the health outcomes that are most directly related to exposure to air pollution.

At each stage in the outcomes evaluation cycle, the opportunity exists to collect evidence that either validates the assumptions that motivated the intervention or points to ways in which the assumptions were incorrect. The collection of such evidence can thus ensure that future interventions are maximally effective.

Ultimately, the framework for outcomes research will need to encompass investigations of the broader consequences of regulations, not just the intended consequences. Unintended consequences should also be investigated, along with the possibility that risks to public health in fact increased, as discussed by Wiener (1998) and others who have advanced the concept of a portfolio of effects of a regulation.

HEI'S OUTCOMES RESEARCH PROGRAM

The first wave of HEI's Outcomes Research program includes nine studies. The study by Dr. Douglas Dockery and colleagues presented in this report is the ninth to be published.

These studies involve the measurement of indicators along the entire outcomes evaluation cycle, from regulatory or other interventions to human health outcomes. Some of the studies focused on interventions that are implemented over relatively short periods of time, such as a ban on the sale of coal, the replacement of old wood stoves with more efficient, cleaner ones, reductions in the sulfur content of fuels, and measures to reduce traffic. Other groups focused on longer-term, wider-ranging interventions or events; for instance, one study assessed complex changes associated with the reunification of the former East and West Germany, including a switch from brown coal to natural gas for fueling power plants and home-heating systems and an increase in the number of modern diesel-powered vehicles in eastern Germany. HEI is also supporting research, including the development of methods, in an especially challenging area, namely, assessment of the effects of regulations implemented incrementally over extended periods of time, such as those, examined in the study by Morgenstern et al. (2012), that resulted from Title IV of the 1990 Clean Air Act Amendments (U.S. EPA 1990), which aimed at reducing sulfur dioxide emissions from power plants by requiring compliance with prescribed emission limitations. Studies on health outcomes funded by HEI to date are summarized in the Table on page xii and described in more detail in an interim evaluation of the HEI Outcomes Research program (van Erp and Cohen 2009; van Erp et al. 2012).

FUTURE DIRECTIONS

As a part of its Strategic Plan for 2010 through 2015 (HEI 2010a), HEI has looked closely at opportunities for unique new contributions to health outcomes research. Key recommendations for future research were made at a December 2009 planning workshop (HEI 2010b), which led to HEI issuing a new RFA in

January 2011 for a second wave of outcomes research. RFA 11-1, "Health Outcomes Research — Assessing the Health Outcomes of Air Quality Actions," solicited applications for studies designed to assess the health effects of actions to improve air quality and to develop methods required for, and specifically suited to, conducting such research. Recently, HEI approved four studies: two will evaluate regulatory and other actions at the national or regional level implemented over multiple years; a third study will evaluate complex sets of actions targeted at improving air quality in large urban areas and major ports with well-documented air quality problems and programs to address them; and a fourth study will develop methods to support such health outcomes research. These studies are currently under way.

In addition, HEI has funded the development of two Web sites intended to enhance transparency and provide other researchers with access to extensive data and software from HEI-funded studies:

1. Data and software from the National Morbidity, Mortality, and Air Pollution Study (NMMAPS), as described by Zeger and colleagues (2006) (data available at the Johns Hopkins Bloomberg School of Public Health Web site *www.ihapss.jhsph.edu*); and
2. Data from the National Particle Component Toxicity (NPACT) initiative on concentrations of components of particulate matter with an aerodynamic diameter ≤ 2.5 µm ($PM_{2.5}$) collected at or near the 54 sites in the EPA's $PM_{2.5}$ Chemical Speciation Trends Network (STN) (data available at the Atmospheric and Environmental Research Web site *https://hei.aer.com*).

The data on pollution and health from a large number of U.S. cities, as documented by the NMMAPS team and made available on the Internet-Based Health and Air Pollution Surveillance System (iHAPSS) Web site, constitute a valuable resource that allows other researchers to undertake additional analyses, possibly including further outcomes studies. The STN Web site provides scientists an opportunity to investigate specific questions about concentrations of $PM_{2.5}$ components and their association with adverse health effects in regions covered by the STN network and to address questions related to outcomes research when interventions in these regions are being planned.

In January 2008, HEI co-organized and cosponsored, with the CDC's National Environmental Public Health Tracking Program and the EPA, a workshop titled "Methodologic Issues in Environmental Public Health Tracking of Air Pollution Effects." The workshop was part of an effort to implement the initiative outlined in HEI's Strategic Plan for 2005 through 2010 (HEI 2005) to "build networks with the U.S. Centers for Disease Control and Prevention and state public health tracking programs to facilitate accountability research."

The workshop built on the work of the CDC's National Environmental Public Health Tracking Program (see the CDC Web site *www.cdc.gov/nceh/tracking/*) in the development of standardized measures of air pollution–related effects on health at the state and local levels in the United States. It brought together representatives of state and federal agencies and academic researchers to discuss methodologic issues in developing standardized measures and made recommendations for their further development and application in assessing the health impacts of air pollution, including the impacts of actions taken to improve air quality. The recommendations were provided in a September 2008 report to the CDC, and the proceedings were published in the journal *Air Quality, Atmosphere & Health* in December 2009 (Matte et al. 2009). The CDC has subsequently funded a pilot project under the National Environmental Public Health Tracking Program to implement the recommendations of the workshop in selected states and metropolitan areas.

HEI will continue to seek opportunities to work with the CDC and the EPA to apply methods newly developed for tracking public health and assessing the effectiveness of environmental regulations.

Investigators who have identified a distinctive opportunity to evaluate the effects of environmental regulations on air pollution and human health are encouraged to contact HEI.

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HEI STATEMENT

Synopsis of Research Report 176

Effect of Coal Bans on Air Quality and Health in Ireland

BACKGROUND

Dr. Douglas W. Dockery and colleagues studied the effects on air quality and human health of regulatory actions to ban the use of coal in 12 cities in Ireland. This study is an important addition to the small number of empirical studies of the effects of regulatory actions and other interventions on air quality and health. The investigators extended their earlier examination of the effects of a coal ban in Dublin in 1990 (published by Clancy et al. in *The Lancet* in 2002) to 11 smaller Irish cities where coal bans were implemented in 1995, 1998, and 2000.

APPROACH

The investigators characterized changes in air pollution levels using measurements of black smoke (BS) and of sulfur dioxide measured as total gaseous acidity (TGA). Measurements of BS and TGA were collected from 1981 to 2004 from a small number of fixed-site monitors in the 12 cities. No monitoring data were available in the areas of Ireland where the bans were not instituted. To evaluate the effects of the bans on air pollution levels, the investigators compared the average daily BS and TGA concentrations for the 5 years before and after each ban.

To evaluate the effects of the bans on health, the authors collected data on mortality, as in the previous study, as well as data on hospital admissions. Data on total nonaccidental and cause-specific mortality were obtained from death certificates from 1981 to 2004 to assess the effects on mortality of the 1990, 1995, and 1998 bans (but not the 2000 ban). Hospital admissions data suitable for analysis were available only for the 1995 and 1998 bans.

The study populations for each ban consisted of the residents of the city as well as the surrounding county (except for Dublin, whose study population consisted of city residents only). In their analyses of mortality, the investigators also included a "comparison" population, residents of the Midlands counties in Ireland in which coal bans were not implemented. Evaluation of this comparison population made it possible to assess whether the mortality effects could be attributed to the coal bans or might have resulted from other factors including the societal changes occurring over the same time period in Ireland. The investigators used an interrupted-time-series analysis to evaluate the effects of the coal bans on mortality and hospitalization rates. They estimated the percent change in total and cause-specific mortality, while adjusting for seasonal and long-term background trends, weather, and

What This Study Adds

- Dockery and colleagues' study of a series of Irish bans on the use of coal is an important addition to air quality and health outcomes research. In this study, the investigators extend their earlier examination of the effects of a coal ban in Dublin in 1990 to 11 smaller Irish cities where coal bans were implemented in 1995, 1998, and 2000.
- The investigators found clear decreases in black smoke concentrations, particularly during the heating season, after each ban. Respiratory mortality decreased significantly, by 17%, after the 1990 ban (confirming the earlier study) and, to a lesser extent, after the 1995 and 1998 bans. However, unlike the earlier study, the current study did not find a reduction in total or cardiovascular mortality after either the 1990 ban or the later bans.
- The study demonstrates the importance — and challenges — of disentangling the effects of an intervention from those of other social and economic factors that might also influence long-term trends in air quality and health.

This Statement, prepared by the Health Effects Institute, summarizes a research project funded by HEI and conducted by Dr. Douglas W. Dockery of the Harvard School of Public Health, Boston, Massachusetts, and colleagues. Research Report 176 contains both the detailed Investigators' Report and a Commentary on the study prepared by the Institute's Health Review Committee.

influenza epidemics. The adjustment for long-term background trends in mortality in both study and comparison populations was done with a smooth function of mortality rates from an Irish "reference" population living in western coastal counties presumably not affected by the bans. Extensive analyses were conducted to evaluate the sensitivity of the results to model choices.

RESULTS AND INTERPRETATION

The investigators confirmed the existence of clear decreases in BS concentrations ranging from 4 to 35 μg/m^3 (−45% to −70%), particularly during the heating season, after the coal bans were implemented in each of the 12 cities over the years from 1990 to 2000. The largest absolute reductions were seen after the earliest ban, in Dublin. No general decrease was seen in TGA concentrations after the bans, probably because of the nonspecificity of the measurement method and the low concentrations that were present during the study period.

The study found that respiratory mortality decreased significantly, by 17%, after the 1990 ban in Dublin (confirming the earlier study) and, to a lesser extent, after the 1995 and 1998 bans, in a pattern largely consistent with the magnitude of BS reductions across the successive bans. Such decreases were not observed in the comparison population (see Figure). However, in a notable difference from the earlier study of the 1990 ban in Dublin, the current study did not find a reduction in total or cardiovascular mortality after either the 1990 or later bans. Analyses of the hospital admissions data were hampered by substantial underreporting issues and the absence of data from a reference population to account for long-term background trends.

In its independent review of the study, the HEI Health Review Committee agreed with the investigators that the previous study had likely overestimated the effects of the Dublin ban on total and cardiovascular mortality but not on respiratory mortality. The Committee thought that the investigators' detailed sensitivity analyses and thorough discussions demonstrated how these major differences in findings could be explained by differences in the studies' approaches to correcting for long-term background trends in mortality rates that were unrelated to the bans.

CONCLUSIONS

Overall, the current study provides evidence that the Irish coal bans improved air quality and respiratory health, confirming earlier observations by Clancy and colleagues in their study of the 1990 ban in Dublin. The study holds important lessons for future intervention studies that plan to use interrupted-time-series designs in the presence of long-term background trends in health. In this case, the study was conducted during a time when the Irish economy was the fastest growing in Europe and Ireland was experiencing a number of social and economic changes, unrelated to the intervention under investigation, that could also have influenced trends in air quality and health. The study demonstrates the importance of using multiple approaches to evaluate and control for the effects of such changes, including the use of comparison populations unaffected by the intervention and the use of simulation and sensitivity analyses to evaluate choices of reference populations and of statistical models adjusting for background trends. At the same time, the study illustrates the considerable challenges faced by this type of analysis in eliminating biases that can lead to either overestimation or underestimation of the effects of an intervention on public health.

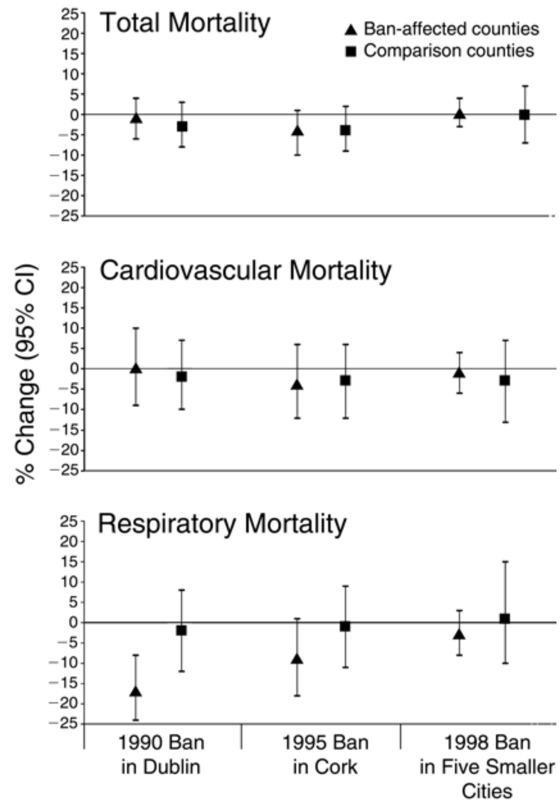

Figure. Percent change in cause-specific mortality for the ban-affected and comparison counties after the 1990, 1995, and 1998 coal bans. CI denotes confidence interval.

Effect of Air Pollution Control on Mortality and Hospital Admissions in Ireland

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ABSTRACT

During the 1980s the Republic of Ireland experienced repeated severe pollution episodes. Domestic coal burning was a major source of this pollution. In 1990 the Irish government introduced a ban on the marketing, sale, and distribution of coal in Dublin. The ban was extended to Cork in 1995 and to 10 other communities in 1998 and 2000. We previously reported decreases in particulate black smoke (BS*) and sulfur dioxide (SO_2) concentrations, measured as total gaseous acidity, in Dublin after the 1990 coal ban (Clancy et al. 2002). In the current study we explored and compared the effectiveness of the sequential 1990, 1995, and 1998 bans in reducing community air pollution and in improving public health.

We compiled records of daily BS, total gaseous acidity (SO_2), and counts of cause-specific deaths from 1981 to 2004 for Dublin County Borough (1990 ban), county Cork (1995 ban), and counties Limerick, Louth, Wexford, and Wicklow (1998 ban). We also compiled daily counts of hospital admissions for cardiovascular, respiratory, and digestive diagnoses for Cork County Borough (1991 to 2004) and counties Limerick, Louth, Wexford, and Wicklow (1993 to 2004). We compared pre-ban and post-ban BS and SO_2 concentrations for each city. Using interrupted time-series methods, we estimated the change in cause-specific, directly standardized mortality rates in each city or county after the corresponding local coal ban. We regressed weekly age- and sex-standardized mortality rates against an indicator of the post- versus pre-ban period, adjusting for influenza epidemics, weekly mean temperature, and a season smooth of the standardized mortality rates in Coastal counties presumably not affected by the bans. We compared these results with similar analyses in Midlands counties also presumably unaffected by the bans. We also estimated the change in cause-specific, directly standardized, weekly hospital admissions rates normalized for underreporting in each city or county after the 1995 and 1998 bans, adjusting for influenza epidemics, weekly mean temperature, and local admissions for digestive diagnoses.

Mean BS concentrations fell in all affected population centers post-ban compared with the pre-ban period, with decreases ranging from 4 to 35 $\mu g/m^3$ (corresponding to reductions of 45% to 70%, respectively), but we observed no clear pattern in SO_2 measured as total gaseous acidity associated with the bans. In comparisons with the pre-ban periods, no significant reduction was found in total death rates associated with the 1990 (1% reduction), 1995 (4% reduction), or 1998 (0% reduction) bans, nor for cardiovascular mortality (0%, 4%, and 1% reductions for the 1990, 1995, and 1998 bans, respectively). Respiratory mortality was reduced in association with the bans (17%, 9%, and 3%, respectively). We found a 4% decrease in hospital admissions for cardiovascular disease associated with the 1995 ban and a 3% decrease with the 1998 ban. Admissions for respiratory disease were not consistently lower

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* A list of abbreviations and other terms appears at the end of the Investigators' Report.

after the bans; admissions for pneumonia, chronic obstructive pulmonary disease (COPD), and asthma were reduced. However, underreporting of hospital admissions data and lack of control and comparison series tempered our confidence in these results.

The successive coal bans resulted in immediate and sustained decreases in particulate concentrations in each city or town, with the largest decreases in winter and during the heating season. The bans were associated with reductions in respiratory mortality but no detectable improvement in cardiovascular mortality. The changes in hospital admissions for respiratory and cardiovascular disease were supportive of these findings but cannot be considered confirming. Detecting changes in public health indicators associated even with clear improvements in air quality, as in this case, remains difficult when there are simultaneous secular improvements in the same health indicators.

INTRODUCTION

Throughout the 1980s Ireland experienced severe air pollution episodes. In one particularly severe episode in 1982 in Dublin, BS concentrations, a measure of ambient particles, were greater than 1500 $\mu g/m^3$ at individual monitoring stations, and citywide concentrations averaged greater than 750 $\mu g/m^3$ (Kelly and Clancy 1984). This episode was associated with a doubling in the case fatality rates at a central Dublin hospital (Kelly and Clancy 1984). The burning of coal in open grates was reported to be the major contributor to the particulate air pollution levels at that time, with most private dwellings (80%) and all local-authority dwellings (i.e., public housing) using solid fuels (coal and peat) for space heating in the mid-1980s (Convery 1988).

Based in part on this and similar air pollution episodes, the Irish government banned the marketing, sale, and distribution of coal in Dublin on September 1, 1990 (Air Pollution Act 1990). This ban led to a reduction in mean ambient BS concentrations of 71%, from 50.2 $\mu g/m^3$ (pre-ban) to 14.6 $\mu g/m^3$ (post-ban), and a reduction in mean SO_2 concentrations of 34%, from 33.4 to 22.1 $\mu g/m^3$. During the 6 years after the ban, there were concomitant 6%, 16%, and 10% reductions in total non-trauma, respiratory, and cardiovascular mortality rates, respectively (Clancy et al. 2002). On October 1, 1995, a similar coal ban was introduced in Cork, the second largest city in Ireland (Air Pollution Act 1994). The ban was extended to cover the cities and towns of Arklow, Drogheda, Dundalk, Limerick, and Wexford on October 1, 1998 (Air Pollution Act 1998), and Celbridge, Galway, Leixlip, Naas, and Waterford on October 1, 2000 (Air Pollution Act 2000).

Several research groups have taken advantage of similar "natural experiments," when an action or event (e.g., an industrial employee strike, a national or regional legislative mandate changing fuel composition or banning the sale of coal, a city-specific traffic-reduction scheme, or a large-scale sporting event) resulted in drastic decreases in the concentration of or changes in the composition of ambient air pollution over a city or region (Pope 1989; Heinrich et al. 2000; Friedman et al. 2001; Clancy et al. 2002; Hedley et al. 2002; Laden et al. 2006; Pope et al. 2007; Parker et al. 2008; Tonne et al. 2008; Pope et al. 2009; Peel et al. 2010). These rapid reductions in pollutant concentrations allowed investigators not only to evaluate the public health benefit of these legislative mandates or events, but also to evaluate disease-specific associations with air pollution to validate previous time-series, case-crossover, and cohort study results. In these same natural experiments, investigators reported decreases in hospital admissions for pneumonia, pleurisy, bronchitis, and asthma (Pope 1989); absenteeism for schoolchildren (Ransom and Pope 1992); total or cause-specific mortality rates (Clancy et al. 2002; Hedley et al. 2002; Laden et al. 2006; Pope et al. 2007); bronchitis prevalence (Heinrich et al. 2000); childhood hospital admissions for respiratory disease (Pope 1991); asthma acute-care events (Friedman et al. 2001); hospital admissions for childhood asthma (Pope 1991); and improvements in life expectancy (Tonne et al. 2008; Pope et al. 2009).

SPECIFIC AIMS

The current study assessed the effects of sequential air-pollution-control interventions in Dublin County Borough (i.e., the city of Dublin) on September 1, 1990; in Cork County Borough on October 1, 1995; and in five cities or towns (Arklow, Drogheda, Dundalk, Limerick, and Wexford) on October 1, 1998, on levels of air pollution, adjusted mortality rates, and adjusted hospital admission rates.

The specific objectives of these assessments were the following:

- To quantify the effects of the coal bans on particulate (BS) and SO_2 pollution;
- To quantify the effect of each coal ban on total (non-trauma), cardiovascular, and respiratory mortality adjusted for age and sex distribution of the population, weather, season (climate), influenza epidemics, and secular trends in mortality; and

- To quantify the effect of the coal bans on cardiovascular and respiratory hospital admissions, adjusted for age and sex distribution of the population, weather, season (climate), and influenza epidemics.

The effects of the bans on air pollution were assessed following the 1990, 1995, 1998, and 2000 bans. The mortality effects were assessed following the 1990, 1995, and 1998 bans. The hospital admissions evaluation was assessed following the 1995 and 1998 bans. The effects were estimated for each ban separately as well as combined across cities in the 1998 ban.

METHODS AND STUDY DESIGN

STUDY AREA

The island of Ireland is historically divided into 32 counties (Figure 1). Of these, 26 are in the Republic of Ireland and 6 are in Northern Ireland. This study was restricted to the Republic of Ireland, and all subsequent references to Ireland refer to the Republic. Irish cities and towns are defined by various administrative units (with historical roots) that have changed over the years (see

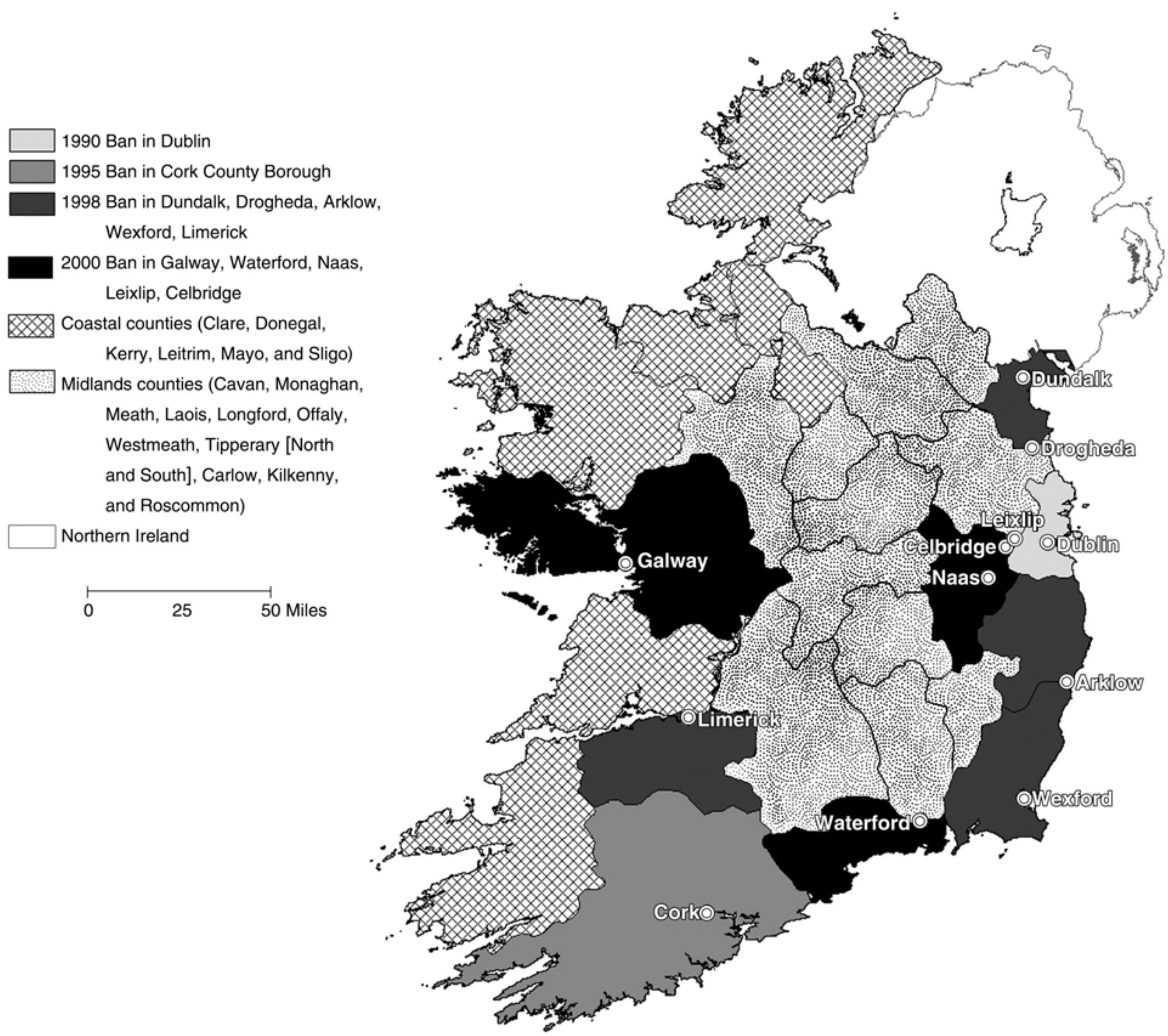


Figure 1. Cities and towns affected by the coal bans of 1990, 1995, 1998, and 2000; also shown are Ireland's 32 counties. See Figure A.5 in Appendix A for a map showing the counties of Ireland in more detail.

Appendix A). Coal bans were applied sequentially in 1990 (Air Pollution Act 1990), 1995 (Air Pollution Act 1994), 1998 (Air Pollution Act 1998), and 2000 (Air Pollution Act 2000) in 12 cities and towns (Figure 1). Table 1 presents the census population of the cities and towns affected by the successive bans and of the surrounding counties in which the cities and towns were located.

The 12 cities and towns affected by the bans are located in three geographic regions: the east (seven cities and towns), south (three cities), and midwest (two cities), with most located on the coast.

Of the seven cities and towns in the east, Dublin, located on the east coast at the mouth of the River Liffey, is the largest city in Ireland. Historically, Dublin was the largest industrial center, although service industries currently dominate the economy. Dublin is the hub of the nation's roadway system, and thus traffic, including both light- and heavy-duty vehicles, is a major source of pollution. The towns of Celbridge, Leixlip, and Naas are all part of the commuter belt inland and west of Dublin and have experienced large population growth in the past decade. Celbridge and Naas are largely residential. Leixlip is a major center of manufacturing (computers and electronics) and information technology. Drogheda and Dundalk are coastal towns north of Dublin. Drogheda is located in a valley and was once a major industrial center. The largest cement plant in Ireland is located in Drogheda, but Drogheda's economy has shifted to technology and service industries. Dundalk is also a center for high-technology manufacturing and services. Arklow is a coastal town south of Dublin with an industrial base of primarily chemical and pharmaceutical industries.

Table 1. Populations of Cities, Towns, and Surrounding Counties Affected by the Coal Bans

Ban Year / Administrative District	Population (1996 Census)
1990	
Dublin County Borough	481,854
1995	
Cork County Borough	127,187
Cork County Borough and County	420,510
1998	
Limerick City	52,039
Limerick City and County	165,042
Arklow	8,557
County Wicklow	102,683
Dundalk	25,762
Drogheda	24,460
County Louth	92,166
Wexford	15,862
County Wexford	104,371
2000	
Galway City	57,241
Galway City and County	188,854
Celbridge	12,289
Leixlip	13,451
Naas	14,074
County Kildare	134,992
Waterford	42,540
County Waterford	94,680

In the south the three cities affected by the bans were Cork, Waterford, and Wexford. Cork, the second largest city in Ireland, is a major port and industrial area. Although Cork remains the industrial center of the south, the mix of industries changed in the 1990s from heavy industry to pharmaceuticals and information technology. Waterford and Wexford are port cities located on the plains and the southeast coast of Ireland. The economies of both cities are dominated by tourism and light industry.

In the midwest the two cities affected by the bans were Limerick, located on a plain on the river Shannon, and Galway, located north of Limerick on a plain on the west coast. Galway is regularly affected by Atlantic weather patterns. The growth in high-tech product manufacturing (e.g., electronics and medical equipment) and information technology in this region was substantial in the 1990s. Galway also has a large economic base in education, the professions, and tourism.

Table 2 presents a summary of census population data for the counties affected by the bans as well as Midlands and Coastal counties for comparison (Central Statistics Office 2005). Dublin County Borough, that is, the city of Dublin, had a 1996 census population of 481,854. The population density (4190 persons/km²) was very high. The 1996 average total income in this commercial center (€ 14,252 per person) was the highest in the country. For consistency with previous analyses (Clancy et al. 2002) we restricted our analyses to Dublin County Borough.

The combined 1996 census population of 420,510 of Cork County and County Borough was comparable with that of Dublin County Borough. However, the population density of 56 persons/km² was lower; 71% of the land was being used for farming. The 1996 average total income was € 12,918 per person.

Table 2. Demographics of Counties Affected by the Coal Bans, Midlands Comparison Counties, and Coastal Reference Counties[a]

County	Population (1996 Census)	Land Area (km^2)	Population Density (per km^2)	Land in Farm Use (%)	Total Income per Person 1996 (€)
1990 Ban					
Dublin County Borough	481,854	115	4190	—	14,252
1995 Ban					
Cork City and County	420,510	7,499	56	71	12,418
1998 Ban					
Limerick City and County	165,042	2,755	60	73	12,325
Louth	92,166	826	112	75	12,668
Wexford	104,371	2,353	44	79	10,554
Wicklow	102,683	2,024	51	50	11,939
Total	**464,262**	**7,958**	**58**	**71**	**11,910**
2000 Ban					
Galway City and County	188,854	6,148	31	55	11,592
Kildare	134,992	1,693	80	67	12,982
Waterford	94,680	1,857	51	67	12,007
Total	**418,526**	**9,698**	**43**	**73**	**12,134**
Midlands					
Cavan	52,944	1,931	27	72	11,112
Monaghan	51,313	1,294	40	77	11,372
Meath	109,732	2,342	47	77	11,984
Laois	52,945	1,720	31	70	10,724
Longford	30,166	1,091	28	68	10,852
Offaly	59,117	2,000	30	61	10,297
Westmeath	63,314	1,840	34	65	11,556
Tipperary North	58,021	2,046	28	78	12,424
Carlow	41,616	896	46	80	10,664
Kilkenny	65,336	2,072	32	78	10,700
Tipperary South	75,514	2,257	33	71	10,940
Roscommon	51,975	2,547	20	63	10,347
Total	**711,993**	**22,036**	**32**	**68**	**11,166**
Coastal					
Clare	94,006	3,450	27	61	11,454
Donegal	129,994	4,814	27	48	10,569
Kerry	126,130	4,746	27	59	10,531
Leitrim	25,057	1,588	16	58	10,809
Mayo	111,524	5,586	20	49	10,397
Sligo	55,821	1,837	30	60	11,497
Total	**542,532**	**22,021**	**25**	**55**	**10,785**

[a] — indicates data not available.

Although the populations in each of the four counties (Limerick in the midwest, Wicklow and Louth in the east, and Wexford in the south) affected by the 1998 ban were substantially smaller than those of Dublin or Cork, together their total 1996 census population of 464,262 was similar to that of each of the two larger study areas. The average population density of 58 persons/km² for the four counties was similar to that of county Cork, as was the percentage of the land being farmed (71%) and the 1996 average total income (€ 11,910).

Similarly, for the three counties affected by the 2000 ban (Galway in the midwest, Kildare in the east, and Waterford in the south), the combined 1996 census total population (418,526), the percentage of land being farmed (73%), and 1996 average total income (€ 12,134) were similar to those of the counties affected by the 1995 and 1998 bans. Population density (43/km²) was lower.

AIR POLLUTION MONITORING

Local authorities measured BS and SO_2 concentrations in each city or town using British Standards Institute methods. BS is measured by reflectometry (BS 1747 method; British Standards Institute 1969). Filter reflectance is related to a mass concentration of particles using a standard calibration curve developed many years ago, when coal was the predominant source of airborne particles (Harrison 1999). As the sources of particles have changed, the calibration curve for conversion to mass concentration has changed. BS is now considered a crude measure of airborne particle concentrations, in that it primarily reflects elemental carbon content rather than mass concentration (Harrison 1999). SO_2 was measured by total gaseous acidity (British Standards Institute 1969, 1983). Although all the gaseous acidity is assumed to be from SO_2, other acidic gases contribute. The Irish Environmental Protection Agency (Irish EPA) compiled these observations and provided the data for these analyses.

In both Dublin and Cork, there were six pollution monitors consistently measuring BS and SO_2 for the 5 years before and after the respective bans. For the cities or towns of the 1998 ban, there were four monitors in Limerick, two in Dundalk, and one each in Drogheda and Arklow. BS was measured at one monitor in Wexford before the 1998 ban, but these measurements were discontinued after the ban was introduced; there were no SO_2 measurements either before or after the introduction of this ban. In the cities affected by the 2000 ban, there was one monitor each in Leixlip, Naas, and Celbridge; two in Waterford; and three in Galway. The locations of the monitoring sites considered in our analyses are listed in Table B.1 of Appendix B.

MORTALITY RATES

We obtained records of all deaths in Ireland from the Irish Central Statistics Office for the 24-year period from January 1, 1981, to December 31, 2004. Details of the death registration and data provided on the death records can be found in Appendix C. Note that when this study began in 2003 there were limited mortality (and hospital admissions) data available post-ban for the cities affected by the 2000 ban. Our analyses of health endpoints were therefore restricted to data associated with the 1990, 1995, and 1998 coal bans.

We abstracted all data on deaths of residents of cities and towns affected by the sequential coal bans and of surrounding counties (see Appendix A). In reviewing the mortality data by year we found apparent inconsistencies in the coding of residence. For example, Figure 2 shows the total number of deaths reported for Limerick City and for county Limerick for the years 1981 to 2004. There is an anomalous drop in the reported number of deaths in Limerick City in 1988 to 1990 and an anomalous increase in the reported number of deaths in county Limerick at least in 1989. These anomalies suggest that there might have been cross-coding of residences between Limerick City and county Limerick in these years. There was also clear evidence for cross-coding between the cities of Drogheda and Dundalk in county Louth. Figure 3 shows the reported counts of deaths for Drogheda and Dundalk combined versus the rest of county Louth. Although the total number of deaths in all of county Louth was fairly constant over the period, there were dramatic shifts in the numbers of deaths reported in Drogheda and Dundalk compared with the rest of the county in 1995 and again in 2002. These unexplained shifts in coding of residence on the death records, between cities and their surrounding counties,

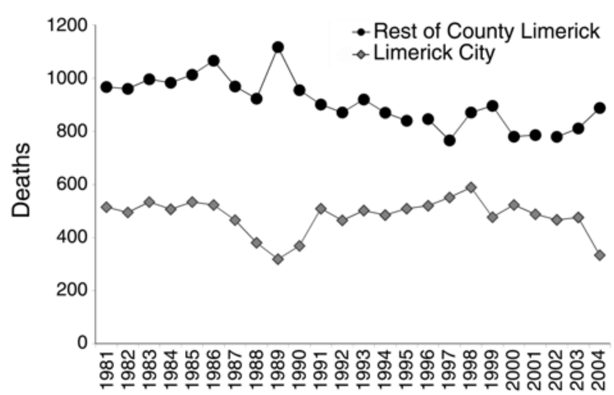


Figure 2. Total reported deaths by year for residents of Limerick City and the rest of county Limerick.

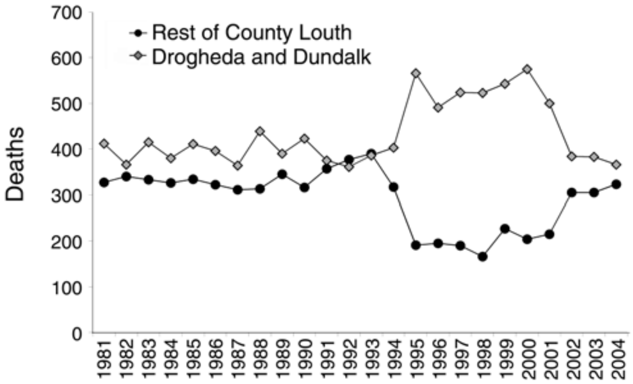


Figure 3. Total reported deaths by year for residents of the cities of Drogheda and Dundalk in county Louth, and the rest of county Louth.

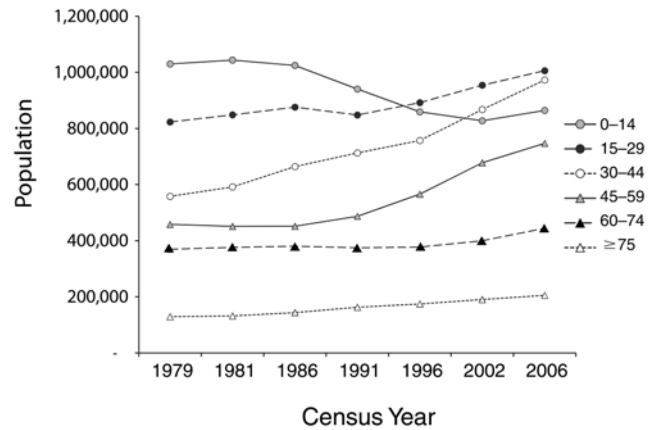


Figure 4. Population by census year, stratified by 15-year age groups.

called into question the reliability of the residence code for geographic areas smaller than a county. Actual addresses were not provided on the death records. As described in Appendix C, the codes for the "place of death registration" were also not reliable indicators of the city of death. We therefore aggregated deaths for the counties rather than the cities and towns affected by the 1995 and 1998 coal bans. This was consistent with hospital admissions data, which were only available at the county level.

Directly Standardized Mortality Rates

For each day we counted sex- and age-specific (by 5-year age groups, i.e., 0–4, 5–9, … 80–84, and ≥ 85 years) non-trauma deaths (International Classification of Diseases, ninth revision [ICD-9] codes < 800). Similarly, we counted sex- and age-specific total respiratory deaths (ICD-9 460 to 519) and cause-specific respiratory deaths, including pneumonia (ICD-9 480 to 487) and COPD (ICD-9 490 to 496). We counted total cardiovascular deaths (ICD-9 390 to 459) and cause-specific cardiovascular deaths, including ischemic heart disease (ICD-9 410 to 414) and cerebrovascular disease (ICD-9 430 to 438). We also counted other, non-respiratory and non-cardiovascular deaths (ICD-9 < 390 or ICD-9 ≥ 520) and deaths from digestive diseases (ICD-9 520 to 579), cancer (ICD-9 140 to 239), and specifically lung cancer (ICD-9 160 to 165).

There have been substantial shifts in the age distribution of the Irish population over the last 25 years (Figure 4). The number of children (0–14 years of age) has decreased, while the number of middle-aged adults (30–59 years) has increased. The number of people 75 years or older remained a small fraction of the total population in all census years between 1981 and 2006 (e.g., 4.8% in 1996), but during that period there was a substantial increase (59%) in this group, from n = 131,897 in 1981 to n = 205,378 in 2006. To adjust for these changes in the total base population and the age and sex distribution of the base population across the study period, we linearly interpolated the sex- and age-specific county-specific population for each day between census counts, which were collected every 5 years (i.e., 1981, 1986, 1991, 1996, and 2002). We then calculated the sex- and age-specific (by 5-year groups) directly standardized mortality rates for each day, using the 1996 Irish population data as the standard (see Appendix C).

For this analysis these daily standardized mortality rates were then summed to produce a standardized rate for each week, expressed as deaths per 1000 person-years (p-yr). This analysis contrasts with an earlier analysis in Dublin (Clancy et al. 2002) that used daily mortality rates. Weekly rates were chosen to match weekly indicators of influenza epidemics. We examined the differences in the estimated effect of the 1990 ban in Dublin, the variance of these estimates (confidence intervals [CIs]), and statistical tests of significance (P values) using daily versus weekly data.

Comparison and Reference Populations and Mortality Rates

The coal bans affected the populations in 12 county boroughs and urban districts, as described previously. We defined the affected populations as the nine counties that included these 12 areas, that is, Dublin County Borough (1990 ban); county Cork (1995 ban); counties Louth, Limerick, Wicklow, and Wexford (1998 ban); and counties Galway, Waterford, and Kildare (2000 ban) (Figure 1). The remaining counties not directly affected by any of the bans included 1,840,935 people in the 1996 census (50.8% of the 1996 total Irish population of 3,626,087). We used population data from these non-ban counties to examine the effects of the bans in a separate, presumably unaffected "comparison" population and to estimate background secular changes in mortality rates, independent of air pollution, over the course of the study in a "reference" population.

For the comparison population, we identified 12 counties in the middle of the country whose populations we assumed were not directly affected by the coal bans (Figure 1). Four of these counties (Laois, Longford, Offaly, and Westmeath) are collectively known as the Midlands region. Their economic base is agriculture, wood processing, and peat harvesting. Four of these counties to the north (Cavan, Meath, Monaghan, and Roscommon) are largely agricultural, although there is a major lead and zinc mine in Meath. Four of these counties to the south (Carlow, Kilkenny, and Tipperary North and South) are largely agricultural. Overall 68% of the land in these 12 counties is devoted to farming (Table 2). Their total population in the 1996 census was 711,993, with a population density of 32 persons/km². The average total income per person was € 11,166 in 1996. The total populations and population characteristics of these 12 counties were similar to those of the counties (except for Dublin) affected by the 1995, 1998, and 2000 coal bans. We defined the residents of these counties as a comparison population unaffected (at least directly) by the bans. In this report, these 12 counties are referred to as the "Midlands counties."

For the reference population, we chose six western counties facing the North Atlantic that were more rural and less developed. These counties were less populated and had less urban development, industry, and agriculture. The six chosen counties (Clare, Donegal, Kerry, Leitrim, Mayo, and Sligo) had a 1996 census population of 542,532 (Table 2). The population density (25 persons/km²) was low; only 55% of the land was devoted to farming. Average total income in 1996 was € 10,785 per person. The western county of Galway was not included in this reference population, because it was directly affected by the 1998 ban. We refer to these rural, less developed counties as the "Coastal counties." The population of these Coastal counties was used as a reference population for assessing secular changes in mortality independent of air pollution.

Table 3 shows the distribution by sex and age categories for the populations of the areas affected by each of the bans and for the reference and comparison populations. The age distributions of the 1996 populations in the Midlands and Coastal counties were similar (Figure 5). The Coastal

Table 3. Population Percentages by Sex and Age Groups of Counties Affected by the Coal Bans, Midlands Comparison Counties, and Coastal Reference Counties

			Age Groups (yr)					
Population (1996 Census)[a]	Males (%)	Females (%)	0–14 (%)	15–29 (%)	30–44 (%)	45–59 (%)	60–74 (%)	≥ 75 (%)
1990 Ban 481,854	48.1	51.9	22.0	27.3	21.7	15.4	9.7	4.0
1995 Ban 420,510	49.7	50.3	23.3	24.5	20.9	15.8	10.6	4.9
1998 Ban 464,262	49.9	50.1	24.2	24.5	20.8	15.9	10.1	4.5
2000 Ban 418,526	50.1	49.9	24.5	25.0	21.2	15.3	9.4	4.5
Midlands 711,993	50.8	49.2	25.1	22.6	20.6	15.5	11.1	5.2
Coastal 542,532	50.6	49.4	24.5	21.9	19.6	16.1	11.6	6.4

[a] Cities, towns, and counties signified by the ban years and regions cited in this table are defined in Table 2.

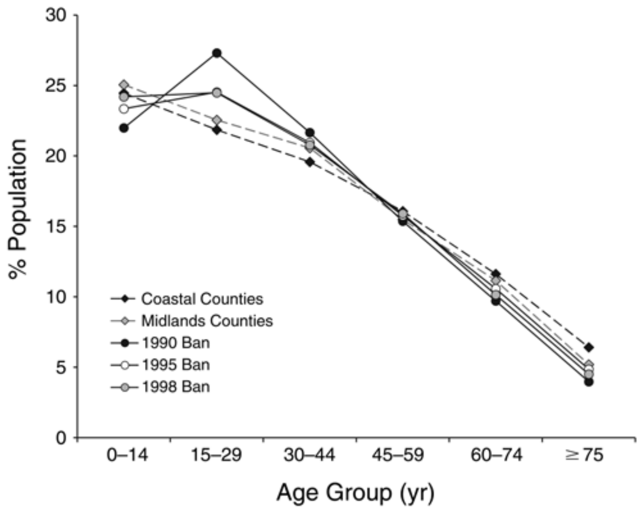


Figure 5. Age distribution of population at 1996 census by 15-year age groups, comparing Coastal and Midlands counties and counties affected by the 1990, 1995, or 1998 coal bans.

counties had a higher percentage of the population in the 60 years or older categories than did the Midlands counties (18.0% versus 16.3%) and, necessarily, a lower percentage in the younger categories (less than 30 years) (46.4% versus 47.7%). The 1996 population of Dublin County Borough, that is, the area analyzed for the effect of the 1990 ban, had a higher percentage of women (51.9%) and of young people from 15 to 29 years old (27.3%) (see Table 3) compared with the other areas.

The counties included in the analyses of the 1995 and 1998 bans were more similar in sex and age distributions (Table 3 and Figure 5) to the Coastal and Midlands counties. Nevertheless, because of the importance of sex and age as risk factors for mortality and morbidity, it was important that rates be adjusted to a common sex and age distribution.

We compared death rates in 1996 for each of the areas affected by the three coal bans, directly standardized by sex and 5-year age groups to the 1996 population for all of Ireland (Table 4). For all non-trauma deaths, the Coastal counties (which, again, served as the reference population) had the lowest directly standardized death rates (8.25 per 1000 p-yr). The highest rates were in Dublin (1990 ban, 8.87) and Cork (1995 ban, 8.79).

Cardiovascular mortality rates were lowest in the Coastal counties, most notably for ischemic heart disease, although cerebrovascular death rates were higher. The Midlands counties had cardiovascular mortality rates similar to those of the counties affected by the bans. On the other hand, respiratory death rates were higher in the

Table 4. Directly Standardized 1996 Mortality Rates by Cause for Counties Affected by the Coal Bans, Midlands Comparison Counties, and Coastal Reference Counties[a]

Population / Cause	1990 Ban	1995 Ban	1998 Ban	Coastal Counties	Midland Counties
Population	481,854	420,510	464,262	542,532	721,993
Non-Trauma[b]	8.87	8.79	8.54	8.25	8.42
Cardiovascular Disease	3.98	4.14	3.95	3.71	3.97
Ischemic heart disease	2.20	2.31	2.14	1.95	2.24
Cerebrovascular disease	0.74	0.76	0.86	0.83	0.80
Respiratory Disease	1.33	1.26	1.43	1.40	1.36
Pneumonia	0.66	0.63	0.61	0.71	0.63
COPD	0.50	0.53	0.60	0.54	0.58
Cardiopulmonary Disease	5.32	5.40	5.38	5.12	5.34
Other	3.55	3.39	3.15	3.13	3.08
Cancer	2.31	2.27	1.99	1.90	1.89
Lung cancer	0.64	0.42	0.42	0.34	0.36
Digestive disease	0.26	0.22	0.25	0.28	0.28

[a] Cities, towns, and counties signified by the ban years and regions cited in this table are defined in Table 2.

[b] Causes in **boldface** are principal categories; the rest are subcategories.

Coastal counties, particularly for pneumonia. Cancer death rates, including lung cancer, were lower in the Coastal and Midlands counties than in the counties affected by the bans.

We calculated cause-specific directly standardized mortality rates for the Coastal counties (1996 population 524,532) and for the Midlands counties (1996 population 721,993) in the same manner as above (Figure 6 and Figure 7, respectively). We adjusted for the cause-specific mortality rates in the Coastal counties (i.e., the reference population) in each of our regression analyses used to estimate the change in mortality associated with specific coal bans. We also estimated the effect of each ban on cause-specific mortality rates in the Midlands counties (i.e., the comparison population), adjusting for mortality in the Coastal counties.

HOSPITAL ADMISSIONS

The Economic and Social Research Institute (ESRI) provided daily hospital admissions data for cardiovascular disease (ICD-9 390 to 459), respiratory disease (ICD-9 460 to 519), and digestive disease (ICD-9 520 to 579) based on discharge diagnoses from Hospital In-Patient Enquiry (HIPE) reports. Appendix D provides a detailed description of the data collected in the HIPE reports. To maintain the confidentiality of individuals as well as of the hospitals, no identifying information below the county level was provided. Hospital admissions data for cardiovascular disease, respiratory disease, and digestive disease were provided for residents of Cork County Borough for the period 1991 to 2004 and for residents of the four counties affected by the 1998 ban (Limerick, Louth, Wexford, and Wicklow) for the period 1993 to 2004.

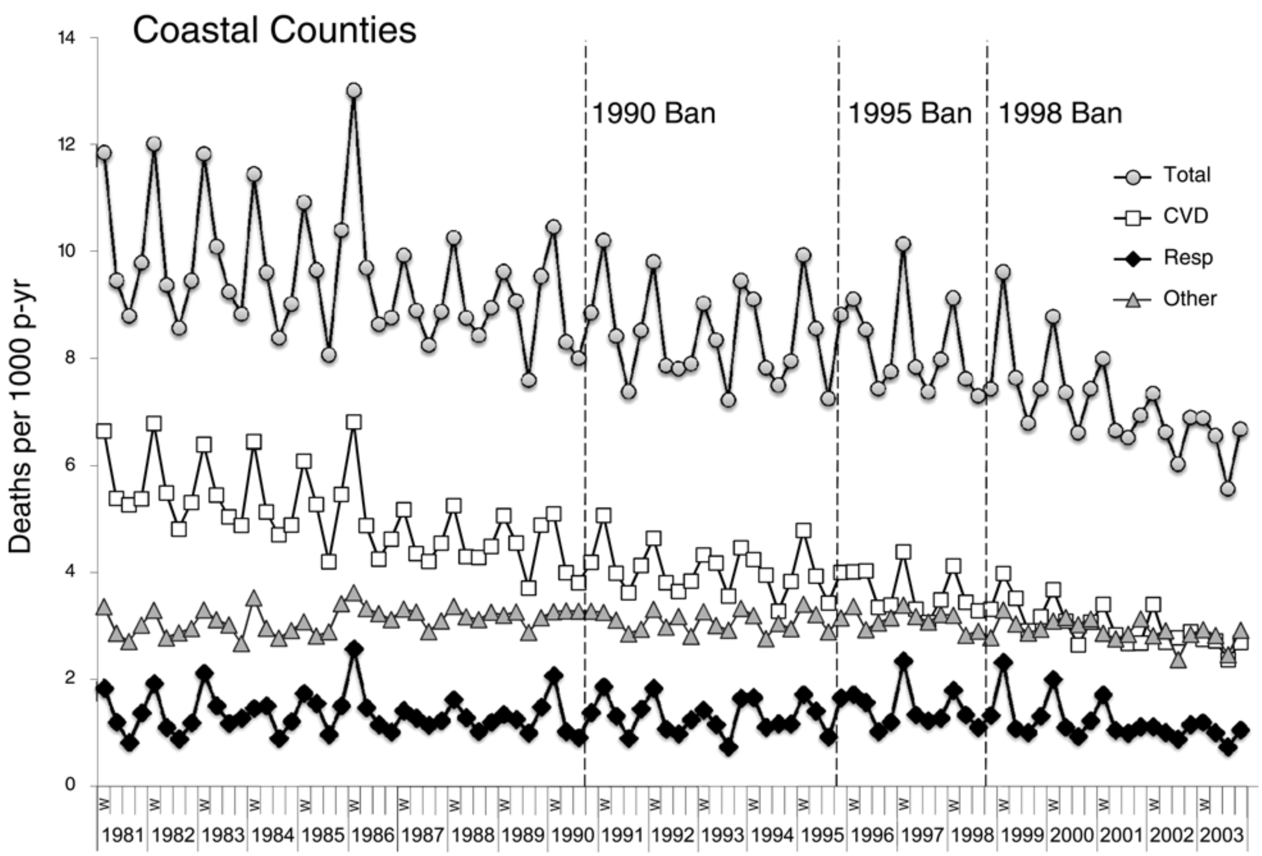


Figure 6. Mortality rates directly standardized for age and sex for Coastal counties by cause and season. Causes include total, cardiovascular (CVD), respiratory (Resp), and other (not cardiovascular or respiratory) disease. W indicates winter.

Total hospital admissions (Appendix D, Table D.1) were roughly evenly distributed across the major classes of primary discharge diagnoses — cardiovascular disease (105,359 admissions), respiratory disease (126,302 admissions), and digestive disease (90,882 admissions). For cardiovascular admissions, we also analyzed data on specific subcategories previously reported to be associated with air pollution — ischemic heart disease (ICD-9 410 to 414; 37,309 admissions) and cerebrovascular disease (ICD-9 430 to 438; 18,823 admissions). For respiratory admissions, similarly, we analyzed data on pneumonia and influenza (ICD-9 480 to 487; 23,239 admissions), COPD (ICD-9 490 to 496; 40,323 admissions), and asthma (ICD-9 493; 18,238 admissions).

Direct Standardization by Age and Sex

To adjust for changes in the total base population and in the age and sex distribution of the base population across the study period, we applied the same direct-standardization methods used for the mortality data. We linearly interpolated the sex-, age-, and county-specific population for each day between census counts. We then calculated admissions rates directly standardized by sex and age (by 5-year groups) for each day, using the 1996 population of Ireland as the reference using the same methods as for mortality (see Appendix C). These daily standardized admission rates were then summed to produce a standardized rate for each week, expressed as admissions per 1000 p-yr.

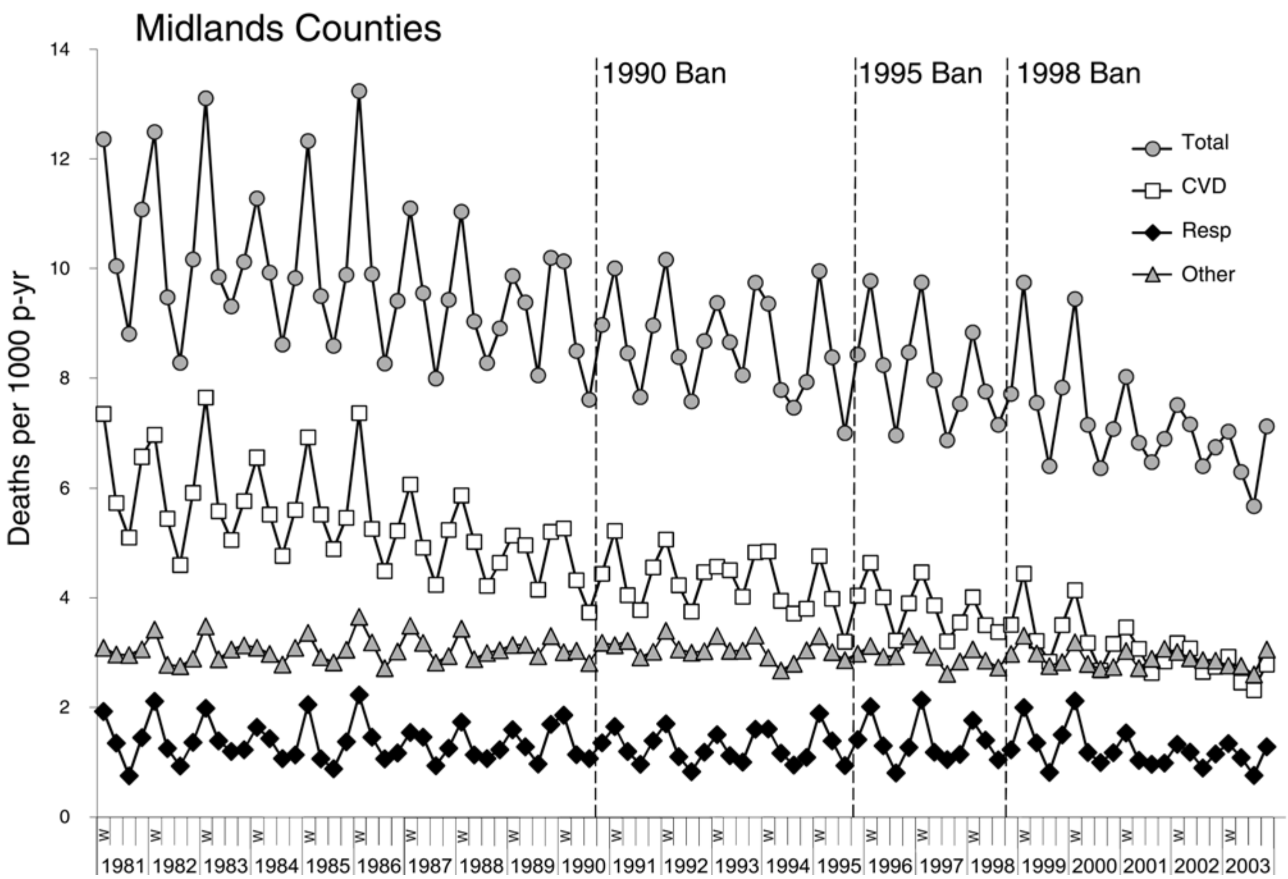


Figure 7. Mortality rates directly standardized for age and sex for Midlands counties by cause and season. Causes include total, cardiovascular (CVD), respiratory (Resp), and other (not cardiovascular or respiratory) disease. W indicates winter.

Adjustment for Incomplete Reporting

ESRI took over management of the HIPE admissions-data reporting system in 1990. Admissions were underreported before 1995 (ESRI 2002). Comparison of the number of hospital admissions in Ireland as estimated by the Department of Health and Children with the number reported to HIPE (Figure 8) showed clear underreporting before 1995 (ESRI 2002, 2007). By 1995, underreporting of HIPE records was estimated to be less than 10%. ESRI recommended not using HIPE data from before 1995 for trends analyses, which would have precluded using HIPE records to assess the effects of the 1990 ban in Dublin and the 1995 ban in Cork. However, our interest in assessing the effects of the 1995 and 1998 bans on hospital admissions dictated that we develop an approach to adjust for this underreporting.

Comparison of the percentage coverage of the HIPE data, that is, the number of HIPE-reported admissions divided by the Department of Health and Children estimate of admissions (ESRI 2002, 2007), with the reported number of hospital admissions for digestive-disease diagnoses in Cork County Borough hospitals (Figure 9) showed the same pattern. We therefore used annual hospital admissions for digestive-disease diagnoses as a basis for adjustment for underreporting.

First, we tabulated monthly mean hospital admissions for digestive diagnoses (Figure 10) for the counties affected by the 1995 ban (Cork) and by the 1998 ban (Limerick, Louth, Wexford, and Wicklow). Second, we assumed that the rate of underreporting was fixed for each calendar year. We adjusted each city-year rate back to the reference digestive admissions rate by dividing the weekly cause-specific values by the digestive admissions for that year and multiplying by a normalizing value of digestive admissions in the calendar year after the ban. This had the effect of "adjusting" for underreporting and for annual changes.

That is:

$$R_{ijk}^{Norm} = R_{ijk} \times \frac{Norm_i}{Digest_{ik}}$$

where R_{ijk}^{Norm} is the normalized cause-specific admission rate for county i, week j, and year k; R_{ijk} is the population-adjusted rate for county i, week j, and year k; $Digest_{ik}$ is the directly standardized admissions rate for digestive diagnoses for year k in county i; and $Norm_i$ is the admissions rate for digestive-disease diagnoses for county i in the calendar year after the ban. To illustrate the effect on digestive admissions, the plot of normalized digestive admissions in Figure 10 shows the removal of underreporting and other long-term trends.

Background Hospital Admissions Rates

Hospital admissions data were provided for the counties affected by the sequential coal bans but not for any of the counties unaffected by the bans (non-ban areas). We therefore did not have hospital admissions data for non-ban

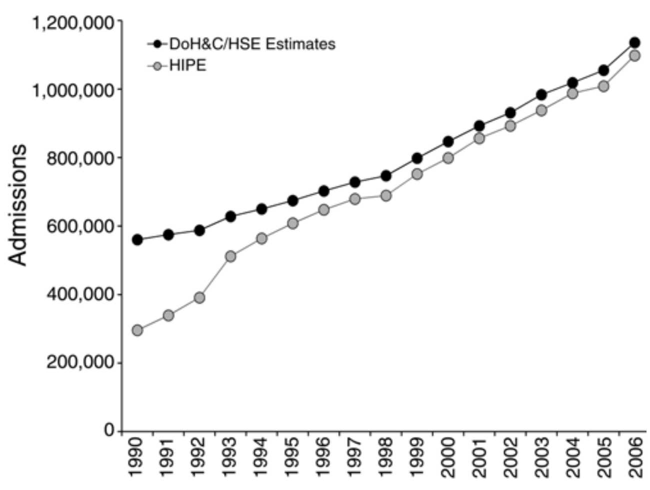


Figure 8. Total hospital admissions as reported to HIPE and as estimated by the Department of Health and Children/Health Service Executive (DoH&C/HSE).

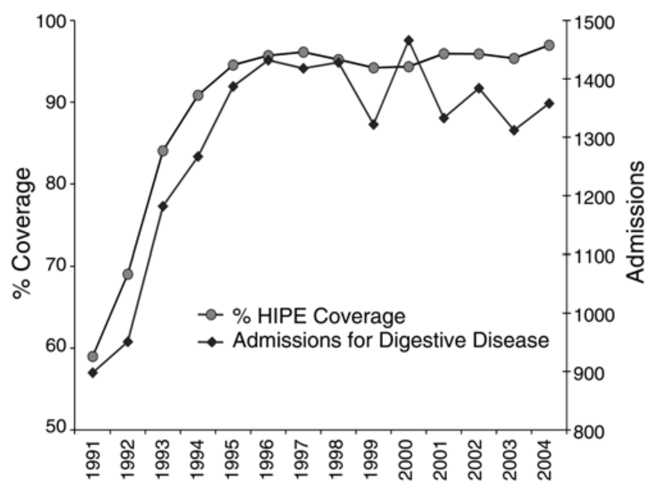


Figure 9. Estimated HIPE percentage coverage and hospital admissions for digestive disease by year in Cork County Borough.

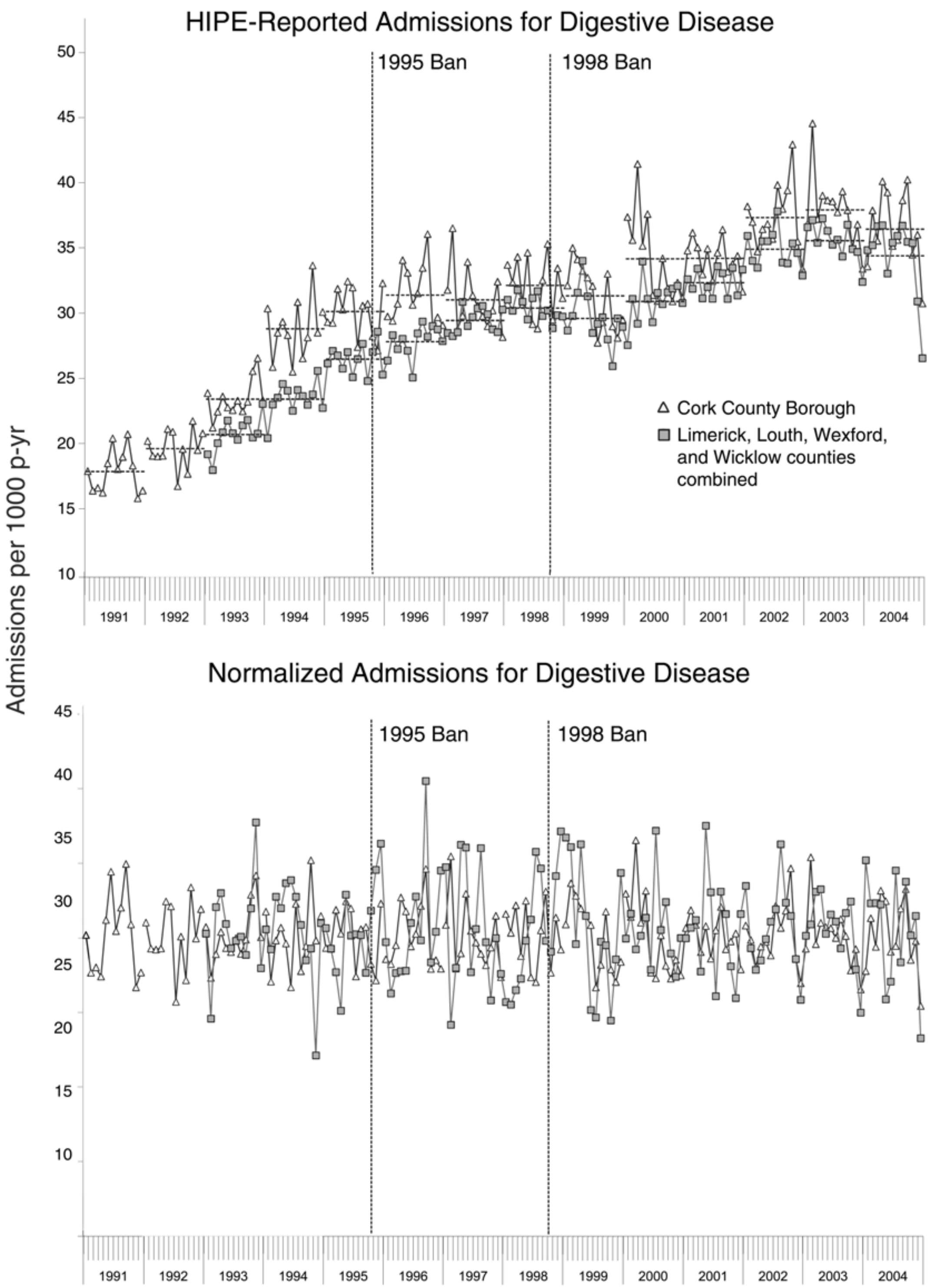


Figure 10. Hospital admissions rates per 1000 p-yr for digestive disease by month for counties affected by the coal bans of 1995 and 1998 as reported to HIPE (upper) and as normalized to the year after each ban (lower). Dashed horizontal lines indicate annual admission rates.

areas to estimate temporal trends, unlike the mortality data, which were available for the entire country. To adjust for secular trends in hospital admissions unrelated to the bans, we included a term for the county-specific hospital admission rate for digestive disease for each week.

PERIOD DEFINITIONS

The weeks from January 1, 1981, to the date of the county-specific coal bans (September 1, 1990, for Dublin; October 1, 1995, for county Cork; or October 1, 1998, for counties Limerick, Louth, Wexford, and Wicklow) were defined as the pre-ban periods. All weeks after the bans up to December 31, 2004, were defined as the post-ban periods. We defined the heating season as the period from November to April (the months with average temperatures below the median) and the non-heating season as the period from May to October. Seasons were defined by month as follows: winter, December to February; spring, March to May; summer, June to August; and autumn, September to November.

INFLUENZA EPIDEMICS

There was no routine influenza surveillance system in Ireland during the study period. We identified episodes of influenza and other respiratory infection outbreaks using the surveillance methods of the U.S. Centers for Disease Control and Prevention (Serfling 1963; Serfling et al. 1967) (Appendix E). For each week of the year, we calculated the percentage of total deaths in Ireland in which pneumonia or influenza (ICD-9 480 to 487) was listed as the cause of death. We then fitted these weekly percentages against sine and cosine functions of 26 and 52 weeks plus sine and cosine terms of the 24-year trend period. For each week, the expected 95th percentile was defined as the expected weekly mean percentage plus 1.96 times the standard deviation of the residuals. Influenza episodes were then defined as at least two consecutive weeks in which the percentage of deaths in Ireland from influenza and pneumonia were above the 95th percentile of the expected percentage. This indicator variable for influenza epidemics weeks was included in all our mortality and hospital admissions analyses.

WEATHER

We calculated the mean temperature for each week during the study period from hourly temperature observations reported by the Met Éireann, the Irish National Meteorological Service (Appendix F). Observations from the weather station at Cork Airport were used for county Cork mortality and admissions analyses, at the Dublin Airport for Dublin and counties Louth (Dundalk and Drogheda) and Wicklow (Arklow), at the Shannon Airport for county Limerick (Limerick city), and at the Rosslare airport for county Wexford (Wexford city). We used this continuous variable in our analyses.

STATISTICAL METHODS AND DATA ANALYSIS

AIR POLLUTION

For the communities with multiple monitors, we first calculated the mean BS and SO_2 concentrations across all the reporting monitors for each day. We calculated descriptive statistics of the city- and day-specific mean BS and SO_2 concentrations for the entire study period and the 5-year pre-ban and 5-year post-ban periods. We calculated the same descriptive statistics during these pre- and post-ban periods for each season. We used *t* statistics to test for differences in pre- and post-ban BS and SO_2 concentrations.

MORTALITY ANALYSES

We examined trends with line plots of cause-specific mortality rates pre- and post-ban. Further, histograms were used to study the distribution of these mortality rates.

Primary analyses modeled weekly cause-specific mortality using Poisson regression. Y_t, the specified weekly cause-specific mortality rate in the ban area of interest, was assumed to follow a Poisson distribution with the mean μ_t such that

$$\log\left[\mu_t\right] = \alpha + \beta_1 B_t + \beta_2 Loess\left(Y_{t0}\right) + \beta_3 T_t + \beta_4 I_t$$

with t indexing the week, B_t as an indicator variable for ban ($B_t = 1$ if post-ban, $B_t = 0$ if pre-ban), a Loess smooth (25-week neighborhood) of the weekly total cause-specific mortality rate Y_{t0} in the reference Coastal counties (Appendix G), T_t as the mean weekly temperature, and I_t as an indicator variable for whether there was an influenza epidemic that week ($I_t = 1$ for influenza epidemic, $I_t = 0$ if not). Within the primary analyses, weekly mortality rates were assumed to be statistically independent conditional on the ban indicator, mortality rates in non-ban counties, temperature, and whether it was a week with an influenza epidemic. We assumed that conditioning on mortality rates in reference Coastal counties would account for any national, observable secular trends that would result in correlations between sequential weeks within the ban areas; and, as such, any remaining correlations across time would be negligible. The Proc Genmod procedure in SAS (SAS

Institute, Cary, NC) was used to estimate the regression parameters by way of maximum likelihood estimation.

In the analyses above, tests for the significance of a ban were conducted via Wald tests. The percentage change in mortality because of the coal ban was estimated as $e^{\hat{\beta}_1}$, with a 95% CI calculated as $e^{\hat{\beta}_1 \pm 1.95 \bullet se(\hat{\beta}_1)}$, where $\hat{\beta}_1$ refers to the maximum likelihood estimate of β_1, and $se(\hat{\beta}_1)$ refers to its standard error.

To examine modifications by season, an indicator variable for the heating season ($\delta_t = 1$ if heating season, $\delta_t = 0$ if non-heating season) and its cross-product with the indicator variable for ban (B_t) were added to the systematic component of the model described above. A test of whether season significantly modified the effect of a ban was conducted with a Wald test of the regression parameter associated with the interaction. To examine modifications by age group, we conducted two distinct sets of analyses using the Poisson regression described above: one for people 0 to 74 years old and one for people 75 years and older.

For the 1998 ban, which was implemented in four counties, the Poisson regression model described above was used to estimate the effect of the ban on each of the four counties separately. Then for any particular cause-specific mortality, a combined estimate of the effect of the ban was calculated using a weighted average, with weights equal to the inverse of the variance for the county-specific estimates. Specifically,

$$\hat{\beta}_{i,pooled} = \frac{\sum_{i=1}^{4} w_i \hat{\beta}_{1,i}}{\sum_{i=1}^{4} w_i}$$

where i indexes each of the four counties, $\hat{\beta}_{1,i}$ is the maximum likelihood estimate of the parameter coefficient associated with the ban indicator in county i, and $w_i = Var(\hat{\beta}_{1,i})$ such that w_i is estimated by the corresponding estimate of the variance of the regression parameter $\hat{\beta}_{1,i}$. The variance of the weighted average is given by

$$Var(\hat{\beta}_{i,pooled}) = \frac{1}{\sum_{i=1}^{4} w_i}.$$

Related CIs can be created by taking the estimate plus or minus 1.96 times the standard error.

HOSPITAL ADMISSIONS

Using Poisson regression, we estimated the change in weekly cause-specific hospital admissions rates (standardized for age and sex and adjusted for underreporting) associated with each county-specific ban on coal sales. We regressed the weekly cause-specific, normalized, standardized hospital admissions rates against predictors, including an indicator variable for the post-ban (versus pre-ban) period, the weekly mean temperature, and an indicator variable for "influenza epidemic week." We estimated the percentage change in cause-specific hospital admissions for all ages, as well as in separate analyses by two age groups (0 to 74 years and 75 years and older). We also estimated the percentage change by heating or non-heating seasons in joint models including interactions terms. We repeated these analyses for specific cardiovascular (ischemic heart disease, ischemic stroke, and cerebrovascular) and respiratory (pneumonia and COPD) diagnoses.

For the 1998 ban, which affected five cities and towns in four counties, we first estimated county-specific hospital admissions rate changes in the same manner and then combined the county-specific estimates using weights equal to the inverse of the variance of the county-specific estimates.

RESULTS

AIR POLLUTION

To meet our first specific aim, we examined the effect of the coal ban in each city on BS and SO_2 air pollution concentrations. We also evaluated whether any change in pollutant concentration was different by season.

Pre- Versus Post-Ban Air Pollution

Black Smoke The effects of the 1990, 1995, 1998, and 2000 coal bans on BS concentrations were dramatic and immediate in all cities. Before the coal bans were put in place, data showing a strong seasonal pattern to the BS concentrations was evident in each city (Figure 11), with the highest concentrations in the winter months. There was an immediate decrease in BS concentrations in the first winter after the ban in each city that persisted throughout the study period (Figure 11).

We compared the city-specific mean BS concentrations in the 5 years before and after the coal ban in each city or town. There was a clear decrease in mean BS concentrations in all cities in the 5 years after the ban compared with the 5 years before the ban (Table 5). There were significant decreases in BS concentrations in all cities after the introduction of the

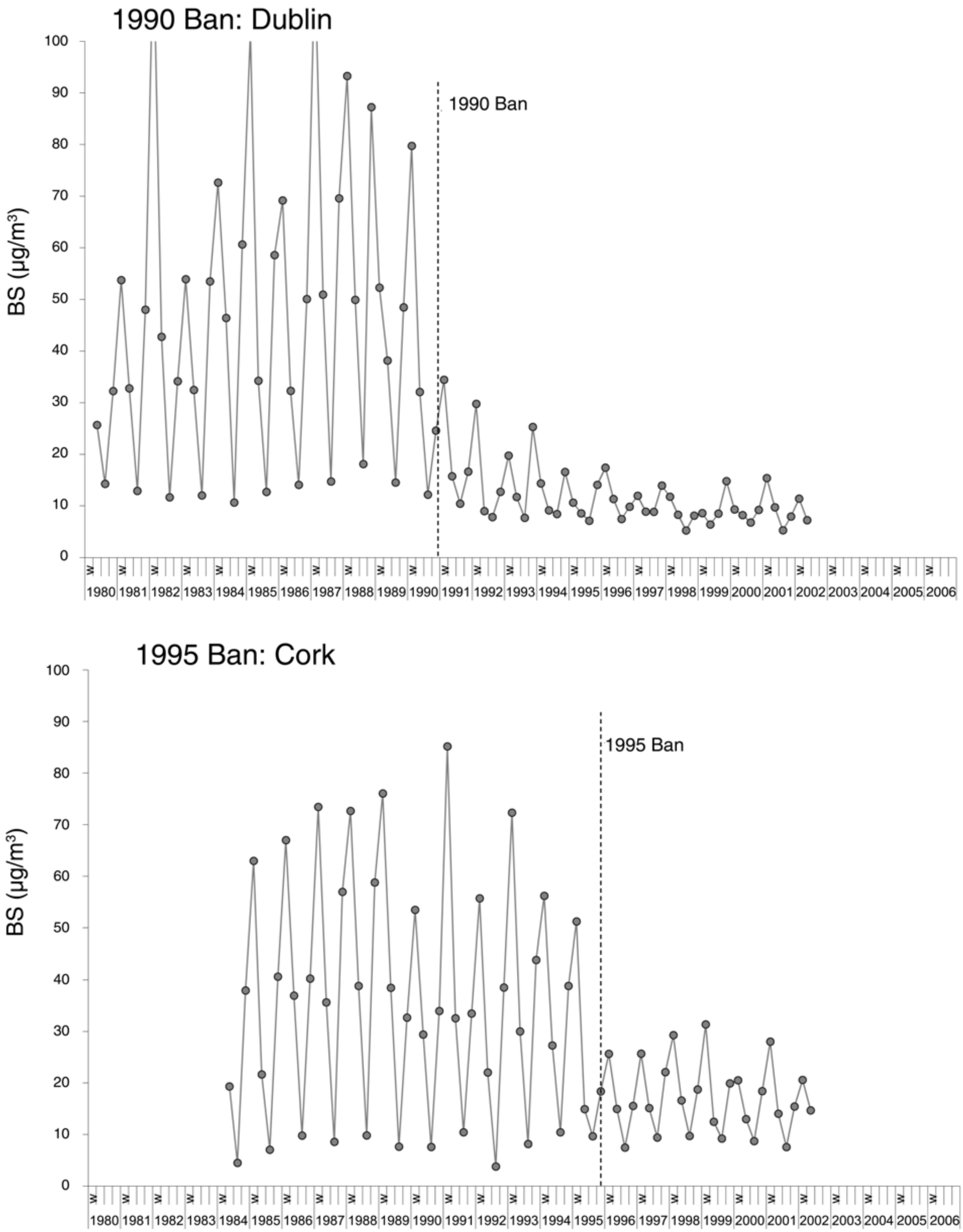


Figure 11. BS concentrations by season for cities and towns affected by the coal bans of 1990, 1995, 1998, and 2000. W indicates winter.

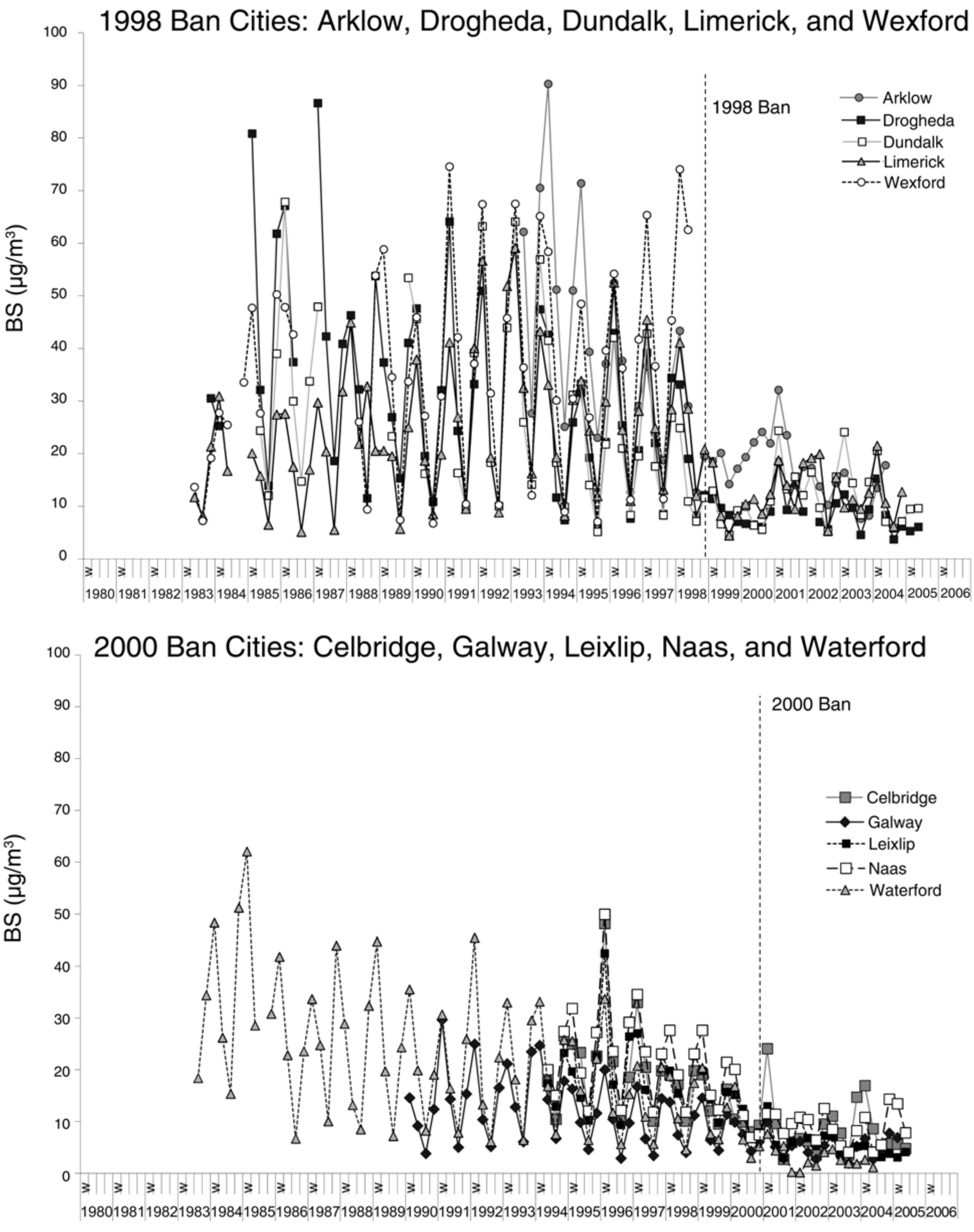


Figure 11 (*Continued*).

Table 5. Mean BS and SO_2 Concentrations by Center for 5-Year Periods Before and After the Coal Bans

		BS (µg/m³)				SO_2 (µg/m³)			
		Observations (*N*)	Mean	SD	Max	Observations (*N*)	Mean	SD	Max
1990 Ban									
Dublin	Pre-ban	1796	50.4	65.6	901	1795	33.1	16.7	205
	Post-ban	1824	15	16.5	198	1817	21.7	10.3	104
	Difference (%)		−35.4 (−70)				−11.4 (−34)		
1995 Ban									
Cork	Pre-ban	1816	33.7	34.8	346	1817	14.5	7.7	45
	Post-ban	1828	17.2	12.6	143	1800	18	7.9	48
	Difference (%)		−16.5 (−49)				3.5 (24)		
1998 Ban									
Arklow	Pre-ban	1620	40	30.8	196	1172	4.7	7.3	54
	Post-ban	1638	18.4	11.7	97	986	5.4	6.8	56
	Difference (%)		−21.6 (−54)				0.7 (14)[a]		
Wexford	Pre-ban	1512	37.7	34.8	307	—	—	—	
	Post-ban	—	—	—		—	—	—	
	Difference (%)								
Limerick	Pre-ban	1826	27.1	20.2	148	1825	14	4	63
	Post-ban	1734	12.5	8.8	58	1375	14.9	6.7	137
	Difference (%)		−14.6 (−54)				0.9 (6)		
Dundalk	Pre-ban	1802	23	28.9	387	1762	14.9	8.8	77
	Post-ban	1786	11.9	11.5	173	1785	14.2	7.9	114
	Difference (%)		−11.1 (−48)				−0.6 (−4)[b]		
Drogheda	Pre-ban	1753	24	25.6	284	1660	16.4	12.8	212
	Post-ban	1588	9.3	7.4	78	1559	11.9	8	61
	Difference (%)		−14.8 (−61)				−4.5 (−27)		
2000 Ban									
Naas	Pre-ban	1694	20.9	17	171	1686	11.1	7.2	57
	Post-ban	1462	8.9	7	56	1463	13.5	9.6	74
	Difference (%)		−12 (−57)				2.4 (21)		
Leixlip	Pre-ban	1687	17.1	14.2	139	1628	32.7	26.8	213
	Post-ban	1436	5.6	5.8	52	1399	14	9.9	60
	Difference (%)		−11.5 (−67)				−18.7 (−57)		
Celbridge	Pre-ban	1724	16.8	13.7	153	1764	14.9	9.4	105
	Post-ban	1475	8.2	10.7	129	1458	14.5	11.1	146
	Difference (%)		−8.6 (−51)				−0.4 (−3)[c]		
Waterford	Pre-ban	1778	13.5	14.9	130	1659	6.2	7.7	120
	Post-ban	1232	3.2	4.4	55	1149	4.3	9.7	160
	Difference (%)		−10.3 (−76)				−1.9 (−30)		
Galway	Pre-ban	1717	9.3	10.3	115	1716	10.3	4.7	127
	Post-ban	1561	5.1	4.8	45	1075	12.5	6.6	64
	Difference (%)		−4.2 (−45)				2.2 (21)		

Note: *P* values are $P < 0.0001$ except as noted. [a] $P = 0.027$, [b] $P = 0.024$, and [c] $P = 0.25$. — indicates no data were available.

respective bans, with reductions ranging from 45% to 76% (Table 5). The largest reduction in mean BS concentrations (70%) was in Dublin, the city with the highest pre-ban mean concentrations (50.4 µg/m^3); concentrations decreased to 15 µg/m^3.

The sequential bans of 1990, 1995, 1998, and 2000 affected not only the mean, but also the extreme values and variations in BS concentrations. The 90th and 95th percentile BS concentrations in Dublin, in the 5 years after each ban, were approximately 25% of those in the 5 years before the ban (Figure 12). In Cork, 90th and 95th percentile BS concentrations post-ban were approximately 50% of those pre-ban. Similarly, in the cities where coal was banned in 1998 and 2000, there were approximately 50% reductions in the 90th and 95th percentile BS concentrations.

Sulfur Dioxide For SO_2 measured as total gaseous acidity, there was no clear evidence of an effect of the coal bans (Figure 13). Mean season-specific SO_2 concentrations in Dublin were lower after the 1990 ban compared with before the ban, but this appears to have been part of a long-term trend and not specifically associated with the ban. In Cork mean SO_2 concentrations were lower than in Dublin before the 1995 ban, with little evidence of seasonality. There was little difference in pre- and post-ban SO_2 concentrations in Cork. In fact, there was an anomalous increase in SO_2 concentrations in the 12 to 15 months after the ban was put in place. This increase was not seen for BS (Figure 11). In four of the cities and towns affected by the 1998 ban, SO_2 concentrations were low both before and after the ban, with little difference after the ban in mean

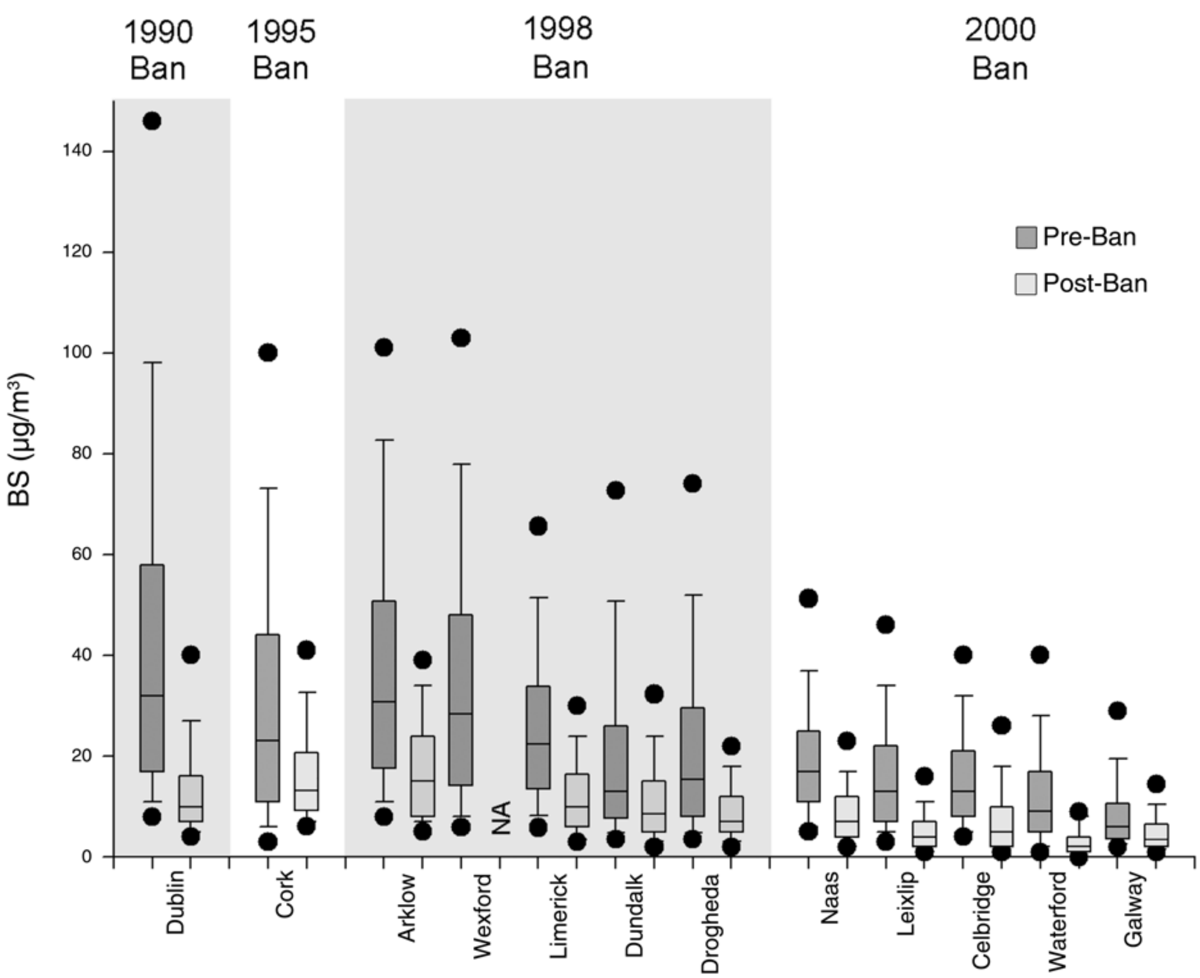


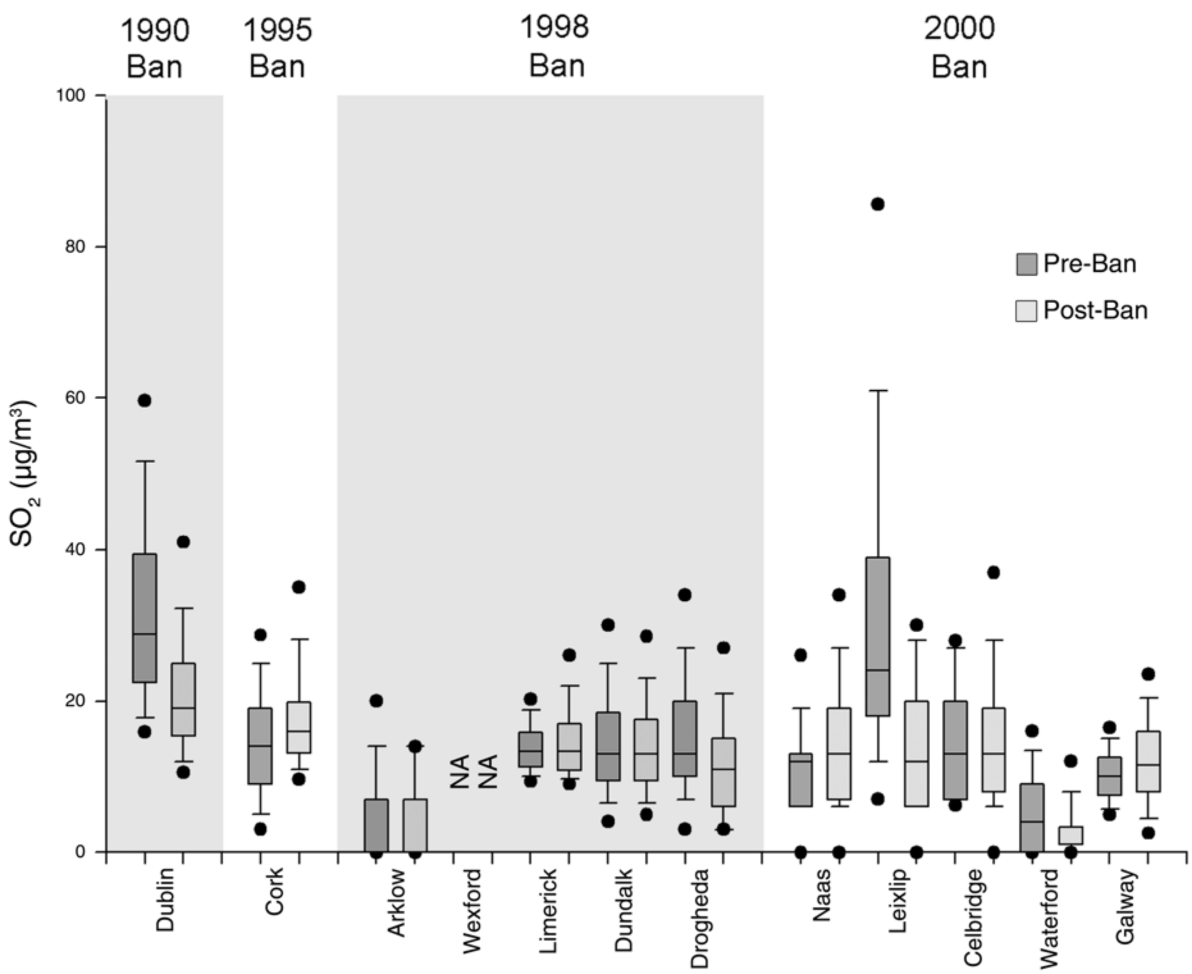
Figure 12. Box plots of the distribution of BS concentrations and SO_2 concentrations in the 5 years before (Pre-Ban) and after (Post-Ban) the coal bans of 1990, 1995, 1998, and 2000. Boxes indicate 25th, 50th, and 75th percentiles, bars indicate 10th and 90th percentiles, and dots indicate 5th and 95th percentiles. (*Continued next page.*)

concentrations. SO_2 concentrations were not monitored in Wexford, the fifth city affected by the 1998 ban. In four of the five cities and towns affected by the 2000 ban (Celbridge, Naas, Galway, and Waterford), SO_2 concentrations before the ban were relatively low and did not show a seasonal pattern. There was little change in mean SO_2 concentrations in these communities after the ban. In Leixlip, however, mean SO_2 concentrations before the ban were generally high and showed a strong seasonal pattern. In contrast with the BS concentrations, which were highest in winter, SO_2 concentrations in Leixlip before the 2000 ban were highest in summer. After the 2000 ban, summer SO_2 concentrations in Leixlip were substantially reduced (Figure 13).

There were inconsistent changes in the mean SO_2 concentrations in the 5 years post-ban compared with the 5 years pre-ban in each city (Table 5). The mean SO_2 concentration in Dublin was 11.4 μg/m³ (34%) lower after the 1990 ban (Table 5). In Leixlip, which had the highest mean SO_2 concentrations prior to the 2000 ban (similar to pre-ban values in Dublin), there was an 18.7 μg/m³ (57%) decrease in SO_2 concentration (Table 5). There were small decreases in mean SO_2 concentrations post-ban in Dundalk, Drogheda, Celbridge, and Waterford but small increases in Cork, Arklow, Limerick, Naas, and Galway (Table 5). In Dublin, Drogheda, and Leixlip there was a decrease in the 90th and 95th percentiles for SO_2 concentrations post-ban (Figure 12). However, for Cork and the other cities affected by the 1998 and 2000 bans, there was little evidence of lower 90th and 95th percentile SO_2 concentrations post-ban compared with those pre-ban (Figure 12).

Season-Specific Effects of Bans

We examined season-specific changes in mean BS and SO_2 concentrations in the 5 years before the ban to the 5 years after the ban in each city or town (Figure 14). The largest decrease in mean BS concentrations was observed



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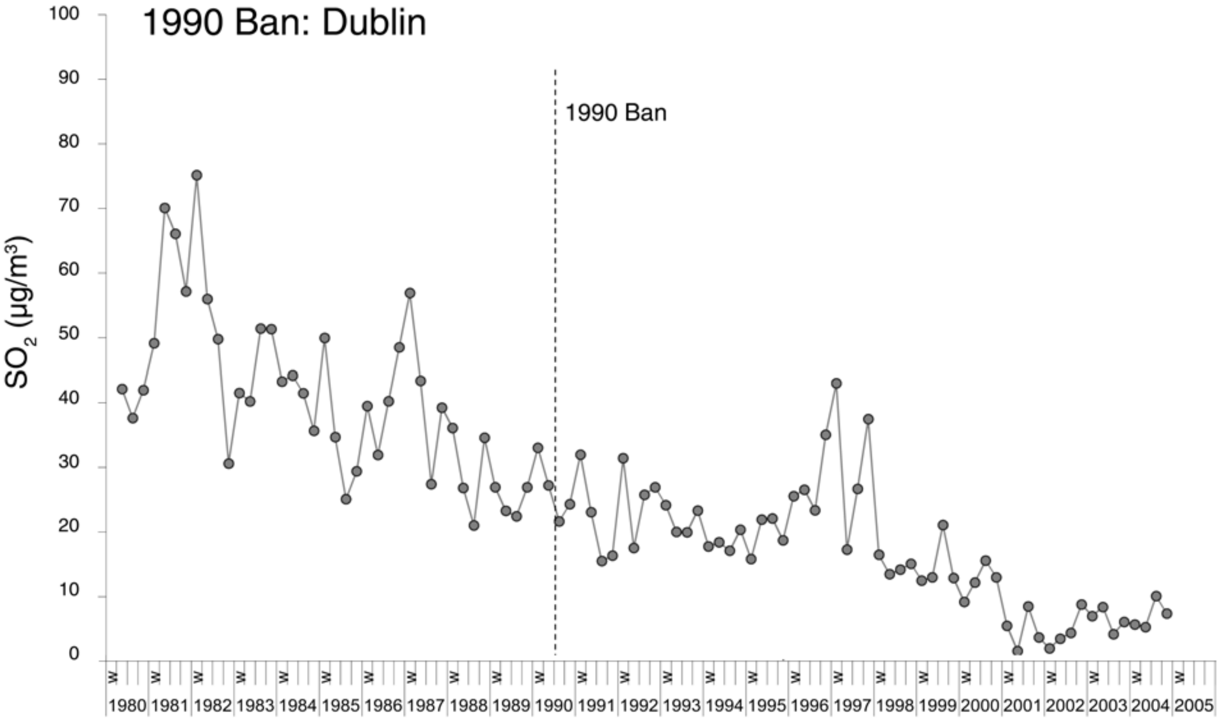


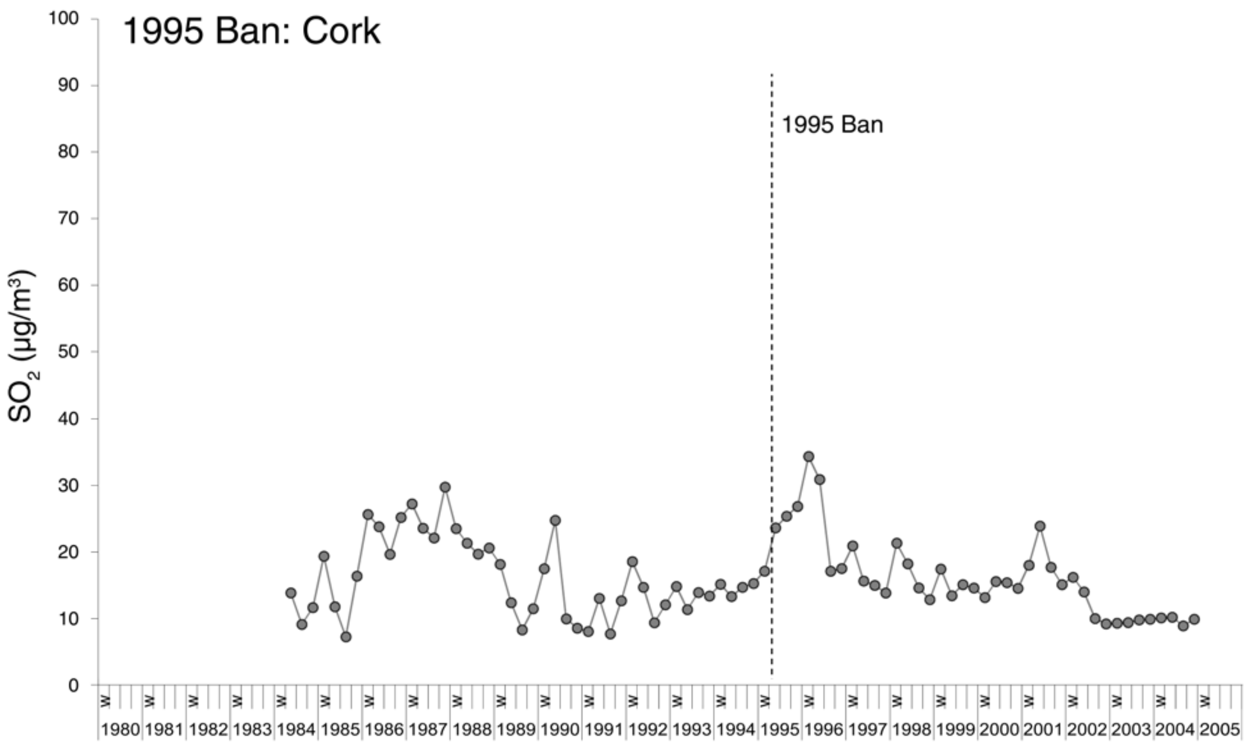


Figure 13. SO_2 concentrations (measured as total gaseous acidity) by season for cities and towns affected by the coal bans of 1990, 1995, 1998, and 2000. W indicates winter. (*Continued next page.*)

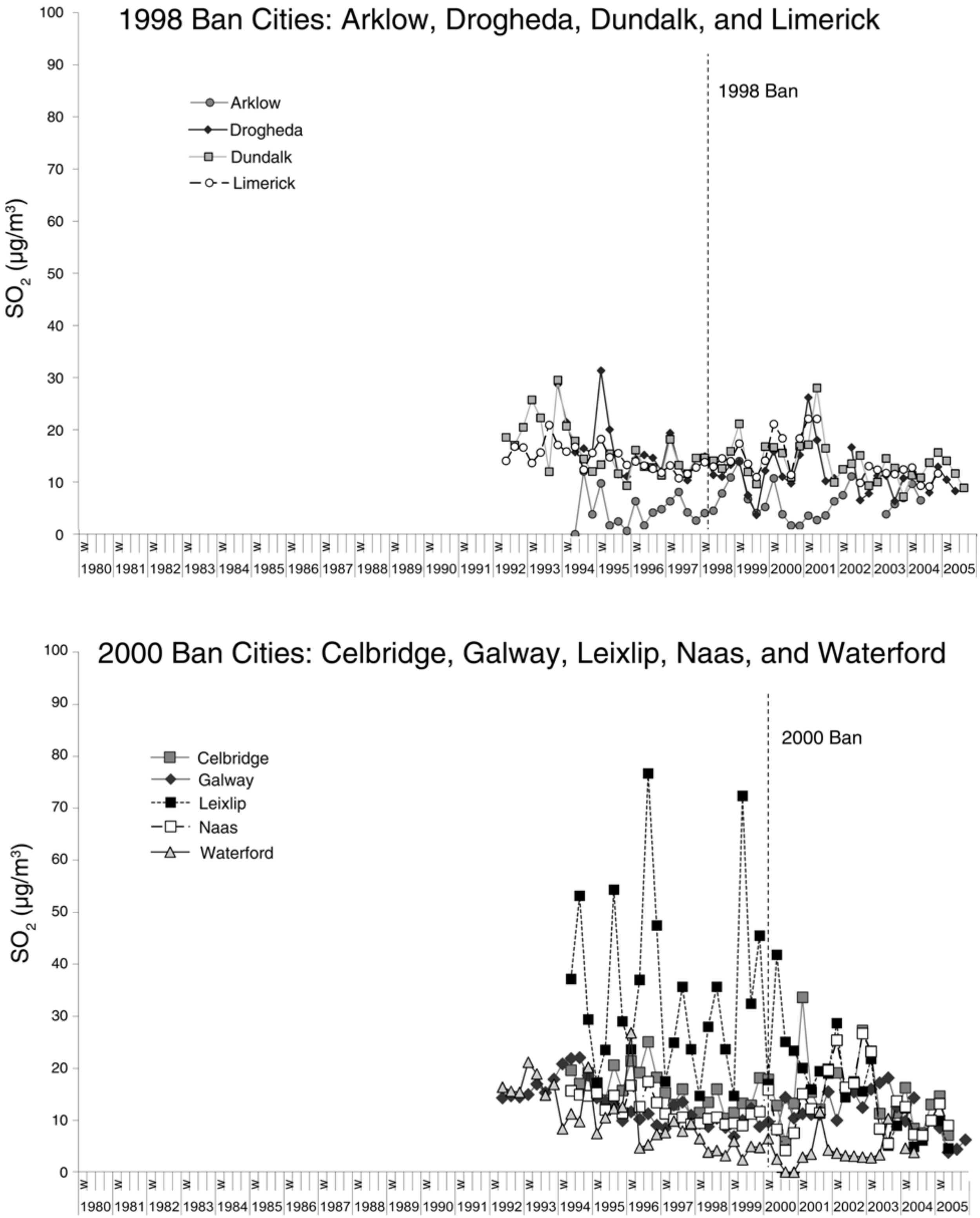


Figure 13 (*Continued*).

in the winter season in all cities or towns. There were little to no changes in mean summer BS concentrations in any of the cities or towns. The largest decrease in mean winter BS concentrations was seen in Dublin, which had the highest pre-ban concentrations. The smallest decreases in mean winter BS concentrations were seen in the 2000 ban cities or towns, which had the lowest pre-ban concentrations (Figure 14).

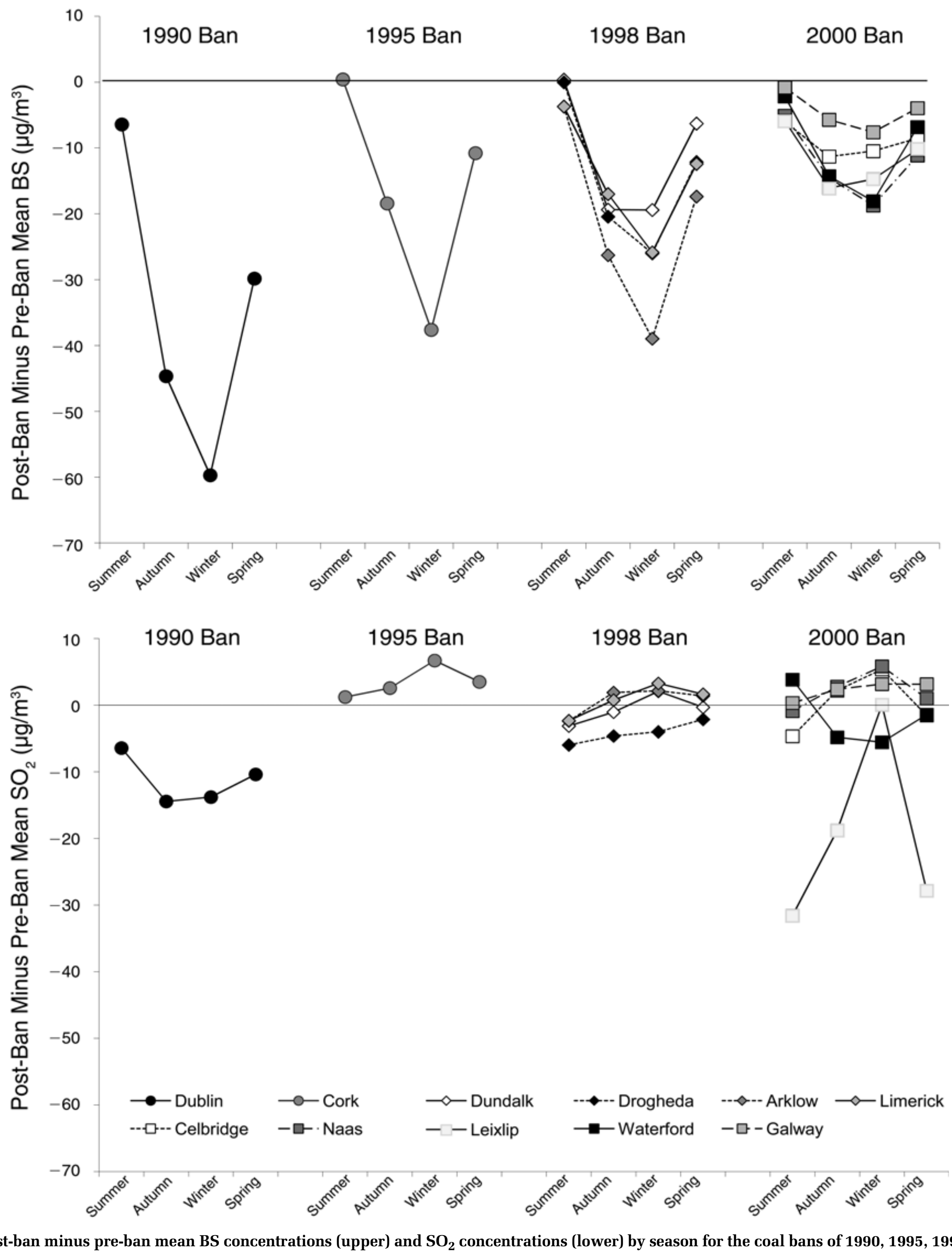


Figure 14. Post-ban minus pre-ban mean BS concentrations (upper) and SO_2 concentrations (lower) by season for the coal bans of 1990, 1995, 1998 and 2000.

In contrast, there was little evidence of reductions in season-specific SO_2 concentrations in the 5 years post-ban compared with the pre-ban years in any of the cities or towns (Figure 14). In Dublin there was a modest decrease in mean SO_2 concentrations in winter and autumn. Mean SO_2 concentrations also decreased in Leixlip in summer and spring but did not improve in winter (Figure 14).

MORTALITY

For the second specific aim, we examined the effect of each coal ban on total mortality (excluding trauma) and on weekly cardiovascular and respiratory mortality, adjusted for the age and sex distribution of the population, weather, season (climate), influenza epidemics, and secular trends in mortality. We estimated the effect of each ban separately and compared the estimated effects for each of the sequential bans.

1995 Ban in Cork

The directly standardized total mortality rate for Cork for the years before the ban (1981–1995) was 9.70 deaths/1000 p-yr (Table 6). The mortality rate was higher during the heating season and showed a steady decrease over the 15 years before the ban (Figure 15). These season-specific rates in Cork were similar to those in the Coastal (Figure 6) and Midland (Figure 7) counties. The directly standardized all-cause mortality rate after the ban had a mean of 7.07 deaths per 1000 p-yr, that is, a decrease of 27% (Table 6). In Poisson regression, adjusted for the total mortality rate in the reference Coastal counties, influenza-epidemics weeks, and temperature, we found a decrease in the total mortality rate (−4.4%; 95% CI, −9.6% to 1.0%; $P = 0.11$) from before to after the 1995 coal ban (Table 6, Figure 16).

Cardiovascular disease was the most frequently reported cause of death. Cardiovascular mortality rates also showed a strong winter peak (Figure 15 and Figure H.1, Appendix H) and a substantial decrease over the entire study period. In Poisson regression, we found a nonsignificant decrease of 3.7% (95% CI, −12.2% to 5.6%; $P = 0.42$) in the total cardiovascular mortality rate associated with the 1995 coal ban (Table 6, Figure 16). Among cardiovascular deaths, the rate of ischemic heart disease deaths — the most frequently reported type — decreased by 10.7% (95% CI, −21.0% to 1.0%; $P = 0.073$), and the rate of cerebrovascular deaths decreased by 10.2% (95% CI, −25.7% to 8.4%; $P = 0.26$) in the adjusted model (Table 6, Figure 16).

Table 6. Estimated Percentage Changes in Cork Mortality Rates by Cause (1981 to 2004) After the 1995 Coal Ban Compared with Pre-Ban Rates[a]

		Deaths per 1000 p-yr		Adjusted Effect of 1995 Ban		
Cause[b]	ICD-9 Code	Pre-Ban	Post-Ban	Change (%)	95% CI	*P*
Total	< 800	9.70	7.07	−4.4	−9.6 to 1.0	0.11
Cardiovascular Disease	390–459	5.00	3.41	−3.7	−12.2 to 5.6	0.42
Ischemic heart disease	410–414	2.65	1.81	−10.7	−21.0 to 1.0	0.073
Cerebrovascular disease	430–438	1.08	0.65	−10.2	−25.7 to 8.4	0.26
Respiratory Disease	460–519	1.35	1.14	−9.3	−18.2 to 0.7	0.067
Pneumonia	480–487	0.65	0.56	−5.5	−18.7 to 9.9	0.46
COPD	490–496	0.58	0.44	−19.1	−31.3 to −4.7	0.011
Other	< 390, > 519	3.35	3.11	−6.5	−12.6 to −0.0	0.049
Cancer	140–239	2.16	2.05	−5.2	−12.4 to 2.6	0.19
Lung cancer	160–165	0.46	0.36	−16.0	−29.8 to 0.6	0.058
Digestive disease	520–579	0.26	0.26	−8.7	−27.6 to 15.0	0.44

[a] Adjusted for smoothed mortality rates by cause in Coastal counties, influenza weeks, and temperature.

[b] Causes in **boldface** are principal categories; the rest are subcategories.

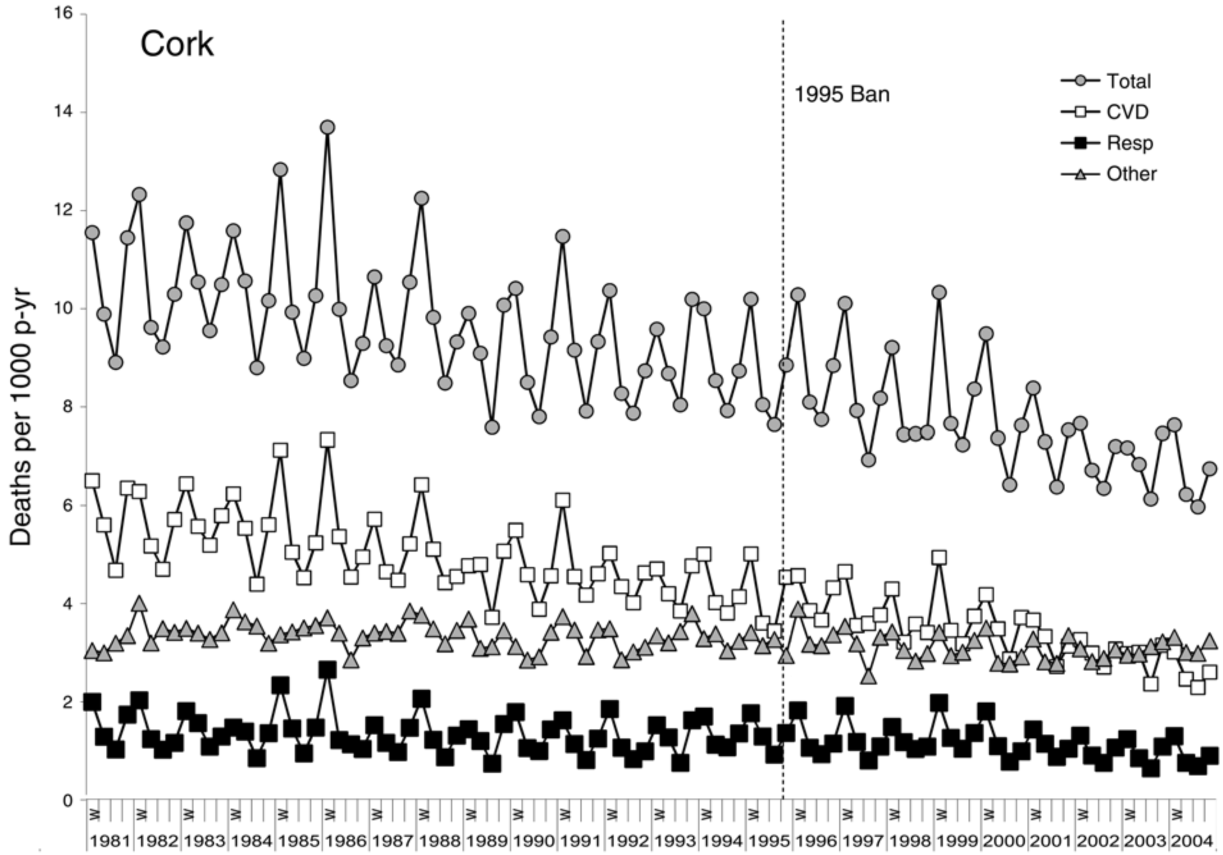


Figure 15. Mean total, cardiovascular (CVD), respiratory (Resp), and other (not cardiovascular or respiratory) mortality rates for county Cork by season, directly standardized to the 1996 Irish population. W indicates winter.

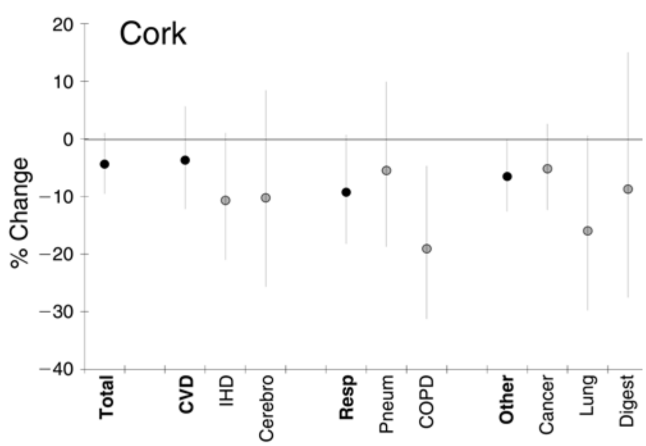


Figure 16. Estimated percentage changes (with 95% CIs) in Cork mortality rates by cause after the 1995 coal ban compared with pre-ban rates, adjusted for smoothed mortality rates by cause in Coastal counties, influenza weeks, and temperature. Causes include total, cardiovascular (CVD), ischemic heart (IHD), cerebrovascular (Cerebro), and respiratory (Resp) disease as well as pneumonia (Pneum), COPD, other, cancer, lung cancer (Lung), and digestive disease (Digest). Boldfaced causes and black data points refer to principal categories; the remaining causes and gray data points refer to subcategories.

Directly standardized mortality rates for respiratory disease were higher during the heating season (i.e., November to April) and decreased over time in parallel with rates in the non-ban counties (Figure 15 and Figure H.2, Appendix H). Respiratory mortality rates decreased by an estimated 9.3% (95% CI, −18.2% to 0.7%; $P = 0.067$) after the ban (Table 6). The largest estimated decrease associated with the 1995 ban was in COPD mortality rates — at 19.1% (95% CI, −31.3% to −4.7%; $P = 0.011$). The decrease in pneumonia mortality rates was small, at 5.5% (95% CI, −18.7% to 9.9%; $P = 0.46$).

The mortality rate for other causes (non-cardiovascular and non-respiratory) (Figure 15, Appendix H Figure H-3) decreased from 3.35 deaths per 1000 p-yr before the ban to 3.11 deaths per 1000 p-yr after the ban (Table 6). After adjustment in Poisson regression the estimated decrease associated with the ban was 6.5% (95% CI, −12.6% to 0.0%; $P = 0.049$; Table 6). Cancer was the second most frequently reported major cause of death (Table 6). Standardized cancer mortality rates dropped from 2.16 deaths per

1000 p-yr before the ban to 2.05 deaths per 1000 p-yr after the ban (Table 6). The adjusted decrease in cancer mortality rates was 5.2% (95% CI, −12.4% to 2.6%; $P = 0.19$). We specifically examined lung cancer deaths, which had a larger estimated decrease of 16.0% (95% CI, −29.8% to 0.6%; $P = 0.058$) after adjustment by Poisson regression. The mortality rate for digestive diseases was low, at 0.26 deaths per 1000 p-yr both before and after the ban (Table 6), with an estimated nonsignificant decrease of 8.7% (95% CI, −27.6% to 15%; $P = 0.44$) associated with the ban after adjustment by Poisson regression.

There was little evidence for differences in the effect of the coal ban in heating versus non-heating seasons (Figure 17 and Table H.1, Appendix H). For example, the estimated decrease in the cardiovascular mortality rate was 2.7% (95% CI, −14.3% to 10.5%; $P = 0.67$) in the heating season compared with a decrease of 4.2% (95% CI, −16.8% to 10.4%; $P = 0.56$) in the non-heating season.

We also examined the potential modifying effects of age and found consistently larger percentage decreases in mortality rates associated with the ban in the younger age range (0–74 years, Figure 18). For example, mortality rates for cardiovascular disease decreased by 10.4% (95% CI, −23.5% to 4.9%; $P = 0.17$) among those 74 and younger compared with a decrease of 1.8% (95% CI, −4.1% to 0.6%; $P = 0.14$) among those 75 years and older (Table H.2, Appendix H).

1995 Ban in Midlands Counties: Control Comparison

As a control comparison, we evaluated the effects of the 1995 ban in Cork on mortality in the Midlands counties, where a ban was not implemented. Table 7 presents the mean mortality rates in the Midlands counties before and after the 1995 ban in Cork. The decreases in mortality rates from pre-ban to post-ban periods were similar to those observed in Cork (Table 6). In Poisson regression, estimating the changes in mortality rates associated with the 1995 ban with adjustments for the smoothed total mortality rate in the Coastal counties, weeks of influenza epidemics, and temperature, we found a 3.6% decrease (95% CI, −8.8% to 2.0%; $P = 0.20$) in the total mortality rate from before to after the ban (Table 7, Figure 19). The 1995 Cork ban was associated with nonsignificant decreases in mortality rates in the Midlands counties from cardiovascular (−3.4%; 95% CI, −12.0% to 6.1%; $P = 0.47$), respiratory (−1.4%; 95% CI, −10.9% to 9.1%; $P = 0.78$), and

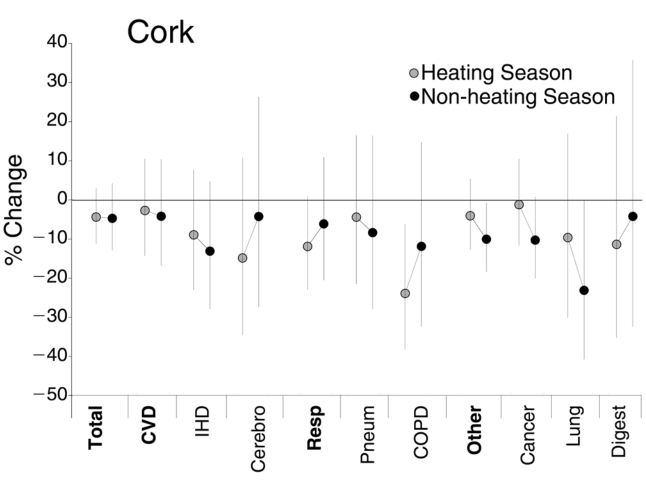


Figure 17. Estimated percentage changes (with 95% CIs) in Cork mortality rates by cause for heating and non-heating seasons after the 1995 coal ban compared with pre-ban rates, adjusted for smoothed mortality rates by cause in Coastal counties, influenza weeks, and temperature. Causes include total, cardiovascular (CVD), ischemic heart (IHD), cerebrovascular (Cerebro), and respiratory (Resp) disease as well as pneumonia (Pneum), COPD, other, cancer, lung cancer (Lung), and digestive disease (Digest). Boldfaced causes refer to principal categories; the remaining causes refer to subcategories.

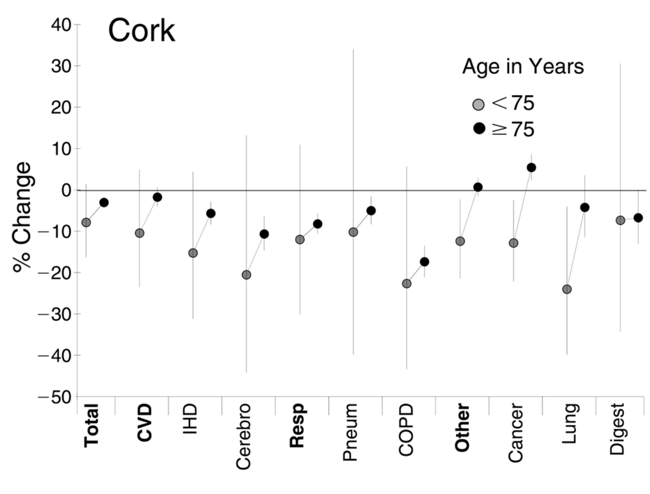


Figure 18. Estimated percentage changes (with 95% CIs) in Cork mortality rates by cause for two age groups (<75 and ≥75 years) after the 1995 coal ban compared with pre-ban rates, adjusted for smoothed mortality rates by cause in Coastal counties, influenza weeks, and temperature. Causes include total, cardiovascular (CVD), ischemic heart (IHD), cerebrovascular (Cerebro), and respiratory (Resp) disease as well as pneumonia (Pneum), COPD, other, cancer, lung cancer (Lung), and digestive disease (Digest). Boldfaced causes refer to principal categories; the remaining causes refer to subcategories.

Table 7. Estimated Percentage Changes in Midlands Counties Mortality Rates by Cause (1981 to 2004) After the 1995 Coal Ban Compared with Pre-Ban Rates[a]

		Deaths per 1000 p-yr		Adjusted Effect of 1995 Ban		
Cause[b]	ICD-9 Code	Pre-Ban	Post-Ban	Change (%)	95% CI	*P*
Total	< 800	9.44	7.41	−3.6	−8.8 to 2.0	0.20
Cardiovascular Disease	390–459	5.05	3.26	−3.4	−12.0 to 6.1	0.47
Ischemic heart disease	410–414	2.67	1.77	−11.2	−21.5 to 0.6	0.06
Cerebrovascular disease	430–438	1.15	0.66	−12.4	−27.3 to 5.5	0.16
Respiratory Disease	460–519	1.34	1.25	−1.4	−10.9 to 9.1	0.78
Pneumonia	480–487	0.61	0.6	6.8	−8.1 to 24.1	0.39
COPD	490–496	0.62	0.48	−19.9	−31.6 to −6.2	0.01
Other	< 390, > 519	3.06	2.9	−3.4	−9.9 to 3.6	0.33
Cancer	140–239	1.99	1.89	−5.2	−12.6 to 3.0	0.21
Lung cancer	160–165	0.4	0.36	−11.3	−26.5 to 7.0	0.21
Digestive disease	520–579	0.25	0.24	−5.6	−25.4 to 19.4	0.63

[a] Adjusted for smoothed mortality rates by cause in Coastal counties, influenza weeks, and temperature.

[b] Causes in **boldface** are principal categories; the rest are subcategories.

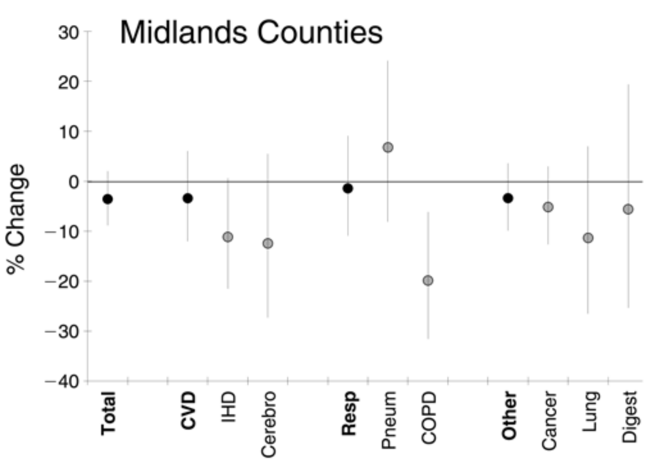


Figure 19. Estimated percentage changes (with 95% CIs) in Midlands counties post-ban mortality rates by cause compared with pre-ban rates, adjusted for smoothed mortality rates by cause in Coastal counties, influenza weeks, and temperature. Causes include total, cardiovascular (CVD), ischemic heart (IHD), cerebrovascular (Cerebro), and respiratory (Resp) disease as well as pneumonia (Pneum), COPD, other, cancer, lung cancer (Lung), and digestive disease (Digest). Boldfaced causes and black data points refer to principal categories; the remaining causes and gray data points refer to subcategories.

other (−3.4%; 95% CI, −9.9% to 3.6%; $P = 0.33$) causes. We observed larger decreases in mortality rates for ischemic heart disease (−11.2%; 95% CI, −21.5% to 0.6%; $P = 0.06$), cerebrovascular disease (−12.4%; 95% CI, −27.3% to 5.5%; $P = 0.16$), COPD (−19.9%; 95% CI, −31.6% to −6.2%; $P = 0.01$), and lung cancer (−11.3%; 95% CI, −26.5% to 7.0%; $P = 0.21$).

Analyses for the estimated effect of the 1995 Cork ban on Midlands counties mortality rates stratified by heating season (Table 8) showed little evidence of seasonal differences in effect. Analyses stratified by age group (Figure 20) showed narrower CIs for the older population (> 75 years) but effectively no difference by age group in the estimated effects of the ban on total mortality in the Midlands counties.

The estimated effects of the 1995 Cork ban on mortality rates in the Midlands were remarkably similar to the estimated effects in Cork (Figure 21). Only the decrease in respiratory mortality associated with the ban was noticeably greater in Cork (−9.3%; 95% CI, −18.2% to 0.7%; $P = 0.067$) compared with that observed in the Midlands counties (−1.4%; 95% CI, −10.9% to 9.1%; $P = 0.78$).

Table 8. Estimated Percentage Changes in Midlands Counties Mortality Rates by Cause (1981 to 2004) for the Heating and Non-Heating Seasons After the 1995 Coal Ban Compared with Pre-Ban Rates[a]

	Heating Season			Non-Heating Season		
Cause[b]	Change (%)	95% CI	*P*	Change (%)	95% CI	*P*
Total	−3.8	−10.8 to 3.8	0.32	−4.2	−12.5 to 5.0	0.36
Cardiovascular Disease	−2.3	−14.0 to 11.0	0.72	−4.1	−16.9 to 10.7	0.57
Ischemic heart disease	−11.1	−25.0 to 5.4	0.18	−11.1	−26.3 to 7.1	0.21
Cerebrovascular disease	−12.5	−32.4 to 13.3	0.31	−12.1	−33.2 to 15.6	0.36
Respiratory Disease	−1.8	−13.9 to 12.0	0.78	−2.3	−16.9 to 15.0	0.78
Pneumonia	9.7	−9.9 to 33.7	0.36	1.7	−19.8 to 29.0	0.89
COPD	−22.5	−36.7 to −5.1	0.01	−17.6	−36.2 to 6.4	0.14
Other	−4.2	−13.2 to 5.6	0.39	−3.0	−12.4 to 7.3	0.55
Cancer	−6.9	−17.2 to 4.7	0.23	−4.2	−15.0 to 8.1	0.49
Lung cancer	−13.0	−33.9 to 14.5	0.32	−10.0	−31.1 to 17.6	0.44
Digestive disease	−6.1	−31.7 to 29.1	0.70	−6.0	−34.1 to 34.0	0.73

[a] Adjusted for smoothed mortality rates by cause in Coastal counties, influenza weeks, and temperature.

[b] Causes in **boldface** are principal categories; the rest are subcategories.

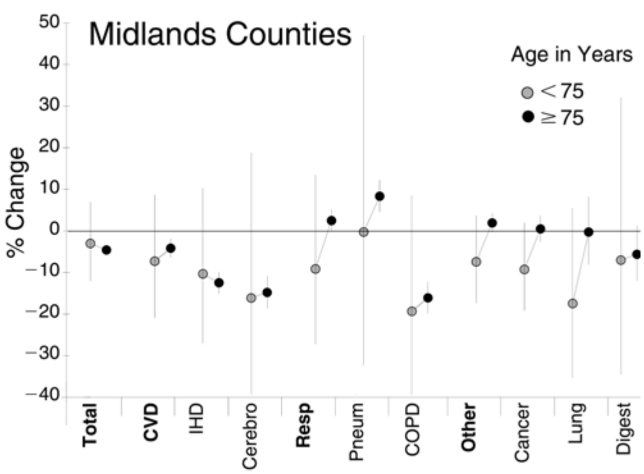


Figure 20. Estimated percentage changes (with 95% CIs) in Midlands counties post-ban mortality rates by cause for two age groups (<75 and ≥75 years) compared with pre-ban rates, adjusted for smoothed mortality rates by cause in Coastal counties, influenza weeks, and temperature. Causes include total, cardiovascular (CVD), ischemic heart (IHD), cerebrovascular (Cerebro), and respiratory (Resp) disease as well as pneumonia (Pneum), COPD, other, cancer, lung cancer (Lung), and digestive disease (Digest). Boldfaced causes refer to principal categories; the remaining causes refer to subcategories.

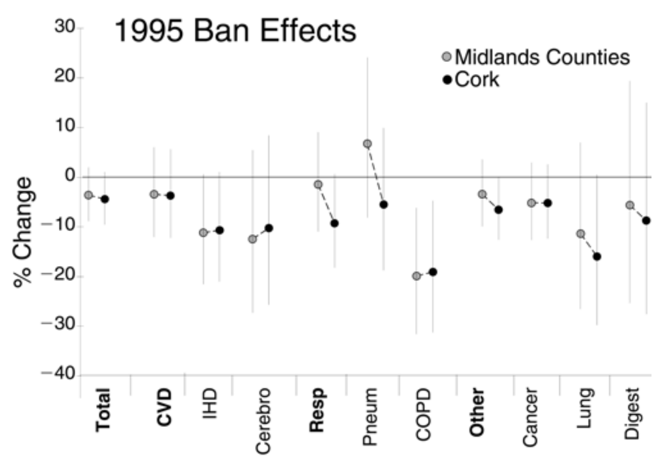


Figure 21. Estimated percentage changes (with 95% CIs) in Cork and Midlands counties mortality rates after the 1995 coal ban compared with pre-ban rates, adjusted for smoothed mortality rates by cause in Coastal counties, influenza weeks, and temperature. Causes include total, cardiovascular (CVD), ischemic heart (IHD), cerebrovascular (Cerebro), and respiratory (Resp) disease as well as pneumonia (Pneum), COPD, other, cancer, lung cancer (Lung), and digestive disease (Digest). Boldfaced causes refer to principal categories; the remaining causes refer to subcategories.

1998 Ban in Limerick, Louth, Wexford, and Wicklow

As in Dublin and Cork, mortality rates in each of the four counties affected by the 1998 ban showed a strong seasonal pattern and a downward trend over the 24 years of our analyses (Figure 22). In county-specific Poisson regression adjusted for smoothed mortality rates in the reference Coastal counties, influenza weeks, and temperature (Figure 23), we found no evidence of significant decreases in total mortality rates associated with the 1998 ban (Table I.1, Appendix I). Combining the county-specific results using inverse-variance weights gave an estimated increase of 0.2% (95% CI, −3.1% to 3.6%; $P = 0.90$) associated with the ban (Table 9).

Mortality rates for cardiovascular disease also showed a strong seasonal pattern and downward trend in each of the four counties (Figure 22). The estimated county-specific changes in cardiovascular mortality rates associated with the 1998 coal ban (Figure 23) were small, ranging from a 3.0% decrease to a 2.0% increase, and were all far from statistically significant (Table I.1, Appendix I). The combined estimated change across all four counties was a decrease of −1.1% (95% CI, −6.1% to 4.1%; $P = 0.67$) associated with the ban (Table 9). Among the cardiovascular mortality rates (Figure I.1, Appendix I), rate decreases were found for ischemic heart disease and cerebrovascular disease in each county (Figure 24 and Table I.1, Appendix I). The combined estimates across all four counties (Table 9) associated with the 1998 ban were statistically significant for deaths both from ischemic heart disease, with a decrease of 9.7% (95% CI, −16.0% to −2.9%; $P = 0.006$), and from cerebrovascular disease, with a decrease of 12.6% (95% CI, −20.9% to −3.5%; $P = 0.008$).

We found less consistency in the analyses of the county-specific mortality rates for respiratory disease. All counties showed a strong seasonal pattern in respiratory mortality rates but less evidence for a temporal trend (Figure 22). We found decreases in respiratory mortality rates (Figure 25 and Table I.1, Appendix I) only for Louth (−8.5%; 95% CI, −18.5% to 2.7%; $P = 0.13$) and Wexford (−12.0%; 95% CI, −22.2 to −0.5%; $P = 0.041$) but effectively no change in Wicklow (0.6%; 95% CI, −10.9% to 13.7%; $P = 0.92$) and an increase in Limerick (9.6%; 95% CI, −2.1% to 22.6%; $P = 0.11$). The combined estimate for deaths from respiratory causes across all four counties was a decrease (−2.6%; 95% CI, −8.1% to 3.4%; $P = 0.39$) associated with the 1998 ban (Table 9).

Pneumonia accounted for one-third to one-half of the respiratory deaths (Figure I.2 and Table I.1, Appendix I). The estimated effects of the 1998 ban on pneumonia death rates were inconsistent across counties, with an increase in Limerick and Wicklow and a decrease in Louth and Wexford (Figure 25 and Table I.1, Appendix I). The combined estimated effect of the ban on mortality rates for pneumonia was therefore an increase of 8.9% (95% CI, −0.2% to 18.8%; $P = 0.055$; Table 9).

In contrast, we found that mortality rates for COPD (Figure I.2, Appendix I) decreased substantially and significantly in all four counties (Figure 25) after the ban. The estimated county-specific decreases ranged from 27.1% to 33.2% (Table I.1, Appendix I), with a combined estimated decrease of 30.2% (95% CI, −36.7% to −23.0%; $P \leq 0.00001$; Table 9).

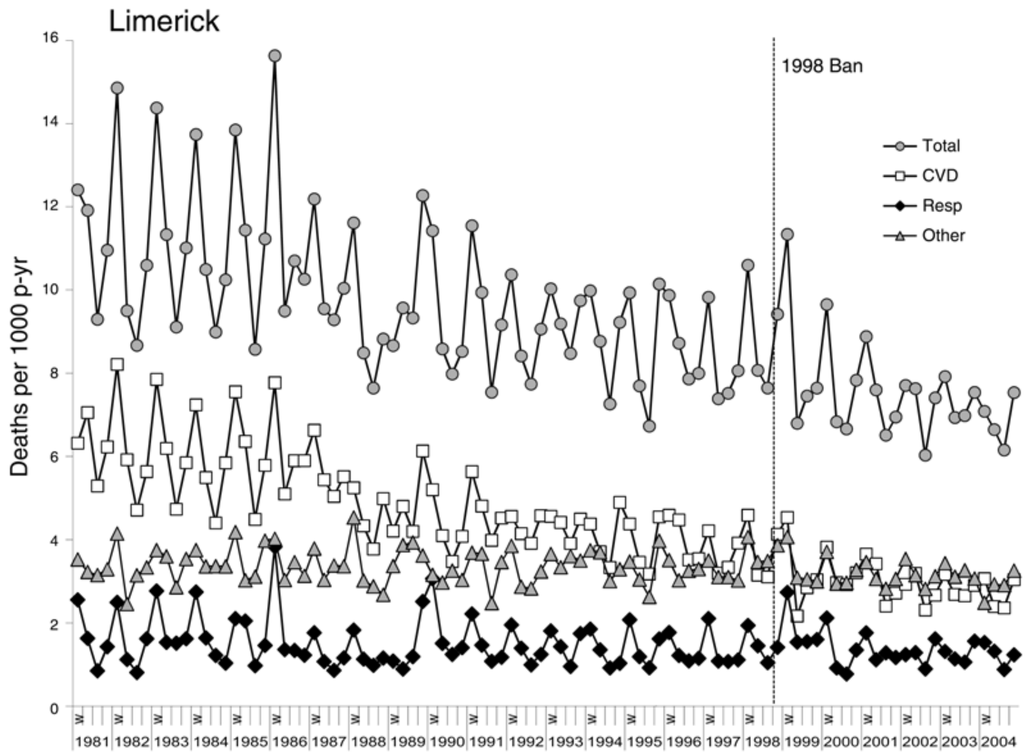
For mortality rates for other — that is, not cardiovascular or respiratory — causes (Figure 22 and Figure I.3, Appendix I), we found less evidence of a seasonal pattern or trend over the period of study. There was weak evidence of a consistent improvement in the county-specific mortality rates for other causes (Figure 23); there was a small 2.8% decrease (95% CI, −6.7% to 1.1%; $P = 0.16$) in the combined estimate (Table 9).

For cancer mortality rates (Figure 26 and Figure I.3, Appendix I) there were consistent decreases in county-specific estimates associated with the 1998 ban, ranging from 5.7% to 10.1% (Table I.1, Appendix I). The combined estimated decrease was 7.2% (95% CI, −11.3% to −2.8%; $P = 0.001$) for mortality rates for all cancers associated with the ban (Table 9). Lung cancer deaths accounted for approximately one-fourth of the cancer deaths before the ban and one-fifth after the ban. We found decreases in estimated lung cancer mortality rates associated with the ban in Louth (−15.8%; 95% CI, −29.7% to 0.9%; $P = 0.062$) and Wicklow (−22.1%; 95% CI, −35.5% to −6.0%; $P = 0.009$) but effectively no decrease in Limerick (−3.0%; 95% CI, −20.1% to 17.7%; $P = 0.76$) and Wexford (−3.5%; 95% CI, −20.3% to 16.8%; $P = 0.71$). The combined estimate for lung cancer mortality rates associated with the 1998 ban was a decrease of 11.8% (95% CI, −19.7% to −3.1%; $P = 0.009$). There was no consistent decrease in mortality rates for digestive disease after the ban in the four counties (Figure 26) or in the combined analyses (Table 9).

In analyses stratified by heating season, we found no evidence of larger decreases in the heating season compared with the non-heating season either in the county-specific analyses (Table I.2, Appendix I) or in the combined analyses (Figure 27 and Table I.2, Appendix I).

1998 Ban in Midlands Counties: Control Comparison

As a control comparison, we evaluated the effect of the 1998 ban on mortality in the Midlands counties (Table 10). In Poisson regression, estimating the associations with the 1998 coal ban adjusted for the smoothed total mortality rate in the Coastal counties, influenza epidemics weeks, and temperature, we found a 0.2% decrease (95% CI, −6.7% to 6.8%; $P = 0.96$) in the total mortality rate from



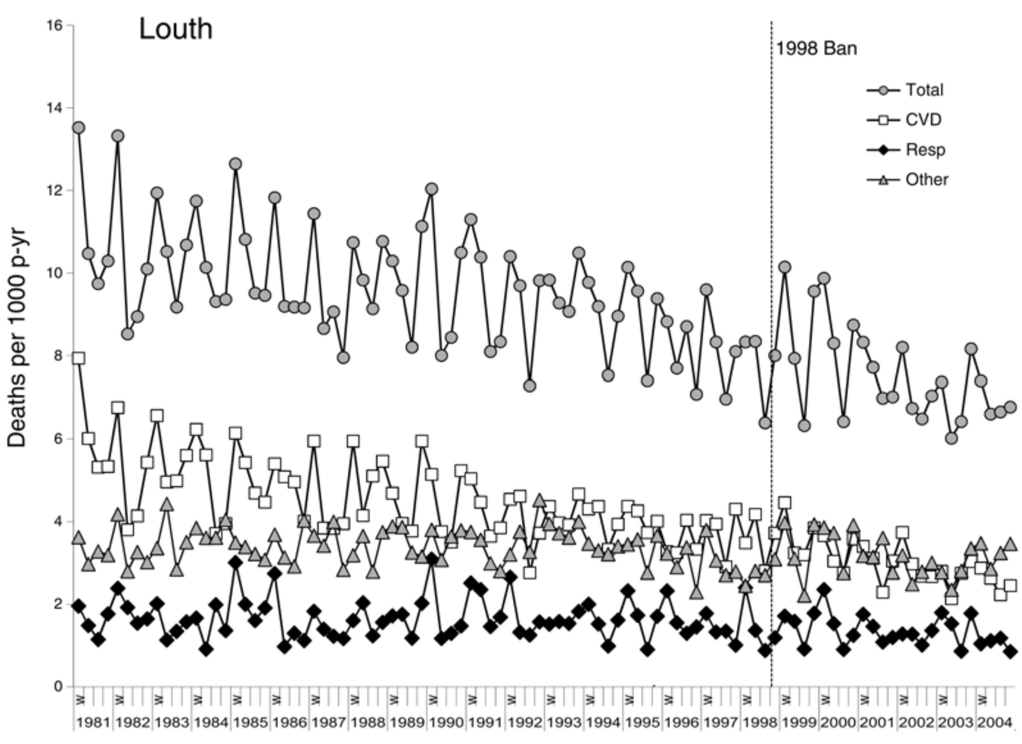


Figure 22. Mortality rates by cause and season, directly standardized for age and sex, for four counties affected by the 1998 coal ban. Causes include total, cardiovascular (CVD), respiratory (Resp), and other (not cardiovascular or respiratory) disease. W indicates winter. (*Figure continues next page.*)

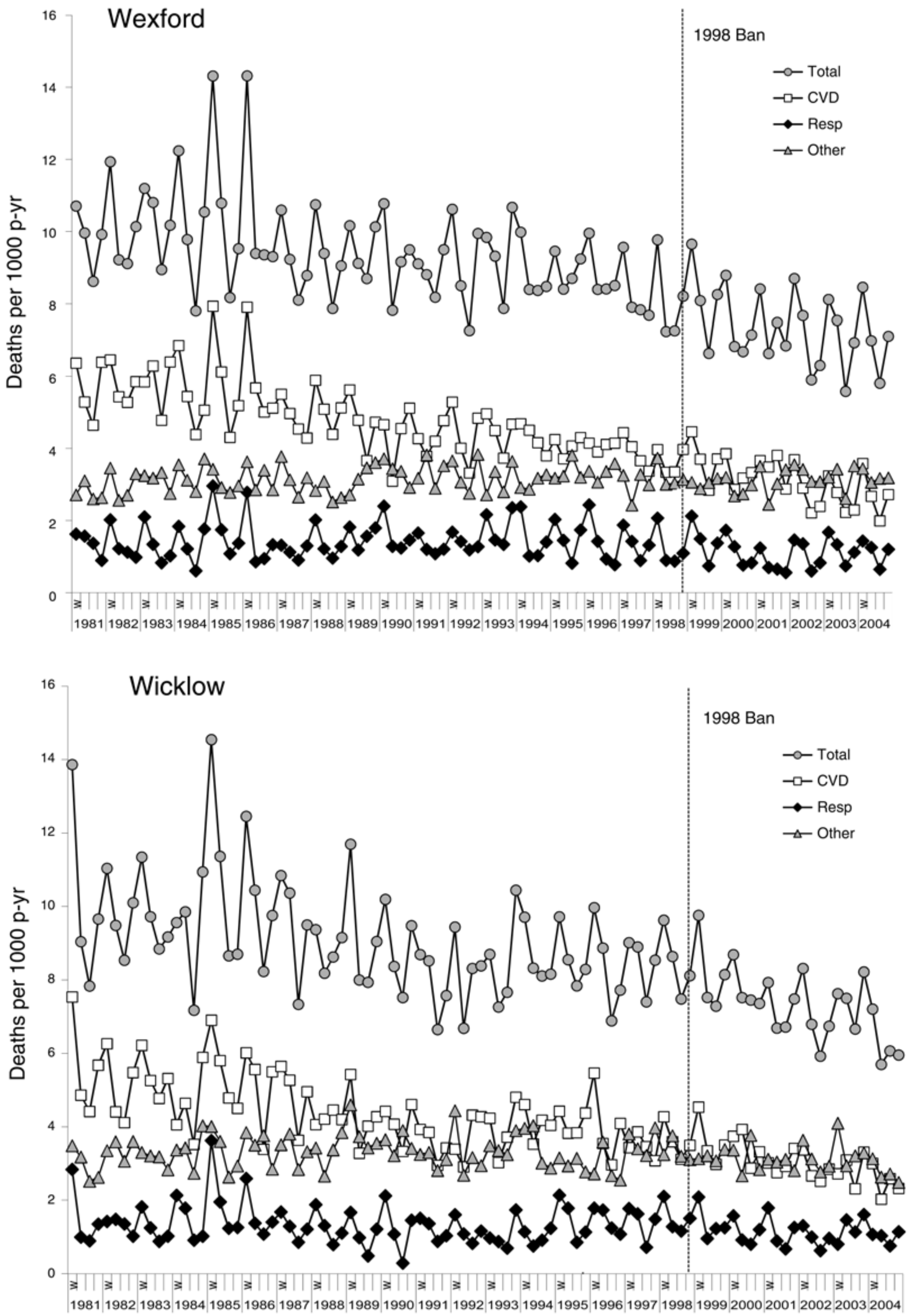


Figure 22 (*Continued*).

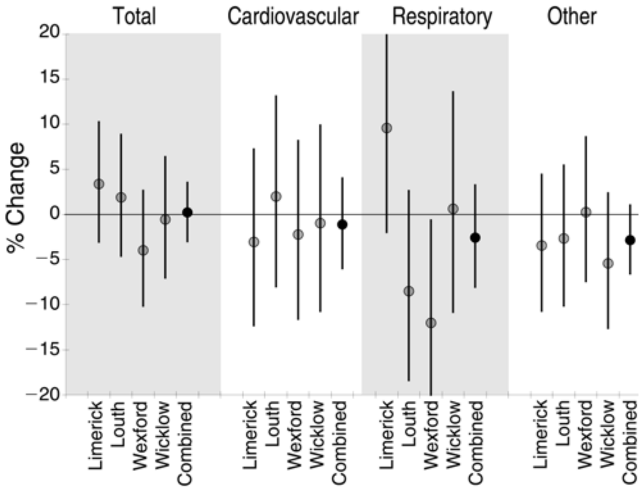


Figure 23. Estimated percentage changes (with 95% CIs) in county and combined mortality rates by cause after the 1998 coal ban compared with pre-ban rates, adjusted for smoothed mortality rates by cause in Coastal counties, influenza weeks, and temperature. Causes include total, cardiovascular, respiratory, and other disease. See Appendix I for tabulated values.

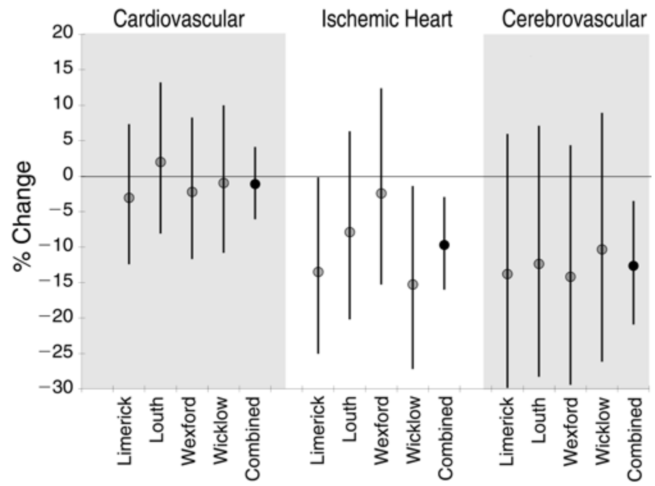


Figure 24. Estimated percentage changes (with 95% CIs) in county and combined mortality rates by cause after the 1998 coal ban compared with pre-ban rates, adjusted for smoothed mortality rates by cause in Coastal counties, influenza weeks, and temperature. Causes include cardiovascular, ischemic heart, and cerebrovascular disease. See Appendix I for tabulated values.

Table 9. Combined Estimated Percentage Changes in Mortality Rates by Cause (1981 to 2004) After the 1998 Coal Ban Compared with Pre-Ban Rates[a]

	Deaths per 1000 p-yr[c]		Adjusted Effect of 1998 Ban		
Cause[b]	Pre-Ban	Post-Ban	Change (%)	95% CI	P
Total	9.47	7.47	0.2	−3.1 to 3.6	0.90
Cardiovascular Disease	4.68	3.07	−1.1	−6.1 to 4.1	0.67
Ischemic heart disease	2.52	1.64	−9.7	−16.0 to −2.9	0.006
Cerebrovascular disease	1.02	0.63	−12.6	−20.9 to −3.5	0.008
Respiratory Disease	1.49	1.26	−2.6	−8.1 to 3.4	0.39
Pneumonia	0.67	0.61	8.9	−0.2 to 18.8	0.055
COPD	0.66	0.43	−30.2	−36.7 to −23.0	< 0.0001
Other	3.31	3.14	−2.8	−6.7 to 1.1	0.16
Cancer	2.16	2.02	−7.2	−11.3 to −2.8	0.001
Lung cancer	0.50	0.44	−11.8	−19.7 to −3.1	0.009
Digestive disease	0.27	0.25	−9.2	−20.0 to 3.1	0.14

[a] Adjusted for smoothed mortality rates by cause in Coastal counties, influenza weeks, and temperature. County estimates were combined using inverse-variance weighting.

[b] Causes in **boldface** are principal categories; the rest are subcategories.

[c] Death rates are means of county-specific death rates.

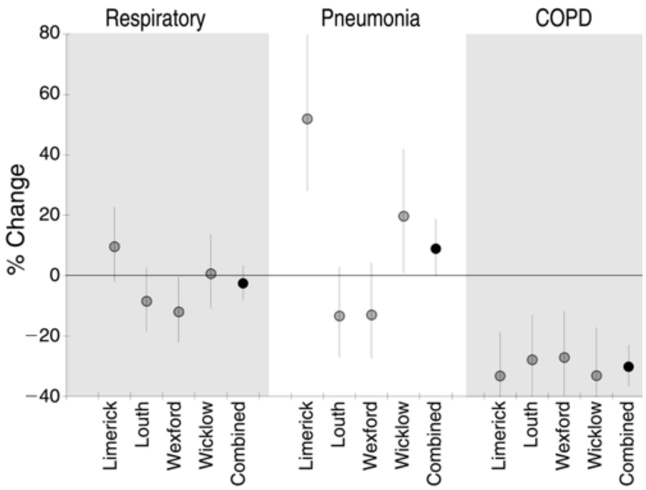


Figure 25. Estimated percentage changes (with 95% CIs) in county and combined mortality rates after the 1998 coal ban compared with pre-ban rates, adjusted for smoothed mortality rates by cause in Coastal counties, influenza weeks, and temperature. Causes include respiratory disease, pneumonia, and COPD. See Appendix I for tabulated values.

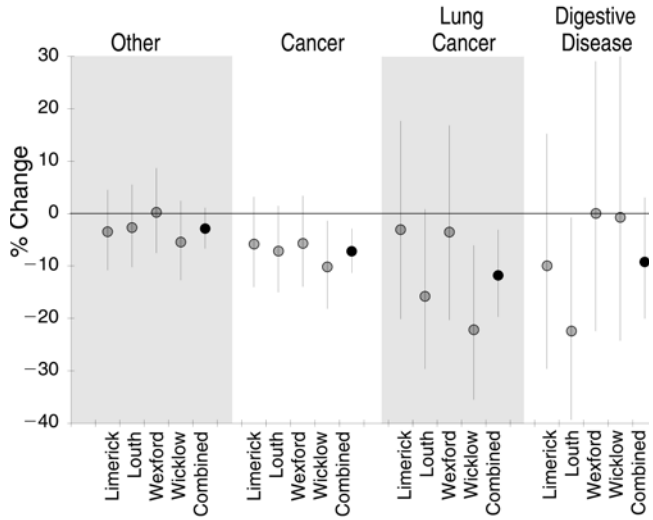


Figure 26. Estimated percentage changes (with 95% CIs) in county and combined mortality rates after the 1998 coal ban compared with pre-ban rates, adjusted for smoothed mortality rates by cause in Coastal counties, influenza weeks, and temperature. Causes include other (not cardiovascular or respiratory) disease, cancer, lung cancer, and digestive disease. See Appendix I for tabulated values.

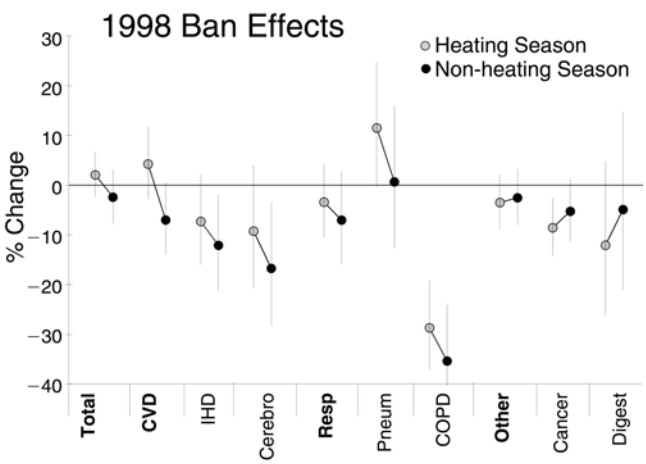


Figure 27. Estimated percentage changes (with 95% CIs) in combined mortality rates by cause for heating and non-heating seasons after the 1998 coal ban compared with pre-ban rates, adjusted for smoothed mortality rates by cause in Coastal counties, influenza weeks, and temperature. Causes include total, cardiovascular (CVD), ischemic heart (IHD), cerebrovascular (Cerebro), and respiratory (Resp) disease as well as pneumonia, COPD, other, cancer, and digestive disease. Boldfaced causes refer to principal categories; the remaining causes refer to subcategories.

Table 10. Estimated Percentage Changes in Midlands Counties Mortality Rates by Cause (1981–2004) After the 1998 Coal Ban Compared with Pre-Ban Rates[a]

	Deaths per 1000 p-yr		Adjusted Effect of 1998 Ban		
Cause[b]	Pre-Ban	Post-Ban	Change (%)	95% CI	*P*
Total	9.22	7.07	−0.2	−6.7 to 6.8	0.96
Cardiovascular Disease	4.84	3.00	−3.1	−12.6 to 7.3	0.54
Ischemic heart disease	2.58	1.60	−14.0	−25.5 to −0.6	0.041
Cerebrovascular disease	1.08	0.62	−6.8	−23.6 to 13.6	0.48
Respiratory Disease	1.34	1.19	1.4	−10.2 to 14.5	0.82
Pneumonia	0.61	0.59	13.4	−5.0 to 35.4	0.16
COPD	0.62	0.42	−23.4	−37.1 to −6.8	0.0078
Other	3.04	2.88	−2.8	−10.6 to 5.6	0.50
Cancer	1.98	1.89	−4.0	−12.7 to 5.4	0.39
Lung cancer	0.39	0.36	−8.9	−26.1 to 12.3	0.38
Digestive disease	0.25	0.22	−10.3	−31.1 to 16.8	0.42

[a] Adjusted for smoothed mortality rates by cause in Coastal counties, influenza weeks, and temperature.

[b] Causes in **boldface** are principal categories; the rest are subcategories.

before to after the 1998 coal ban. The 1998 ban was associated with nonsignificant changes in mortality rates in the Midlands counties from cardiovascular (−3.1%; 95% CI, −12.6% to 7.3%; P = 0.54), respiratory (1.4%; 95% CI,−10.2% to 14.5%, P = 0.82), and other (−2.8%; 95% CI, −10.6% to 5.6%; P = 0.50) causes. We found statistically significant decreases in mortality rates for ischemic heart disease (−14.0%; 95% CI, −25.5% to −0.6%; P = 0.041) and for COPD (−23.4%; 95% CI, −37.1% to −6.8%; P = 0.0078). The estimated effects of the 1998 ban on mortality rates in the Midlands were remarkably similar to the estimated effects in the combined analysis of counties Limerick, Louth, Wexford, and Wicklow (Figure 28).

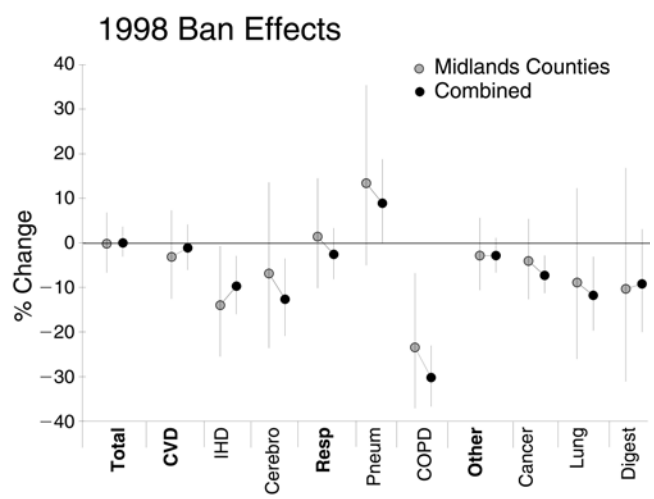


Figure 28. Estimated percentage changes (with 95% CIs) in Midlands counties and combined mortality rates by cause after the 1998 coal ban compared with pre-ban rates, adjusted for smoothed mortality rates by cause in Coastal counties, influenza weeks, and temperature. Causes include total, cardiovascular (CVD), ischemic heart (IHD), cerebrovascular (Cerebro), and respiratory (Resp) disease as well as pneumonia (Pneum), COPD, other, cancer, lung cancer (Lung), and digestive (Digest) disease. Boldfaced causes refer to principal categories; the remaining causes refer to subcategories.

1990 Ban in Dublin

Previously published analyses (Clancy et al. 2002) of mortality data from Dublin (i.e., Dublin County Borough) were limited to the period from 1984 to 1996, the 5 years before and after the September 1990 coal ban. For the current study, we applied the same analytic methods to a longer time series of Dublin County Borough data, namely for the 24-year period from 1981 to 2004.

Age- and sex-standardized total mortality rates in Dublin (Figure 29) showed a steady decrease over the entire 24-year period, similar to that observed in the total mortality rates for counties Cork, Louth, Limerick, Wicklow, and Wexford. The mean directly standardized mortality rate dropped from 9.87 deaths per 1000 p-yr before the Dublin coal ban to 8.20 deaths per 1000 p-yr after the ban (Table 11). In Poisson regression, adjusting for the weekly standardized mortality rates in the reference Coastal counties, influenza epidemic weeks, and temperature, we found a 1.0% decrease (95% CI, −6.0% to 4.4%; P = 0.72)

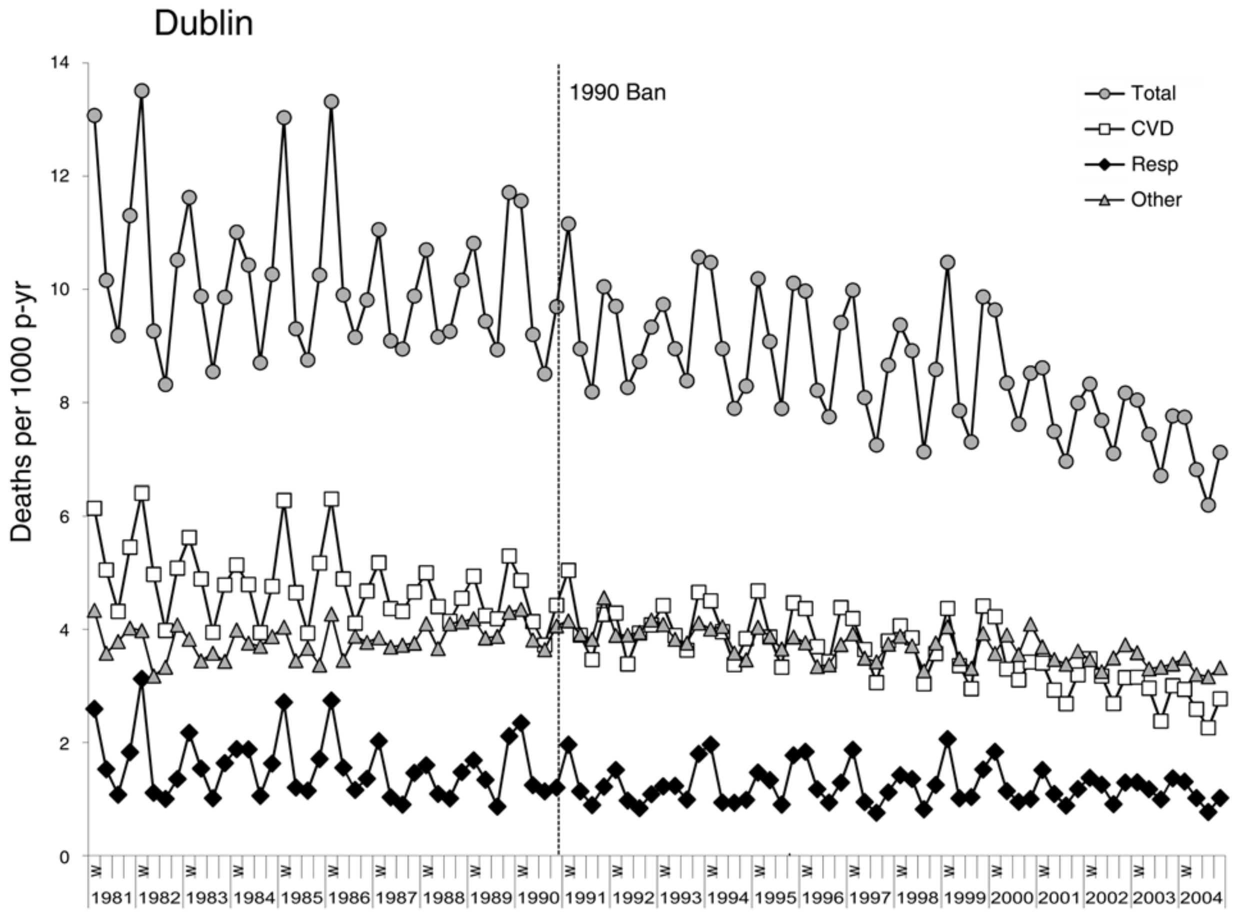


Figure 29. Dublin County Borough mortality rates by cause and season, directly standardized for age and sex. Causes include total, cardiovascular (CVD), respiratory (Resp), and other (not cardiovascular or respiratory) disease. W indicates winter.

in weekly directly standardized mortality rates in Dublin associated with the 1990 ban (Table 11, Figure 30).

As with total mortality rates, cardiovascular mortality rates showed a strong seasonal pattern and a substantial decrease over the entire 24-year period (Figure 29 and Figure J.1, Appendix J). In regression analyses, we found effectively no decrease in mortality rates for cardiovascular disease after the ban (0.1%; 95% CI, −8.5% to 9.5%; $P = 0.98$; Table 11 and Figure 30). In subcategory analyses (Table 11 and Figure 30), we found a negligible decrease of 0.2% (95% CI, −11.7% to 12.8%; $P = 0.97$) in mortality rates for ischemic heart disease and a nonsignificant 8.1% decrease (95% CI, −24.8% to 12.4%; $P = 0.41$) in cerebrovascular mortality rates. Mortality rates for respiratory disease (Figure 29 and Figure J.2, Appendix J) decreased by 16.8% (95% CI, −24.4% to −8.4%; $P = 0.0002$) in association with the coal ban (Table 11 and Figure 30). We found significant decreases associated with standardized mortality rates for pneumonia (−21.1%; 95% CI, −31.6% to −8.9%; $P = 0.0012$) and COPD (−22.1%; 95% CI, −32.8% to −9.7%; $P = 0.0009$) (Table 11 and Figure 30). Other causes of death (Figure 29 and Figure J.3, Appendix J), that is, not cardiovascular or respiratory, decreased nonsignificantly (−1.3%; 95% CI, −7.1% to 4.8%; $P = 0.66$) after the ban (Table 11 and Figure 30). Among these other causes, a 6.7% decrease (95% CI, −13.1% to 0.2%; $P = 0.057$) was found in mortality rates for cancer and a nonsignificant 3.7% increase (95% CI, −15.6% to 27.5%; $P = 0.73$) in mortality rates for digestive disease (Table 11 and Figure 30). Lung cancer mortality rates decreased by 14% (95% CI; −24.8% to −1.7%; $P = 0.027$) after the ban.

Examination of the estimated effects of the 1990 coal ban on mortality rates (Figure 31 and Table J.1, Appendix J) showed no evidence of larger effects in total, cardiovascular, or other mortality rates in the heating season compared with the non-heating season. However, we did find a larger decrease in respiratory mortality rates after the ban in the heating season compared with the non-heating season

Table 11. Estimated Percentage Changes in Dublin County Borough Mortality Rates by Cause (1981–2004) After the 1990 Coal Ban Compared with Pre-Ban Rates[a]

		Deaths per 1000 p-yr		Adjusted Effect of 1990 Ban		
Cause[b]	ICD-9 Code	Pre-Ban	Post-Ban	Change (%)	95% CI	*P*
Total	< 800	9.87	8.20	−1.0	−6.0 to 4.4	0.72
Cardiovascular Disease	390–459	4.55	3.39	0.1	−8.5 to 9.5	0.98
Ischemic heart disease	410–414	2.56	1.77	−0.2	−11.7 to 12.8	0.97
Cerebrovascular disease	430–438	0.92	0.70	−8.1	−24.8 to 12.4	0.41
Respiratory Disease	460–519	1.46	1.23	−16.8	−24.4 to −8.4	0.0002
Pneumonia	480–487	0.70	0.59	−21.1	−31.6 to −8.9	0.0012
COPD	490–496	0.64	0.45	−22.1	−32.8 to −9.7	0.0009
Other	< 390, > 519	3.86	3.57	−1.3	−7.1 to 4.8	0.66
Cancer	140–239	2.60	2.32	−6.7	−13.1 to 0.2	0.057
Lung cancer				−14.0	−24.8 to −1.7	0.027
Digestive disease	520–579	0.29	0.32	3.7	−15.6 to 27.5	0.73

[a] Adjusted for smoothed mortality rates by cause in Coastal counties, influenza weeks, and temperature.

[b] Causes in **boldface** are principal categories; the rest are subcategories.

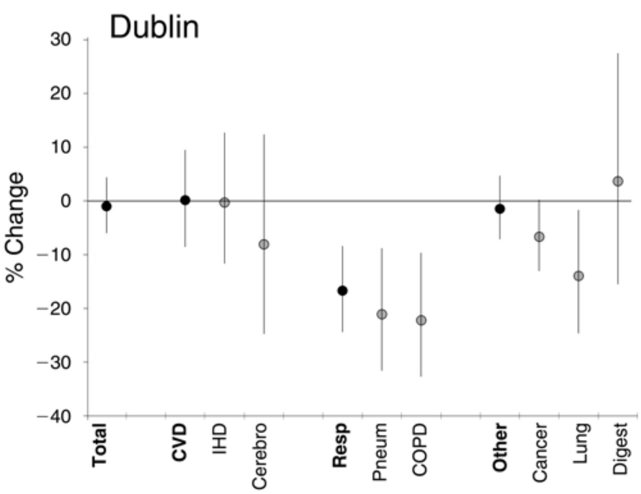


Figure 30. Estimated percentage changes (with 95% CIs) in Dublin City mortality rates by cause after the 1990 coal ban compared with pre-ban rates, adjusted for smoothed mortality rates by cause in Coastal counties, influenza weeks, and temperature (1981–2004). Causes include total, cardiovascular (CVD), ischemic heart (IHD), cerebrovascular (Cerebro), and respiratory (Resp) disease as well as pneumonia (Pneum), COPD, other, cancer, lung cancer (Lung), and digestive (Digest) disease. Boldfaced causes and black data points refer to principal categories; the remaining causes and gray data points refer to subcategories.

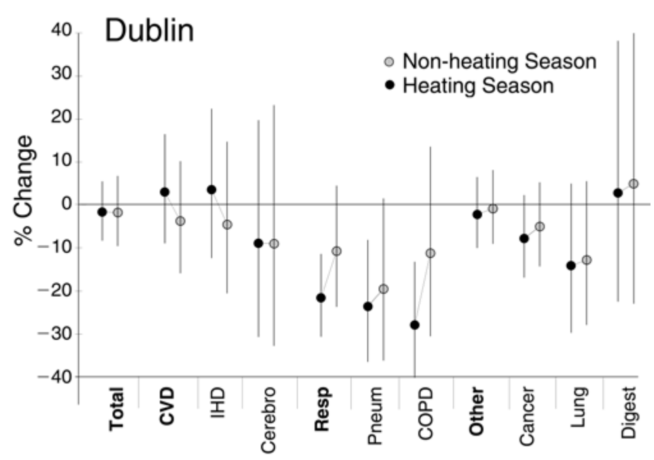


Figure 31. Estimated percentage changes (with 95% CIs) in Dublin City mortality rates by cause for heating and non-heating seasons after the 1990 coal ban compared with pre-ban rates (1981 to 2004). Causes include total, cardiovascular (CVD), ischemic heart (IHD), cerebrovascular (Cerebro), and respiratory (Resp) disease as well as pneumonia (Pneum), COPD, other, cancer, lung cancer (Lung), and digestive (Digest) disease. Boldfaced causes refer to principal categories; the remaining causes refer to subcategories.

(Figure 31 and Table J.1, Appendix J). Examination of the effects of the ban by age group (74 years or less compared with 75 years and older) showed a smaller decrease in total and cardiovascular deaths for the older population (Figure 32 and Table J.2, Appendix J). Note that the CIs were much wider for the younger population.

1990 Ban in Midland Counties: Control Comparison

In Poisson regression, we estimated the effects of the 1990 Dublin coal ban on mortality rates in the Midlands counties, adjusted for the smoothed total mortality rate in the Coastal counties, influenza epidemics weeks, and temperature. We found a 2.7% decrease (95% CI, −7.7% to 2.7%; $P = 0.32$) in the total mortality rate from before to after the ban in Dublin (Table 12). The 1990 ban was associated with nonsignificant decreases in mortality rates in the Midlands counties for cardiovascular (−1.8%; 95% CI, −10.0% to 7.2%; $P = 0.68$), respiratory (−2.3%; 95% CI, −11.5% to 7.9%; $P = 0.65$), and other (−1.7%; 95% CI, −8.1% to 5.1%; $P = 0.62$) causes. We found a statistically significant decrease in the mortality rate for COPD (−17.1%; 95% CI, −28.5% to −3.9%; $P = 0.013$). The estimated effects of the 1990 ban on mortality rates in the Midlands were similar to the estimated effects in Dublin County Borough (Figure 33), except for the effects on mortality rates for respiratory disease, which decreased by 16.8% (95% CI, −24.4% to −8.4%; $P = 0.002$; Table 11) in Dublin compared with a 2.3% decrease in the Midlands. This difference in respiratory mortality rates was primarily associated with mortality from pneumonia.

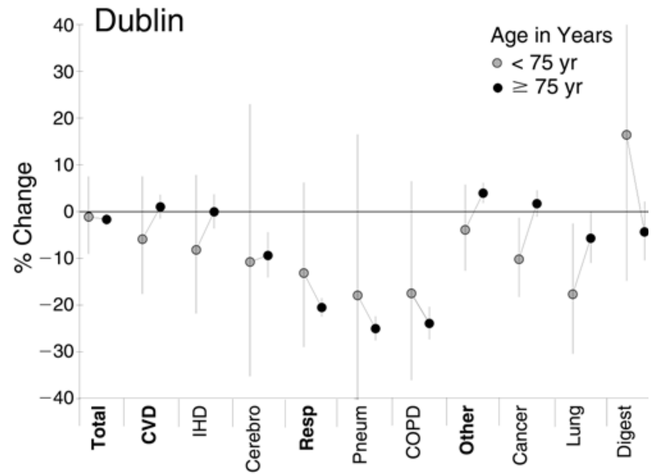


Figure 32. Estimated percentage changes (with 95% CIs) in Dublin City mortality rates for two age groups (<75 and ≥75 years) after the 1990 coal ban compared with pre-ban rates (1981 to 2004). Causes include total, cardiovascular (CVD), ischemic heart (IHD), cerebrovascular (Cerebro), and respiratory (Resp) disease as well as pneumonia (Pneum), COPD, other, cancer, lung cancer (Lung), and digestive (Digest) disease. Boldfaced causes refer to principal categories; the remaining causes refer to subcategories.

Comparison of Estimated Effects of 1990 Dublin Ban

The effects of the 1990 Dublin ban estimated in our current analyses were substantially different from those reported previously by Clancy and colleagues (2002). For example, in our analysis, the total non-trauma mortality rate was estimated to have decreased nonsignificantly by

Table 12. Estimated Percentage Changes in Midlands Counties Mortality Rates by Cause (1981–2004) After the 1990 Coal Ban Compared with Pre-Ban Rates[a]

	Deaths per 1000 p-yr		Adjusted Effect of 1990 Ban		
Cause[b]	Pre-Ban	Post-Ban	Change (%)	95% CI	P
Total	9.88	7.84	−2.7	−7.7 to 2.7	0.32
Cardiovascular Disease	5.45	3.62	−1.8	−10.0 to 7.2	0.68
Ischemic heart disease	2.79	2.00	5.7	−6.3 to 19.2	0.37
Cerebrovascular disease	1.29	0.74	−13.1	−27.9 to 4.8	0.14
Respiratory Disease	1.37	1.26	−2.3	−11.5 to 7.9	0.65
Pneumonia	0.63	0.59	4.2	−10.4 to 21.2	0.59
COPD	0.64	0.52	−17.1	−28.5 to −3.9	0.013
Other	3.06	2.96	−1.7	−8.1 to 5.1	0.62
Cancer	1.97	1.94	−1.5	−9.1 to 6.8	0.71
Lung cancer	0.40	0.37	−6.4	−22.1 to 12.4	0.48
Digestive disease	0.25	0.24	−4.5	−24.0 to 19.9	0.69

[a] Adjusted for smoothed mortality rates by cause in Coastal counties, influenza weeks, and temperature.

[b] Causes in **boldface** are principal categories; the rest are subcategories.

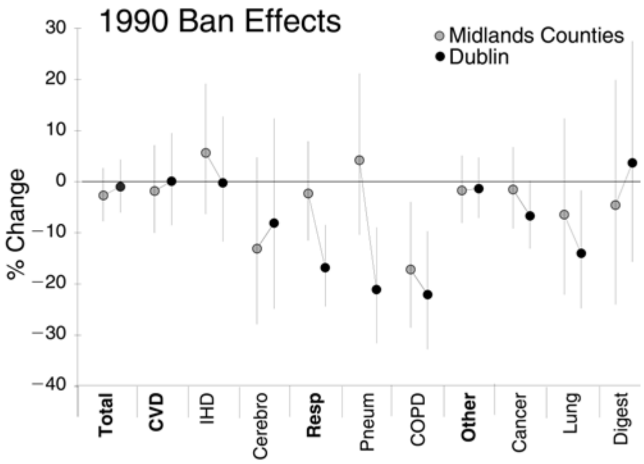


Figure 33. Estimated percentage changes (with 95% CIs) in Midlands counties and Dublin County Borough mortality rates by cause after the 1990 ban compared with pre-ban rates, adjusted for smoothed mortality rates by cause in Coastal counties, influenza weeks, and temperature. Causes include total, cardiovascular (CVD), ischemic heart (IHD), cerebrovascular (Cerebro), and respiratory (Resp) disease as well as pneumonia (Pneum), COPD, other, cancer, lung cancer (Lung), and digestive (Digest) disease. Boldfaced causes refer to principal categories; the remaining causes refer to subcategories.

1.0% (95% CI, −6.0% to 4.4%; $P = 0.72$). In contrast, Clancy and colleagues (2002) reported that the Dublin non-trauma mortality rate was estimated to have decreased significantly by 5.7% (95% CI, −7.2% to −4.1%; $P < 0.0001$). The differences between the two analyses were greatest for cardiovascular mortality rates: Clancy and colleagues (2002) reported an estimated decrease of 10.3% (95% CI, −12.6% to −8.0%; $P < 0.0001$), and in the current analysis we estimated that there was no change, that is, an increase of 0.1% (95% CI, −8.5% to 9.5%; $P = 0.98$). On the other hand, the estimated effects on mortality rates for respiratory disease were similar in the earlier analysis (−15.5%; 95% CI, −19.1% to −11.6%; $P < 0.001$) and the current analyses (−16.8%; 95% CI, −24.4% to −8.4%; $P = 0.0002$).

The basic approach was similar in both analyses. The logarithms of directly standardized mortality rates in Dublin were regressed assuming a Poisson distribution on an indicator of the post-ban period, adjusting for weather, day of week, and the log of directly standardized mortality rates in a reference population in Ireland. However, there were differences in data and methods used in the previous and current analyses. They include the period studied (6 years before and after the 1990 ban versus the 24-year period from 1981 to 2004), the intervals used for calculating mortality rates (daily versus weekly), the reference-population mortality rate used (all of Ireland except Dublin versus the Coastal counties), the adjustment made for secular trends (time-matched reference mortality rates versus time-matched Loess smoothed [25 week] reference mortality rates), and the method used for fitting robust M-Estimator (hereafter "Robust") regression versus linear GenMod regression.

Table 13 helps to illustrate the impact of these analytic choices on the estimated effects of the Dublin ban on total, cardiovascular, respiratory, and other mortality rates. In the table, each row represents one of the models. For each cause of death, the first row (models T0, C0, R0, and O0) reproduces the results of Clancy and colleagues (2002), and the last line (models $T3_S$, $C3_S$, $R3_S$, and $O3_S$) presents the results from the current analysis.

The first two rows compare analyses adjusted for daily mortality rates (models T0, C0, R0, and O0) with a Loess smooth of daily mortality rates (models $T0_S$, $C0_S$, $R0_S$, and $O0_S$), using Robust regression on the original 12-year (1984–1996) data set. For total non-trauma mortality rates, the estimated effect of the ban changed from a decrease of 5.7% (95% CI, −7.2% to −4.1%; $P < 0.0001$) in the original analysis (model T0) to a decrease of only 1.3% (95% CI, −4.4% to 1.8%; $P = 0.41$) in the Loess smooth model (model $T0_S$). The most dramatic difference between the two models was observed for cardiovascular mortality, which changed from a decrease of 10.3% (95% CI, −12.6% to −8.0%; $P < 0.0001$; model C0) to a decrease of 0.2% (95% CI, −4.8% to 4.6%; $P = 0.93$; model $C0_S$). On the other hand, there was little change for respiratory mortality, from a decrease of 15.5% (95% CI, −19.1% to −11.6%; $P < 0.0001$; model R0) to a decrease of 15.2% (95% CI, −22.1% to −7.7%; $P = 0.00015$; model $R0_S$), or for other mortality, from an increase of 1.7% (95% CI, −0.7% to 4.2%; $P = 0.17$; model O0) to 3.6% (95% CI, −1.2% to 8.7%; $P = 0.14$; model $O0_S$).

In comparing the "1" models with the "0" models, we found that the estimated effect of the ban was not sensitive to the use of the Robust or GenMod regression. For example, for total mortality, the estimated effect of the ban using the GenMod approach (model T1) was a decrease of 4.9% (95% CI, −6.9% to −2.9%; $P < 0.0001$) compared with a decrease of 5.7% (95% CI, −7.2% to −4.1%; $P < 0.0001$) using the Robust approach (model T0). Likewise, the GenMod estimates adjusted for the Loess smooth of mortality in the rest of Ireland (an increase of 1.3%; 95% CI, −1.1% to 3.9%; $P = 0.29$; model $T1_S$) were similar to those for the Robust estimates (a decrease of 1.3%; 95% CI, −4.4% to 1.8%; $P = 0.41$; model $T0_S$). For cardiovascular, respiratory, and other mortality, we found the GenMod estimates similarly were equivalent to the Robust estimates.

We next examined the approach used in the current analyses, that is, using weekly rather than daily mortality rates and adjusting for the Coastal mortality rate rather than the mortality rate for all of Ireland other than Dublin,

Table 13. Comparison of Alternative Data and Methods for Estimating the Effects of the 1990 Coal Ban on Dublin Mortality Rates by Cause[a]

Model	Algorithm	Period	Frequency	Observations (*N*)	Adjustment	Effect (%)	95% CI	*P*
Total								
T0	Robust	1984–1996	Daily	4383	Ireland	−5.7	−7.2 to −4.1	< 0.0001
$T0_S$	Robust	1984–1996	Daily	4383	Loess (Ireland)	−1.3	−4.4 to 1.8	0.41
T1	GenMod	1984–1996	Daily	4383	Ireland	−4.9	−6.9 to −2.9	< 0.0001
	GenMod	1984–1996	Daily	4383	Offset (Ireland)	1.4	−0.6 to 3.4	0.18
$T1_S$	GenMod	1984–1996	Daily	4383	Loess (Ireland)	1.3	−1.1 to 3.9	0.29
T2	GenMod	1984–1996	Weekly	627	Coastal	−5.4	−10.4 to −0.2	0.041
$T2_S$	GenMod	1984–1996	Weekly	627	Loess (Coastal)	−2.3	−7.9 to 3.7	0.44
T3	GenMod	1981–2004	Weekly	1253	Coastal	−7.2	−11.2 to −3.0	0.0008
$T3_S$	GenMod	1981–2004	Weekly	1253	Loess (Coastal)	−1.0	−6.0 to 4.4	0.72
Cardiovascular								
C0	Robust	1984–1996	Daily	4383	Ireland	−10.3	−12.6 to −8.0	< 0.0001
$C0_S$	Robust	1984–1996	Daily	4383	Loess (Ireland)	−0.2	−4.8 to 4.6	0.93
C1	GenMod	1984–1996	Daily	4383	Ireland	−10.0	−12.9 to −7.1	< 0.0001
	GenMod	1984–1996	Daily	4383	Offset (Ireland)	2.7	−0.3 to 5.8	0.081
$C1_S$	GenMod	1984–1996	Daily	4383	Loess (Ireland)	−0.5	−4.6 to 3.8	0.83
C2	GenMod	1984–1996	Weekly	627	Coastal	−9.9	−17.2 to −2.0	0.015
$C2_S$	GenMod	1984–1996	Weekly	627	Loess (Coastal)	−3.1	−12.6 to 7.5	0.55
C3	GenMod	1981–2004	Weekly	1253	Coastal	−12.9	−19.0 to −6.2	0.0002
$C3_S$	GenMod	1981–2004	Weekly	1253	Loess (Coastal)	0.1	−8.5 to 9.5	0.98
Respiratory								
R0	Robust	1984–1996	Daily	4383	Ireland	−15.5	−19.1 to −11.6	< 0.0001
$R0_S$	Robust	1984–1996	Daily	4383	Loess (Ireland)	−15.2	−22.1 to −7.7	0.00015
R1	GenMod	1984–1996	Daily	4383	Ireland	−16.0	−20.4 to −11.3	< 0.0001
	GenMod	1984–1996	Daily	4383	Offset (Ireland)	−14.1	−18.6 to −9.3	< 0.0001
$R1_S$	GenMod	1984–1996	Daily	4383	Loess (Ireland)	−11.8	−16.5 to −6.8	< 0.0001
R2	GenMod	1984–1996	Weekly	627	Coastal	−14.4	−25.1 to −2.2	0.022
$R2_S$	GenMod	1984–1996	Weekly	627	Loess (Coastal)	−14.9	−25.6 to −2.8	0.018
R3	GenMod	1981–2004	Weekly	1253	Coastal	−18.4	−25.8 to −10.2	< 0.0001
$R3_S$	GenMod	1981–2004	Weekly	1253	Loess (Coastal)	−16.8	−24.4 to −8.4	0.00017
Other								
O0	Robust	1984–1996	Daily	4383	Ireland	1.7	−0.7 to 4.2	0.17
$O0_S$	Robust	1984–1996	Daily	4383	Loess (Ireland)	3.6	−1.2 to 8.7	0.14
O1	GenMod	1984–1996	Daily	4383	Ireland	1.8	−1.3 to 5.0	0.27
$O1_S$	GenMod	1984–1996	Daily	4383	Loess (Ireland)	2.5	−0.8 to 5.9	0.14
O2	GenMod	1984–1996	Weekly	627	Coastal	0.9	−6.8 to 9.3	0.82
$O2_S$	GenMod	1984–1996	Weekly	627	Loess (Coastal)	1.0	−6.8 to 9.5	0.80
O3	GenMod	1981–2004	Weekly	1253	Coastal	−2.3	−7.9 to 3.6	0.43
$O3_S$	GenMod	1981–2004	Weekly	1253	Loess (Coastal)	−1.3	−7.1 to 4.8	0.66

[a] Results were compared using the 12 years centered on the ban (1984–1996) versus the entire period of record (1981–2004), using daily versus weekly directly standardized mortality rates, using directly standardized mortality rates for all of Ireland except Dublin versus the Coastal counties, adjusting for time-matched mortality rates versus Loess-smoothed mortality rates, and using the method for fitting Robust regression versus linear GenMod regression.

for the same 12-year period ("2" models compared with "0" models). We found that the estimated effect of the ban on the Dublin weekly mortality rate adjusted for Coastal rates ("2" models) was equivalent to that for the Dublin daily mortality adjusted for rates in the rest of Ireland ("0" models). For example, for total mortality, the estimated effect of the ban was a decrease of 5.7% (95% CI, −7.2% to 4.1%; $P < 0.0001$; model T0) with the original daily data versus a decrease of 5.4% (95% CI, −10.4% to −0.2%; $P = 0.041$; model T2) with the weekly data. However, the standard errors (and 95% CIs) in model T2 were approximately 2.6-fold larger, roughly equal to the square root of the decreased sample size ($\sqrt{7}$). This had the effect of reducing the significance (P values) from < 0.0001 (model T0) to 0.041 (model T2). Similarly, adjusting for a Loess smooth of daily mortality rates in Ireland (a decrease of 1.3%; 95% CI, −4.4% to 1.8%; $P = 0.41$, model $T0_S$) compared with weekly mortality rates in the Coastal counties (a decrease of 2.3%; 95% CI, −7.9% to 3.7%; $P = 0.44$; model $T2_S$) produced little change in the effect estimates but did produce wider CIs. Similarly, for cardiovascular disease, respiratory disease, and other causes of mortality, we found that analyses of weekly mortality adjusting for Coastal rates ("2" and "2_S" models) only affected the width of the CIs, and therefore tests of significance, compared with daily mortality adjusting for rates in Ireland other than Dublin ("0" and "0_S" models).

Finally, we found that including the 24-year period of weekly mortality (from 1981 to 2004; "3" and "3_S" models) produced similar estimated effects of the ban compared with the 12-year period (from 1984 to 1996; "2" and "2_S" models) but narrower CIs and therefore less statistical significance (P values).

The model and data used to estimate the effect of all the bans in the analyses in the current report correspond to the last line in each category ("3_S" models). This model produced much smaller estimated effects of the Dublin ban compared with that of the original approach ("0" models) for total and cardiovascular mortality but similar results for respiratory disease and other causes of mortality. This reduced effect was caused by the adjustment of a Loess smooth of mortality rates in the reference counties, not the fitting algorithm, the specific counties chosen for reference, the use of weekly versus daily mortality, nor the expanded period of analyses. However, the use of weekly rather than daily data and the longer period of analyses had the expected effect of increasing the width of the CIs in proportion to the square root of the sample size. The tests of significance (P values) were most dramatically altered by the changes in the estimated effects of the Dublin ban by adjustment for smoothed reference mortality rates and only modestly affected by changes in the sample size.

HOSPITAL ADMISSIONS

For the third specific aim, we examined the effect of the 1995 and 1998 coal bans on the rates of hospital admissions for cardiovascular and respiratory diseases after adjusting for the age and sex distribution of the population, underreporting of hospital admissions, weather, influenza epidemics, and secular trends in hospital admissions. We estimated the effect of each ban separately and compared the estimated effects of the two bans.

1995 Ban in Cork

Cork hospital admissions rates were directly standardized to the sex and age distribution of the total Irish population in the 1996 census and normalized to the rates of admissions for diagnoses of digestive disease in the calendar year after the 1995 ban. Figure 34 shows the season-specific adjusted hospital admissions rates for cardiovascular, respiratory, and digestive diagnoses for residents of Cork County Borough. The estimated decrease in admissions for cardiovascular diagnoses (adjusted for weekly temperature, influenza, and admissions for digestive disease) was 3.6% (95% CI, −9.8% to 2.9%; $P = 0.27$; Table 14 and Figure 35). Standardized and normalized admissions for ischemic heart disease and cerebrovascular disease diagnoses showed little seasonal variability (Figure K.1, Appendix K). We found no significant decreases in admissions for ischemic heart disease (a decrease of 3.7%; 95% CI, −13.3% to 6.9%; $P = 0.48$) or cerebrovascular disease (a decrease of 10.6%; 95% CI, −23.4% to 4.4%; $P = 0.16$) (Table 14 and Figure 35).

Rates of admissions for respiratory disease (ICD-9 460 to 519) showed a strong pattern of seasonality (Figure 34). There was little change in total respiratory admissions in the pre-ban period (17.31 admissions per 1000 p-yr) compared with the post-ban period (17.19 admissions per 1000 p-yr) (Table 14). In Poisson regression, adjusting for weekly temperature, influenza, and smoothed admissions for diagnoses of digestive disease, we found a small, nonsignificant increase (3.6%; 95% CI, −2.5% to 10.0%; $P = 0.25$) (Table 14 and Figure 35). Respiratory diagnoses for both pneumonia and COPD showed strong seasonal variation (Figure K.2, Appendix K) and a substantial reduction in mean normalized admission rates in the post-ban period compared with the pre-ban period (Table 14). After adjusting for weekly temperature, influenza, and smoothed admissions for digestive disease (Table 14 and Figure 35) we found a nonsignificant 8.0% decrease (95% CI, −20.4% to 6.3%; $P = 0.26$) in admissions for pneumonia and a nonsignificant 6.7% decrease (95% CI, −15.7% to 3.3.%; $P = 0.18$) in admissions for COPD. A substantial portion of the COPD admissions was for asthma, considered a subcategory of COPD (ICD-9 493), which had a mean of 3.55 admissions

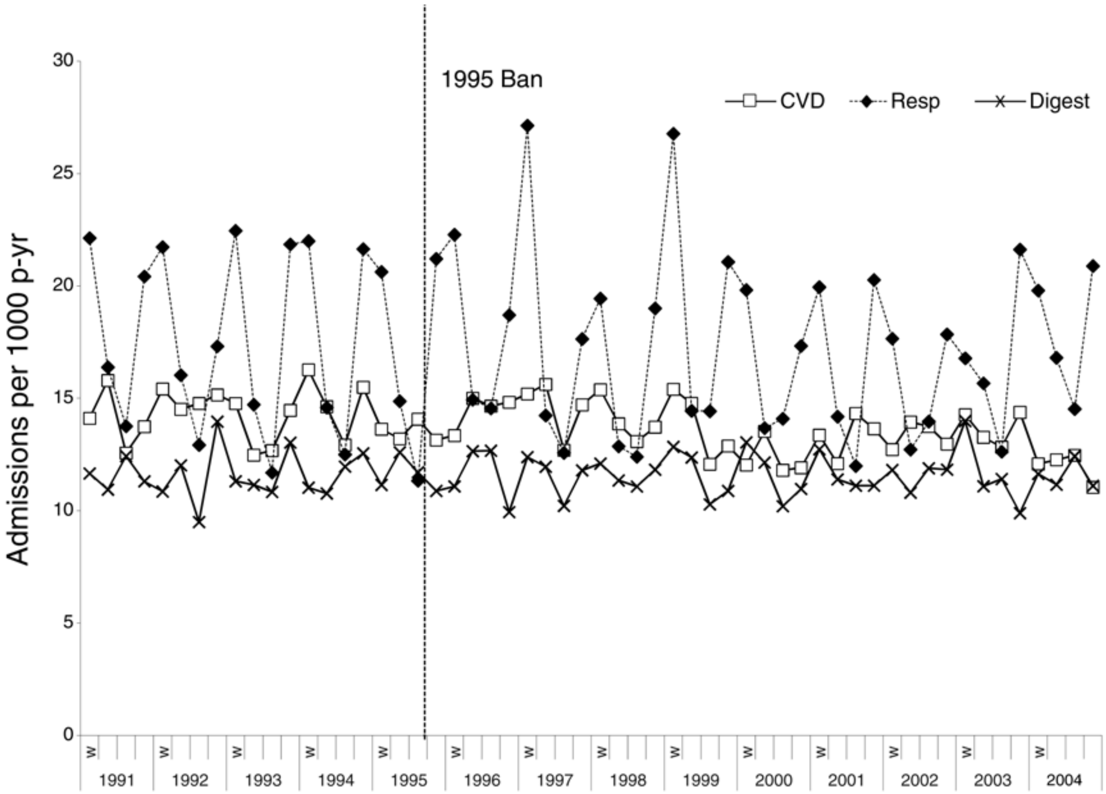


Figure 34. Mean Cork County Borough hospital admissions rates by cause and season, directly standardized to the 1996 Irish population and normalized for underreporting to 1996 annual admissions rates for digestive disease. Causes include cardiovascular (CVD), respiratory (Resp), and digestive (Digest) disease. W indicates winter.

Table 14. Estimated Percentage Changes in Cork County Borough Standardized, Normalized Hospital Admissions Rates by Cause (1991 to 2004) After the 1995 Coal Ban Compared with Pre-Ban Rates[a]

		Admissions per 1000 p-yr		Adjusted Effect of 1995 Ban		
Cause[b]	ICD-9 Code	Pre-Ban	Post-Ban	Change (%)	95% CI	*P*
Cardiovascular Disease	390–459	14.25	13.49	−3.6	−9.8 to 2.9	0.27
Ischemic heart disease	410–414	5.87	5.17	−3.7	−13.3 to 6.9	0.48
Cerebrovascular disease	430–438	2.39	2.45	−10.6	−23.4 to 4.4	0.16
Respiratory Disease	460–519	17.31	17.19	3.6	−2.5 to 10.0	0.25
Pneumonia	480–487	3.08	2.80	−8.0	−20.4 to 6.3	0.26
COPD	490–496	6.74	5.23	−6.7	−15.7 to 3.3	0.18
Asthma	493	3.55	2.80	−2.9	−15.5 to 11.6	0.68

[a] Estimated by Poisson regression adjusted for weekly temperature, influenza epidemics, and hospital admissions for digestive disease.

[b] Causes in **boldface** are principal categories; the rest are subcategories.

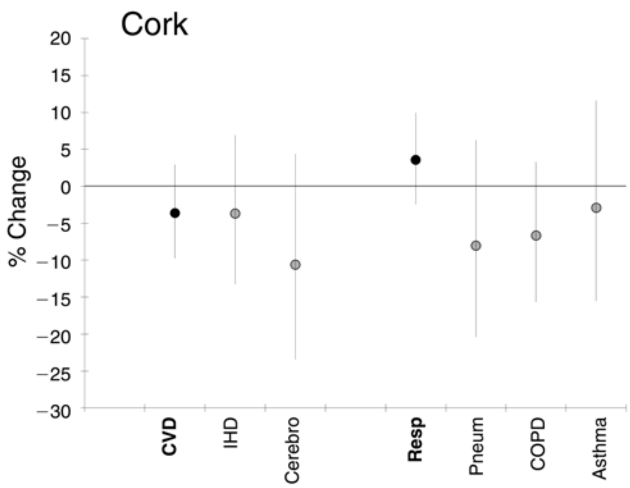


Figure 35. Percentage changes (with 95% CIs) in Cork County Borough directly standardized, normalized hospital admissions rates by cause after the 1995 ban compared with pre-ban admissions rates, estimated by Poisson regression adjusted for weekly temperature, influenza epidemics, and admissions rates for digestive disease. Causes include cardiovascular (CVD), ischemic heart (IHD), cerebrovascular (Cerebro), and respiratory (Resp) disease as well as pneumonia (Pneum), COPD, and asthma. Boldfaced causes and black data points refer to principal categories; the remaining causes and gray data points refer to subcategories.

per 1000 p-yr before the ban compared with 2.80 admissions per 1000 p-yr after the ban (Table 14). However, after adjusting for weekly temperature, influenza, and smoothed admissions for digestive disease, the estimated change in asthma admissions associated with the ban was a decrease of 2.9% (95% CI, −15.5% to 11.6%; $P = 0.68$).

In analyses by heating season (Table 15), we found little difference in estimated changes in hospital admissions rates for cardiovascular disease during the heating season compared with the non-heating season. For total respiratory admissions we found a nonsignificant 4.4% decrease (95% CI, −12.0% to 3.7%; $P = 0.28$) in the heating season compared with a 13.6% increase (95% CI, 3.2% to 25.1%; $P = 0.01$) in the non-heating season (Table 15). Admissions for pneumonia decreased by 19.9% (95% CI, −33.6% to 3.3%; $P = 0.021$) in the heating season, with a smaller decrease of 3.5% (95% CI, −23.8% to 22.2%; $P = 0.77$) in the non-heating season (Table 15). COPD admissions also decreased significantly by 17.4% in the heating season (95% CI, −28.3% to −4.8%; $P = 0.008$), with a smaller decrease of 9.4% (95% CI, −22.1% to 5.3%; $P = 0.20$) in the nonheating season. Admissions for asthma similarly had a significant decrease in the heating season and effectively no decrease in the nonheating season (Table 15).

1998 Ban in Limerick, Louth, Wexford, and Wicklow

Figure 36 shows the season-specific adjusted hospital admissions rates for cardiovascular, respiratory, and digestive-disease diagnoses for residents of Limerick, Louth, Wexford, and Wicklow, the counties affected by the 1998 coal ban. The combined estimated change in admissions rates for diagnoses of cardiovascular disease for the four counties, adjusted for weekly temperature, influenza, and admissions for digestive disease, was a decrease of 3.2% (95% CI, −5.7% to −0.6%; $P = 0.016$; Table 16 and Figure 37). Standardized, normalized admissions for ischemic heart disease decreased significantly in the combined analysis (−10.6%; 95% CI, −14.5% to −6.5%; $P < 0.00001$), although significant decreases were seen only in counties Limerick and Louth (Table 16). We did not find a significant decrease in admissions for cerebrovascular disease in the combined analyses (Table 16 and Figure 37), although there was a significant decrease in Limerick.

Table 15. Estimated Percentage Changes in Cork County Borough Standardized, Normalized Hospital Admissions Rates by Cause for the Heating and Non-Heating Seasons (1991 to 2004) After the 1995 Coal Ban Compared with Pre-Ban Rates

	Heating Season			Non-Heating Season		
Cause[b]	Change (%)	95% CI	P	Change (%)	95% CI	P
Cardiovascular Disease	−4.4	−13.4 to 5.4	0.37	−2.5	−11.3 to 7.1	0.59
Ischemic heart disease	−9.1	−22.3 to 6.3	0.23	−10.1	−22.3 to 4.1	0.16
Cerebrovascular disease	8.8	−14.5 to 38.5	0.49	−8.7	−26.8 to 13.9	0.42
Respiratory Disease	−4.4	−12.0 to 3.7	0.28	13.6	3.2 to 25.1	0.01
Pneumonia	−19.9	−33.6 to −3.3	0.021	−3.5	−23.8 to 22.2	0.77
COPD	−17.4	−28.3 to −4.8	0.008	−9.4	−22.1 to 5.3	0.20
Asthma	−23.9	−37.5 to −7.2	0.007	−1.3	−19.3 to 20.8	0.90

[a] Estimated by Poisson regression adjusted for weekly temperature, influenza epidemics, and hospital admissions for digestive disease.

[b] Causes in **boldface** are principal categories; the rest are subcategories.

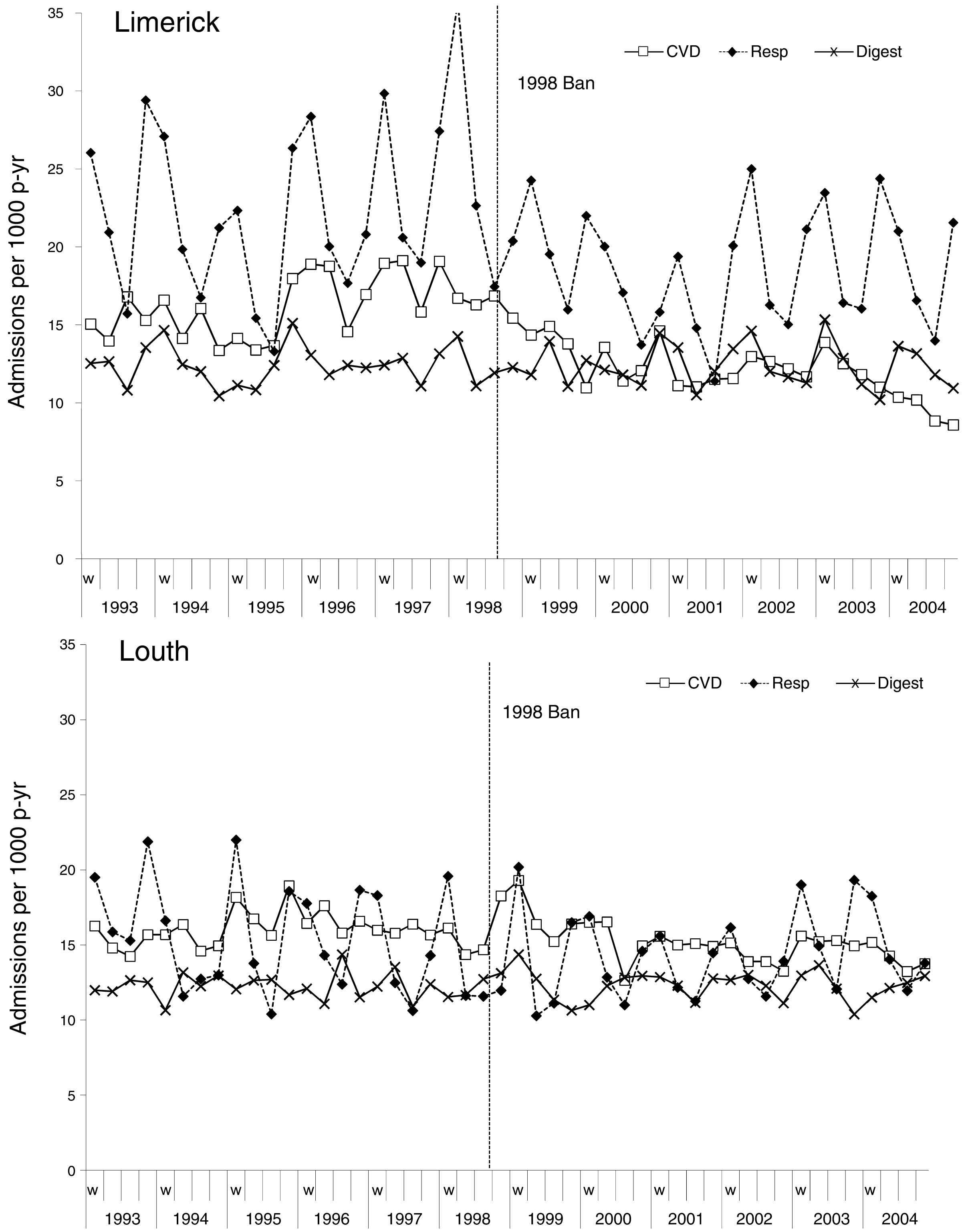


Figure 36. Mean hospital admissions rates by cause and season for four counties affected by the 1998 coal ban, directly standardized to the 1996 Irish population and normalized for underreporting to 1998 annual admissions rates for digestive disease. Causes include cardiovascular (CVD), respiratory (Resp), and digestive (Digest) disease. W indicates winter. (*Figure continues next page.*)

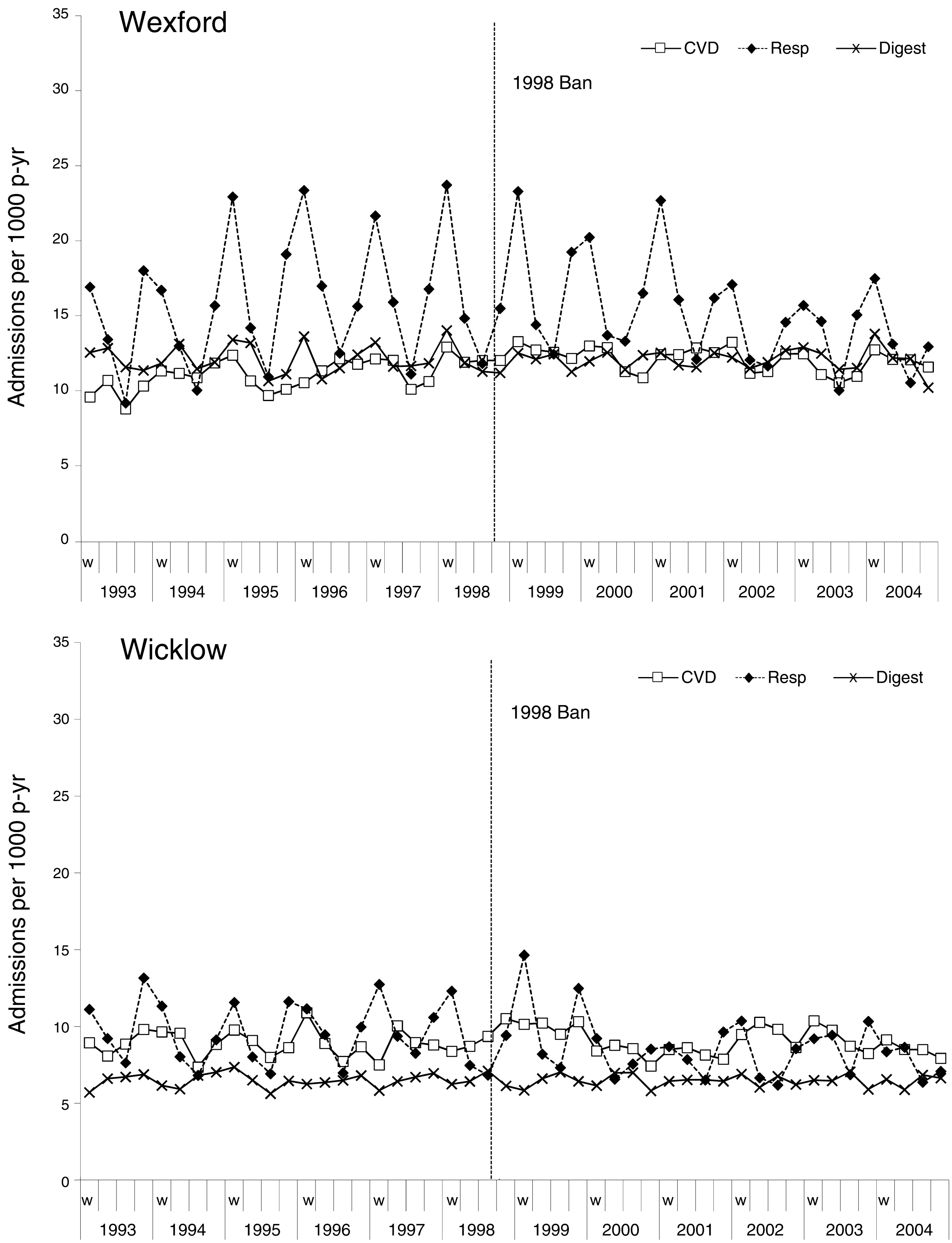


Figure 36 (*Continued*).

Table 16. Estimated Percentage Changes in County and Combined Standardized, Normalized Hospital Admissions Rates by Cause (1993 to 2004) After the 1998 Coal Ban Compared with Pre-Ban Rates[a]

Cause / County	Admissions per 1000 p-yr		Adjusted Effect of 1998 Ban		
	Pre-Ban	Post-Ban	Change (%)	95% CI	*P*
Cardiovascular disease					
Limerick	16.45	12.16	−18.0	−22.2 to −13.6	< 0.0001
Louth	15.86	15.13	−2.5	−7.4 to 2.7	0.34
Wexford	11.09	12.13	9.0	3.6 to 14.6	0.0008
Wicklow	8.88	9.02	−0.2	−5.5 to 5.4	0.95
Combined			−3.2	−5.7 to −0.6	0.016
Ischemic heart disease					
Limerick	5.74	3.58	−30.5	−36.7 to −23.7	< 0.0001
Louth	5.68	4.90	−12.8	−20.2 to −4.7	0.0025
Wexford	4.09	4.28	6.2	−2.3 to 15.4	0.16
Wicklow	3.18	3.11	−5.0	−13.3 to 4.2	0.28
Combined			−10.6	−14.5 to −6.5	< 0.00001
Cerebrovascular disease					
Limerick	3.01	2.41	−15.2	−24.9 to −4.2	0.008
Louth	2.53	2.67	8.4	−4.6 to 23.1	0.22
Wexford	1.78	2.14	12.3	−0.6 to 26.8	0.062
Wicklow	1.70	1.91	10.8	−1.9 to 25.1	0.10
Combined			3.3	−2.9 to 9.9	0.30
Respiratory disease					
Limerick	22.80	18.67	−14.0	−17.7 to −10.1	< 0.0001
Louth	15.21	14.18	0.6	−4.8 to 6.2	0.83
Wexford	15.87	15.25	−5.9	−9.9 to −1.7	0.006
Wicklow	9.52	8.55	−12.3	−16.9 to −7.4	< 0.0001
Combined			−8.5	−10.6 to −6.2	< 0.00001
Pneumonia					
Limerick	2.96	2.46	−11.4	−21.5 to 0.1	0.052
Louth	2.58	2.93	24.0	9.0 to 41.0	0.0010
Wexford	4.26	3.09	−30.4	−36.3 to −23.9	< 0.0001
Wicklow	2.04	2.16	1.6	−9.2 to 13.7	0.78
Combined			−11.2	−15.9 to −6.2	0.00002
COPD					
Limerick	7.90	5.79	−15.6	−21.8 to −9.0	0.00001
Louth	5.85	4.34	−17.0	−24.4 to −9.0	0.00008
Wexford	4.65	3.74	−18.4	−24.9 to −11.3	< 0.0001
Wicklow	3.80	2.49	−36.3	−42.0 to −30.0	< 0.0001
Combined			−21.4	−24.7 to −18.0	< 0.00001
Asthma					
Limerick	4.21	2.14	−36.6	−43.4 to −28.9	< 0.0001
Louth	3.06	1.45	−47.9	−54.8 to −40.0	< 0.0001
Wexford	1.92	1.44	−19.6	−29.6 to −8.1	0.0014
Wicklow	1.32	0.66	−51.5	−59.2 to −42.3	< 0.0001
Combined			−38.2	−42.2 to −33.8	< 0.00001

[a] Estimated by Poisson regression adjusted for weekly temperature, influenza epidemics, and hospital admissions for digestive disease. County estimates were combined by inverse-variance weighting.

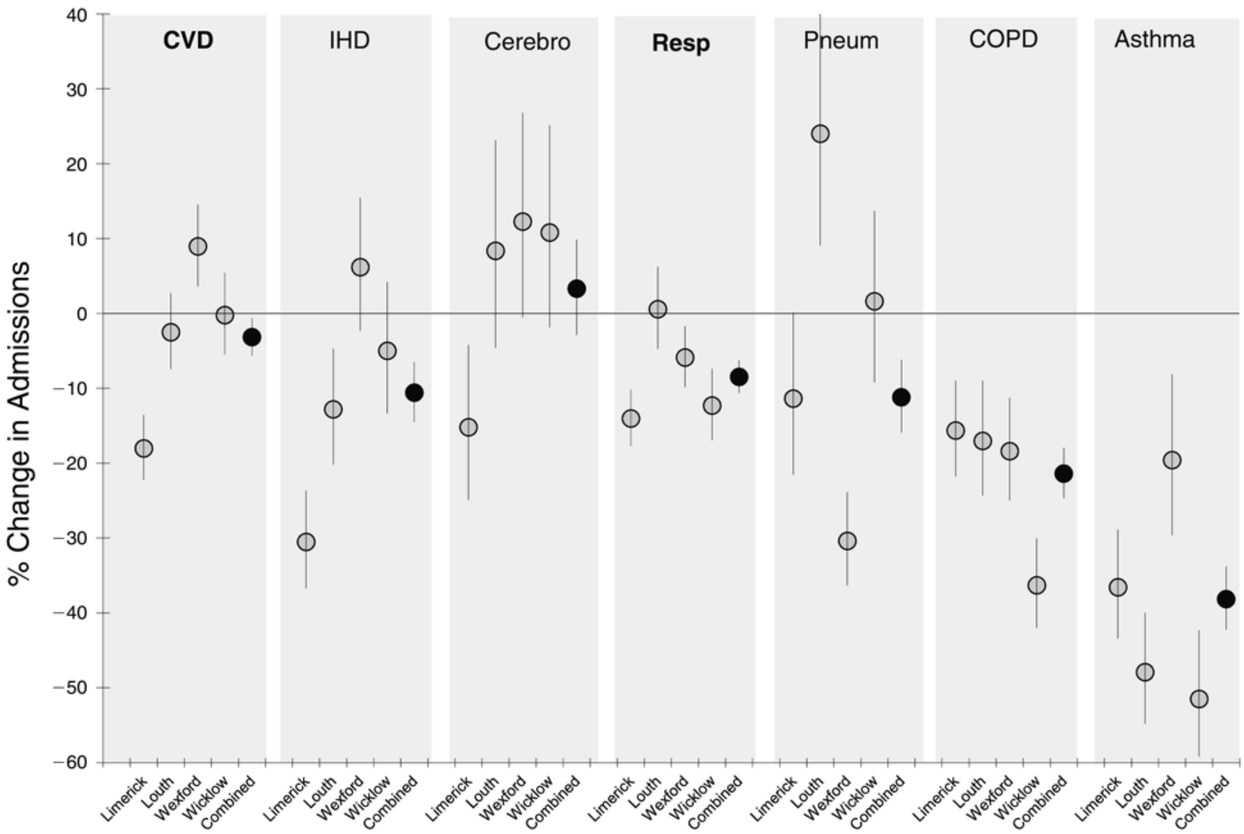


Figure 37. Percentage changes (with 95% CIs) in county and combined directly standardized, normalized hospital admissions rates by cause after the 1998 coal ban compared with pre-ban admissions, estimated by Poisson regression adjusted for weekly temperature, influenza epidemics, and hospital admissions rates for digestive disease. Causes include cardiovascular (CVD), ischemic heart (IHD), cerebrovascular (Cerebro), and respiratory (Resp) disease as well as pneumonia (Pneum), COPD, and asthma. Boldfaced causes refer to principal categories; the remaining causes refer to subcategories.

As in Cork, hospital admissions for respiratory disease showed a strong seasonal pattern (Figure 36). Respiratory admissions in Limerick show particularly large seasonal variations that decreased after the 1998 coal ban (Figure 36). Mean normalized admissions rates were lower after the ban compared with the pre-ban period in all four counties (Table 16 and Figure 37). We found a decrease in normalized admissions for respiratory disease in three of the four counties after adjusting for temperature, influenza, and smoothed admissions for digestive disease in the same week (Table 16 and Figure 37). In combined analysis across all four counties, we found an 8.5% decrease in normalized admissions for respiratory disease (95% CI, −10.6% to −6.2%; $P < 0.00001$). Admissions for pneumonia (Figure L.2 in Appendix L) decreased significantly in the pooled analysis (−11.2%; 95% CI, −15.9% to −6.2%; $P = 0.00002$) across the four counties (Table 16 and Figure 37), although decreases were seen only in Limerick and Wexford. In contrast, admissions for COPD decreased in each of the four counties (Figure L.2 in Appendix L) and had a highly significant decrease in the pooled analyses (−21.4%; 95% CI, −24.7% to −18.0%; $P < 0.00001$) (Table 16 and Figure 37). Within the COPD category, admissions for asthma showed evidence of decreases in the season-specific means immediately after the coal ban (Figure L.2 in Appendix L). Admissions for asthma decreased significantly in all four counties (Table 16), although there was heterogeneity in the estimates. Across the four counties we found an estimated decrease of 38.2% (95% CI, −42.2% to −33.8%; $P < 0.00001$) in admissions for asthma (Table 16).

In analyses by heating season (Table 17 and Table L.1 in Appendix L) we found a small, nonsignificant decrease (−1.5%; 95% CI, −5.4% to 2.5%; $P = 0.45$) in admissions for cardiovascular disease after the ban in the combined

Table 17. Estimated Percentage Changes in Standardized, Normalized Hospital Admissions Rates by Cause for the Heating and Non-Heating Seasons (1993 to 2004) in Limerick, Louth, Wexford, and Wicklow Combined After the 1998 Coal Ban, Compared with Pre-Ban Rates [a]

	Heating Season			Non-Heating Season		
Cause[b]	Change (%)	95% CI	*P*	Change (%)	95% CI	*P*
Cardiovascular Disease	−1.5	−5.4 to 2.5	0.45	4.4	0.2 to 8.7	0.04
Ischemic heart disease	−7.5	−13.6 to −0.9	0.03	−0.4	−6.9 to 6.7	0.92
Cerebrovascular disease	8.1	−1.7 to 18.9	0.11	6.3	−3.3 to 16.8	0.20
Respiratory Disease	−3.6	−6.8 to −0.2	0.04	0.6	−3.3 to 4.7	0.75
Pneumonia	−8.6	−15.2 to −1.4	0.02	−7.2	−15.6 to 2.0	0.12
COPD	−14.1	−19.2 to −8.8	< 0.0001	−14.2	−19.7 to −8.3	< 0.0001
Asthma	−31.1	−37.5 to −24.1	< 0.0001	−27.7	−34.6 to −20.2	< 0.0001

[a] County estimates were combined by inverse-variance weighting. See Appendix L, Table L.1, for estimates by county.

[b] Causes in **boldface** are principal categories; the rest are subcategories.

results across the four counties (Table 17) compared with a significant increase (4.4%; 95% CI, 0.2% to 8.7%; $P = 0.04$) in the non-heating season. Admissions for ischemic heart disease decreased significantly in the post-ban heating season (−7.5%; 95% CI, −13.6% to −0.9%; $P = 0.03$) compared with effectively no changes in the non-heating season (−0.4%; 95% CI, −6.9% to 6.7%; $P = 0.92$). Admissions for respiratory disease also were decreased significantly in the heating season (−3.6%; 95% CI, −6.8% to −0.2%; $P = 0.04$), with no decrease in the non-heating season (0.6%; 95% CI, −3.3% to 4.7%; $P = 0.75$). However, we found little difference in the effects of the 1998 ban by heating season for admission rates for pneumonia, COPD, and asthma (Table 17).

DISCUSSION AND CONCLUSIONS

AIR POLLUTION

After a series of bans on the marketing, sale, and distribution of coal in 12 cities and towns in the Republic of Ireland from 1990 to 2000, BS concentrations decreased rapidly and dramatically. This decrease appeared in each city regardless of the year of the ban, city population, topographic and weather characteristics, location, and concentration of BS before the ban. The largest decreases were in winter, when coal would previously have been used for residential space heating; there was little difference in BS concentrations in the summer. There was less seasonal variability in mean BS concentrations, and there were sharp reductions in the extreme BS concentrations (90th and 95th percentiles) in the post-ban period compared with the pre-ban period in all cities. These reductions were sustained in all cities until at least 2004 (4 to 14 years post-ban). In contrast, there was no consistent pattern or decrease in SO_2, measured as total gaseous acidity across the cities, suggesting little effect of the bans. These results are consistent with studies in other locations in Europe, Asia, and North America, where air pollution improvements have been observed after implementation of policies to reduce air pollution directly (Hedley et al. 2002), national political realignment (Heinrich et al. 2000), temporary closing of industrial facilities because of an employee strike (Pope 1989; Pope et al. 2007), or temporary regulations during large sporting events (Friedman et al. 2001; Lee et al. 2007).

The interventions in Ireland were happening when the Irish economy was the fastest growing in Europe, with a 60% increase in gross domestic product (GDP) between 1990 and 1998 (Healy 2001). There was a similar growth in energy usage, up 60% over the same period (Healy 2001).

In almost all the cities and towns included in this analysis, BS concentrations were decreasing in the years before the city-specific bans (Figure 11). Dublin was the main center for the importation of coal, and the local ban in Dublin might have affected availability in other cities. Coal imports dropped by half between 1980 and 1993, with the most dramatic reduction in 1991 after the ban in Dublin (Myers 1994; Healy 2001). During this period in Ireland, there was a general switch to the use of natural gas for space heating; natural gas usage increased sixfold (Healy

2001). Even with these long-term temporal trends toward lower BS, there was an immediate improvement in BS concentrations apparent in the first winter after each of the city-specific coal bans (Figure 11).

After the introduction of the coal ban, only five of the 11 cities and towns with SO_2 data, as represented by total gaseous acidity, showed a decrease in concentrations. In addition to the various coal bans, Ireland was also trying to reduce its overall SO_2 emissions as part of a European Union national emissions-ceiling directive (European Union 2001). In 1990 the total SO_2 emissions from all sectors in Ireland were estimated to be 183,000 tons. Of these, 56% was from electricity generation and 21% from residential and industrial sources (EPA Ireland 2006). A specific breakdown of emissions from the residential sector was not available. By 2005 the total emissions were estimated to be 71,000 tons (a 61% reduction). This was achieved at a time when energy use, as noted above, was increasing significantly. There was no substantial change in the percentage contributions from residential and industrial sectors over this time (EPA Ireland 2006).

The largest decreases in measured SO_2 concentrations were observed in Dublin and Leixlip. There are several possible explanations for why SO_2 decreases of a similar magnitude were not seen in the other Irish cities and towns. First, most of the ambient SO_2 might not have been a product of coal burning but might have been attributable to other sources, such as oil heating, emissions from diesel vehicles, or sources outside of the local area. Leixlip accounts for about 7% of all manufacturing employment in Ireland, although this is mainly in high-technology computer-related manufacturing. Second, detecting any change in SO_2 concentrations is difficult because of the nonspecific technique — the total gaseous acidity method (BS 1747 method, British Standards Institute 1983) — used to measure SO_2. This measurement method for SO_2 was designated in 1969, when SO_2 concentrations were substantially higher than those during our study period (1981–2004). Indeed SO_2 concentrations during our study period were often close to the limits of detection of the method. The BS 1747 method assumes that all acidity is attributable to SO_2 (World Health Organization 1994), with the result that nitrogen dioxide and other acidic gases are misclassified as SO_2. Therefore, although these results show that total acidity did not decrease consistently after the bans, there might have been a change in SO_2 concentrations that was masked by increased concentrations of nitrogen dioxide or other acidic gases.

In summary, we observed statistically significant, large, immediate, and sustained decreases in BS concentrations in several Irish cities after a series of legislative bans on the marketing, sale, and distribution of coal in 1990, 1995, 1998, and 2000. No consistent effect was observed in total gaseous acidity as a surrogate measure of SO_2 concentrations.

MORTALITY

In an earlier analysis of the effects of the 1990 Dublin ban (Clancy et al. 2002), we found that in the 72 months (6 years) after the ban (September 1990 to August 1996) mortality from total, cardiovascular, and respiratory causes had decreased significantly compared with the 72 months before the ban (September 1984 to August 1990). In a comparison of these results with the current analyses of the 24-year period from 1981 to 2004, we saw a similar estimate of the decrease associated with the ban for respiratory causes and, as in the earlier analysis, no association with the ban for other causes. However, there was a striking difference in the estimated associations with the ban for total and cardiovascular mortality, which were previously reported to have significantly decreased but in the present analysis showed effectively no change.

In simulation analyses (Appendix G) and in sensitivity analyses of the effects of the Dublin ban (Table 13), we found that the estimates of the effect of an assumed step-change in mortality rates were sensitive to adjustment for background secular trends in mortality. For the case of small long-term secular trends, the estimated effects of an intervention were not biased. However, secular trends in mortality rates produced a biased estimate in the simulation. We found that adjustment in the simulation for a long-term nonparametric smooth of the assumed background mortality rate produced unbiased estimates of the effect of an assumed air pollution intervention. Applying this approach (i.e., a smooth of reference mortality) to the Dublin data likewise produced no change in the estimated effects of the ban in the case of small secular trends (i.e., for respiratory disease and other causes of mortality) but substantially reduced estimated effects in the presence of substantial secular trends (i.e., for cardiovascular and total mortality).

These simulation analyses and sensitivity analyses demonstrate that detecting acute temporal changes in mortality rates in the presence of strong secular trends is analytically difficult. We now believe the previous analyses (Clancy et al. 2002) overestimated the Dublin ban's effects on mortality rates for those causes with substantial long-term trends, that is, total and cardiovascular mortality.

Wittmaack (2007) suggested earlier that the decrease in mortality in Dublin after the coal ban was explained by the long-term decrease in mortality seen throughout Ireland. In the original analysis we had used the daily mortality rates in the rest of Ireland (counties other than Dublin) to adjust for these long-term trends. However, as noted above, we found this analytic approach could produce a biased result. In sensitivity analyses we found that adjustment for a nonparametric smooth of mortality in reference populations, which captures the linear trend and seasonal variation, led to less biased estimates.

When there was limited evidence of long-term trends in mortality, such as in mortality from respiratory causes, we found that the estimated associations were not biased. Wittmaack (2007) suggested that the observed change might also be attributable to excess mortality caused by respiratory epidemics. In our analyses adjusting for weeks with anomalously high respiratory mortality, we found that for the 1990 Dublin ban the estimated effect on mortality was not sensitive to these respiratory epidemics.

Ultimately, validation of the Dublin results does not come from secondary analyses or even reanalyses of the original data, but by replication in independent settings. Thus the primary objective of this study was to assess the effects of the coal bans in other cities and in other years. In addition, we have estimated the effect of each ban on total and cause-specific mortality in comparison counties unaffected by the bans. Table 18 is a compilation of the estimated effects for each of the successive coal bans on total and cause-specific mortality in the affected counties and the unaffected Midlands comparison counties. Each of these analyses was adjusted for mean temperature, influenza epidemics, and a Loess smooth of mortality in the Coastal reference counties.

For Dublin we found no effect of the 1990 ban in total (−1%; 95% CI, −6% to 4%; $P = 0.72$), cardiovascular (0%; 95% CI, −9% to 10%; $P = 0.98$), or other (−1%; 95% CI, −7% to 5%; $P = 0.66$) mortality (Table 18). This was consistent with the estimated decreases in the unaffected Midlands counties after the 1990 ban of 3% (95% CI, −8% to 3%; $P = 0.32$) for total mortality, 2% (95% CI, −10% to 7%; $P = 0.68$) for cardiovascular mortality, and 2% (95% CI, −8% to 5%; $P = 0.62$) for mortality from other causes. There was a suggestion of a decrease in respiratory mortality in Dublin (−17%; 95% CI, −24% to −8%; $P = 0.0002$), which contrasted with a small nonsignificant decrease in the Midlands counties (−2%; 95% CI,−12% to 8%; $P = 0.65$). This difference between Dublin and the unaffected Midlands counties was largely attributable to a significant decrease of 21% (95% CI, −32% to −9%; $P = 0.0012$) in pneumonia deaths in Dublin compared with a nonsignificant increase of 4% (95% CI, −10% to 21%; $P = 0.59$) in the Midlands counties. COPD mortality also decreased significantly in Dublin by 22% (95% CI, −33% to −10%; $P = 0.0009$), but there was a similar decrease in the Midlands counties of 17% (95% CI, −29% to −4%; $P = 0.013$). The only other cause of mortality in Dublin that decreased significantly was lung cancer, with a 14% decrease (95% CI, −25% to −2%; $P = 0.027$) that was larger than the 6% decrease (95% CI, −22% to 12%; $P = 0.48$) observed in the Midlands counties.

We found that the extension of the coal ban to Cork County Borough in 1995 was associated with nonsignificant decreases in total (−4%; 95% CI, −10% to 1%; $P = 0.11$) and cardiovascular (−4%; 95% CI, −12% to 6%; $P = 0.42$) mortality rates among residents of county Cork (Table 18). This was similar to the estimated decrease in the unaffected Midlands counties for total mortality (−4%; 95% CI, −9% to 2%; $P = 0.20$) and for cardiovascular mortality (−3%; 95% CI, −12% to 6%; $P = 0.47$) (Table 18). We found the largest post-ban decreases in cardiovascular mortality in county Cork for ischemic heart disease (−11%; 95% CI, −21% to 1%; $P = 0.073$), but this was the same as the observed decrease in the Midlands counties (−11%; 95% CI, −22% to 1%; $P = 0.06$). Cerebrovascular mortality decreased in county Cork (−10%; 95% CI,−26% to 8%; $P = 0.26$) and by a similar amount in the Midlands counties (−12%; 95% CI, −27% to 6%; $P = 0.016$) (Table 18).

For county Cork we found a decrease of 9% (95% CI, −18% to 1%; $P = 0.067$) in mortality rates for respiratory disease compared with a decrease of only 1% (95% CI, −11% to 9%; $P = 0.78$) in the unaffected Midlands counties. The estimated decrease in COPD deaths was similar in both county Cork (−19%; 95% CI, −31% to −5%; $P = 0.011$) and the Midlands counties (−20%; 95% CI, −32% to −6%; $P = 0.010$). However, pneumonia deaths were estimated to have decreased in county Cork (−5%; 95% CI, −19% to 10%; $P = 0.46$) but to have increased in the Midlands (7%; 95% CI, −8% to 24%; $P = 0.39$).

For other causes of death, we found decreases after the 1995 ban in both county Cork (−7%; 95% CI, −13% to 0%; $P = 0.049$) and the Midlands counties (−3%; 95% CI,−10% to 4%; $P = 0.33$). For the category of noncardiovascular, nonrespiratory causes of deaths, we saw equivalent nonsignificant decreases in deaths from digestive disease in county Cork and the Midlands counties (Table 18). We did find slightly larger decreases in mortality from lung cancer in county Cork (−16%; 95% CI, −30% to 1%; $P = 0.058$) compared with the Midlands counties (−11%; 95% CI, −27% to 7%; $P = 0.21$).

In 1998 the coal ban was extended to Dundalk, Drogheda, Wexford, Limerick, and Arklow, towns of small to moderate size. Among the residents of the four counties affected by the 1998 ban, effectively no reductions were found in total (0%; 95% CI,−3% to 4%; $P = 0.90$) and cardiovascular (−1%; 95% CI, −6% to 4%; $P = 0.67$) mortality. This was equivalent to the estimated decrease in the unaffected Midlands counties (Table 18). Respiratory mortality in the affected counties decreased by 3% (95% CI, −8% to 3%;

Table 18. Estimated Percentage Changes in Post-Ban Mortality Rates by Cause Compared with Pre-Ban Rates for Dublin (1990); Cork (1995); Limerick, Louth, Wexford, and Wicklow combined (1998); and the Midlands Counties

Cause[a] / Ban[b]	Affected Counties			Midlands Counties		
	Change (%)	95% CI	*P*	Change (%)	95% CI	*P*
Total						
1990	−1	−6 to 4	0.72	−3	−8 to 3	0.32
1995	−4	−10 to 1	0.11	−4	−9 to 2	0.20
1998	0	−3 to 4	0.90	0	−7 to 7	0.96
Cardiovascular Disease						
1990	0	−9 to 10	0.98	−2	−10 to 7	0.68
1995	−4	−12 to 6	0.42	−3	−12 to 6	0.47
1998	−1	−6 to 4	0.67	−3	−13 to 7	0.54
Ischemic heart disease						
1990	0	−12 to 13	0.97	6	−6 to 19	0.37
1995	−11	−21 to 1	0.073	−11	−22 to 1	0.06
1998	−10	−16 to −3	0.006	−14	−26 to −1	0.041
Cerebrovascular disease						
1990	−8	−25 to −3	0.41	−13	−28 to 5	0.14
1995	−10	−26 to 8	0.26	−12	−27 to 6	0.16
1998	−13	−21 to −4	0.008	−7	−24 to 14	0.48
Respiratory Disease						
1990	−17	−24 to −8	0.0002	−2	−12 to 8	0.65
1995	−9	−18 to 1	0.067	−1	−11 to 9	0.78
1998	−3	−8 to 3	0.39	1	−10 to 15	0.82
Pneumonia						
1990	−21	−32 to −9	0.0012	4	−10 to 21	0.59
1995	−5	−19 to 10	0.46	7	−8 to 24	0.39
1998	9	0 to 19	0.055	13	−5 to 35	0.16
COPD						
1990	−22	−33 to −10	0.0009	−17	−29 to −4	0.013
1995	−19	−31 to −5	0.011	−20	−32 to −6	0.010
1998	−30	−37 to −23	< 0.0001	−23	−37 to −7	0.0078
Other						
1990	−1	−7 to 5	0.66	−2	−8 to 5	0.62
1995	−7	−13 to 0	0.049	−3	−10 to 4	0.33
1998	−3	−7 to 1	0.16	−3	−11 to 6	0.5
Cancer						
1990	−7	−13 to 0	0.057	−2	−9 to 7	0.71
1995	−5	−12 to 3	0.19	−5	−13 to 3	0.21
1998	−7	−11 to −3	0.001	−4	−13 to 5	0.39
Lung cancer						
1990	−14	−25 to −2	0.027	−6	−22 to 12	0.48
1995	−16	−30 to 1	0.058	−11	−27 to 7	0.21
1998	−12	−20 to −3	0.009	−9	−26 to 12	0.38
Digestive disease						
1990	4	−16 to 28	0.73	−5	−24 to 20	0.69
1995	−9	−28 to 15	0.44	−6	−25 to 19	0.63
1998	−9	−20 to 3	0.14	−10	−31 to 17	0.42

[a] Causes in **boldface** are principal categories; the rest are subcategories.

[b] Cities, towns, and counties signified by the ban years cited in this column are defined in Table 2.

P = 0.39) compared with a 1% increase (95% CI, −10% to 15%; P = 0.82) in the unaffected Midlands counties. We found significant decreases in mortality from COPD in both the affected (−30%; 95% CI, −37% to −23%; P < 0.0001) and unaffected (−23%; 95% CI, −37% to −7%; P = 0.0078) counties. Mortality rates for pneumonia increased in both the affected (9%; 95% CI, 0% to 19%; P = 0.055) and unaffected (13%; 95% CI, −5% to 35%; P = 0.16) counties (Table 18), although less so in the former.

Thus, in summary, across the 1990, 1995, and 1998 coal bans there was no evidence for decreased total, cardiovascular, or other (not cardiovascular or respiratory) mortality associated with the bans (Figure 38). We estimated the effect of each of these bans on mortality rates in the Midlands, a population presumably unaffected by the bans, using the same methods (Table 18), and found no effect of any of the coal bans on total, cardiovascular, or other mortality rates. The lack of any association with the bans in the affected or unaffected counties suggests that there was indeed no change in total, cardiovascular, or other mortality associated with the bans detectable using these methods.

On the other hand, we did find a significant 17% decrease (95% CI, −24% to −8%; P = 0.0002) in respiratory mortality in Dublin after the 1990 ban, a 9% decrease (95% CI, −18% to 1%; P = 0.067) in Cork after the 1995 ban, and a 3% decrease (95% CI, −8% to 3%; P = 0.39) in our combined analyses in the four affected counties after the 1998 ban. In contrast, we found no decreases in respiratory mortality in the Midlands counties after the 1990 ban (−2%; 95% CI, −12% to 8%; P = 0.65), the 1995 ban (−1%; 95% CI, −11% to 9%; P = 0.78), or the 1998 ban (1%; 95% CI, −10% to 15%; P = 0.82). Thus there was a suggestion of an improvement in respiratory mortality in the affected counties after the coal bans, but not in the unaffected counties. One might argue that this decreasing magnitude of the effect of the coal bans on respiratory mortality is consistent with the decreasing magnitude of the reductions in BS concentrations across the three sequential bans (Table 5).

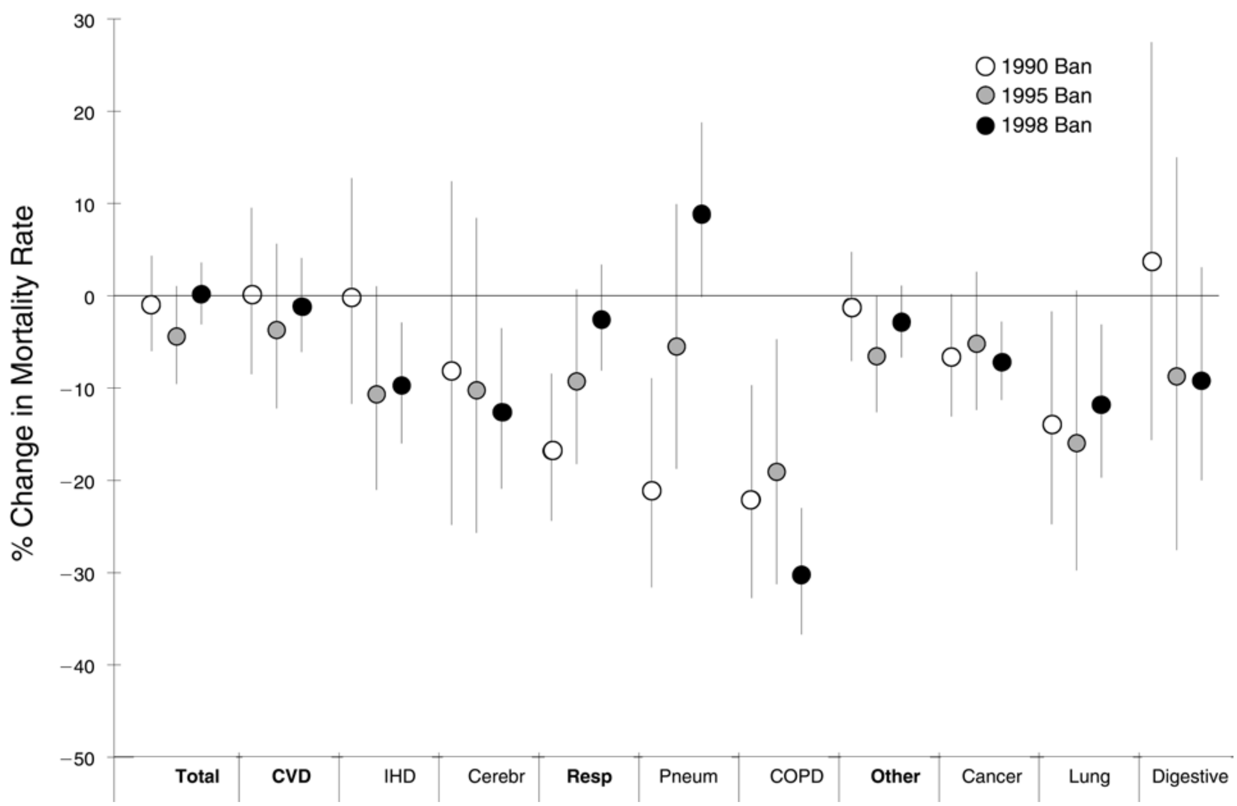


Figure 38. Estimated percentage changes (with 95% CIs) in post-ban mortality rates by cause compared with pre-ban rates for Dublin (1990), Cork (1995), and Limerick, Louth, Wexford, and Wicklow combined (1998). Causes include total, cardiovascular (CVD), ischemic heart (IHD), cerebrovascular (Cerebro), and respiratory (Resp) disease as well as pneumonia (Pneum), COPD, other, cancer, lung cancer (Lung), and digestive disease (Digestive). Boldfaced causes refer to principal categories; the remaining causes refer to subcategories.

Given that the effect of the coal bans was to reduce BS concentrations during the heating season (Goodman et al. 2009) and the suggestion in the earlier Dublin analysis (Clancy et al. 2002) that the largest reductions in respiratory and cardiovascular mortality were observed in winter, we a priori expected cardiovascular and respiratory mortality to decrease during the heating season (i.e., November to April). However, we observed no consistent evidence of a larger decrease in cardiovascular or respiratory mortality in the heating season compared with the nonheating season in Dublin (Figure 31), in Cork (Figure 17), or in the combined analyses of the 1998 ban counties (Figure 27).

HOSPITAL ADMISSIONS

Our analyses of hospital admissions were limited by the availability of data and the quality of the reporting system. Regular reporting of hospital admissions began in 1990; no data were available before the 1990 coal ban in Dublin, and only limited amounts of data were available before the 1995 and 1998 bans. Even these data were compromised by incomplete reporting of admissions before 1995. We adjusted for underreporting based on rates of hospital admissions for diagnoses of digestive disease, assuming admissions for these would not be affected by local air pollution concentrations. Even with this assumption, fewer than 4 years of cardiovascular and respiratory hospital admissions data were available before the 1995 ban in Cork. For the five cities affected by the 1998 ban, we obtained hospital admissions data starting in 1993 (five years before the ban). For these five cities, hospital admissions data were available only for the residents of the county, not for cities or towns. Thus we had to assess the effects of the city-specific bans on the populations in the four larger counties encompassing the five affected cities (Appendix A), as in the mortality analyses. The hospital admissions data also had substantial underreporting (see Appendix D); we applied the same methods to the cardiovascular and respiratory admissions data for the four counties to adjust for underreporting.

Hospital admissions can also be affected by the availability of beds. The Department of Health and Children has recommended an 85% hospital occupancy rate (Health Boards Executive 2003). When there is a shortage of beds and competition for admissions, priority is given to life-threatening conditions, such as acute coronary events.

Keeping in mind these data issues and the limitations they placed on our analyses, we found no significant reduction in admissions for cardiovascular disease in Cork after the 1995 ban. Admission for ischemic heart and cerebrovascular disease did not decrease significantly. We found reduced admissions for cardiovascular disease after the 1998 ban, although the association was not consistent across cities. Although respiratory admissions did not decrease after the ban in Cork, we did see a nonsignificant 8% decrease ($P = 0.26$) in admissions for pneumonia and a nonsignificant 7% decrease ($P = 0.18$) in admissions for COPD. For the counties affected by the 1998 ban, we found decreases in admissions for respiratory disease in three counties (Limerick, Wexford, and Wicklow). The evidence for an effect of the 1998 ban on admissions for pneumonia was inconsistent, with decreases in two counties and increases in two. This was consistent with the lack of effect for pneumonia admissions in Cork County Borough. As in Cork, we did find substantial and significant reductions in admissions for COPD, and specifically for asthma, after the 1998 ban in all four counties.

We compared the estimated effects of the 1995 ban in Cork and the combined effects of the 1998 bans across the four affected counties (Figure 39). We found a small reduction in admissions for cardiovascular diagnoses, specifically ischemic heart disease diagnoses, after both the 1995 and 1998 bans. For admissions for cerebrovascular disease, there was not a significant decrease associated with either the 1995 or the 1998 bans (Figure 39).

For total respiratory and pneumonia admissions (Figure 39), the observed decrease associated with the 1998 ban was not observed to be associated with the 1995 ban. Moreover, the pooled evidence for a decrease associated with the 1998 ban was not consistent across the four affected counties (Figure 37). However, there were large and consistent decreases in admissions for COPD, and specifically for asthma, associated with both the 1995 and 1998 bans (Figure 39). These decreases were also seen consistently in each of the four counties affected by the 1998 ban (Figure 37).

There was no consistent evidence of a larger decrease in hospital admissions for cardiovascular disease in the heating season compared with the non-heating season (Figure 40). On the other hand, there were larger decreases in admissions for COPD and asthma in the heating season associated with the 1995 ban but not with the 1998 ban (Figure 40). Interestingly, although there was no decrease in admissions for pneumonia in the non-heating season (Figure 40), there were statistically significant decreases in pneumonia admissions associated with both the 1995 and 1998 bans in the heating season.

In summary, hospital admissions data were only available starting in 1991 and were considered reliable only after 1995. After normalizing reported cardiovascular and respiratory admission for underreporting (based on admissions for digestive disease), we found evidence of decreased admissions after the 1995 and 1998 bans that

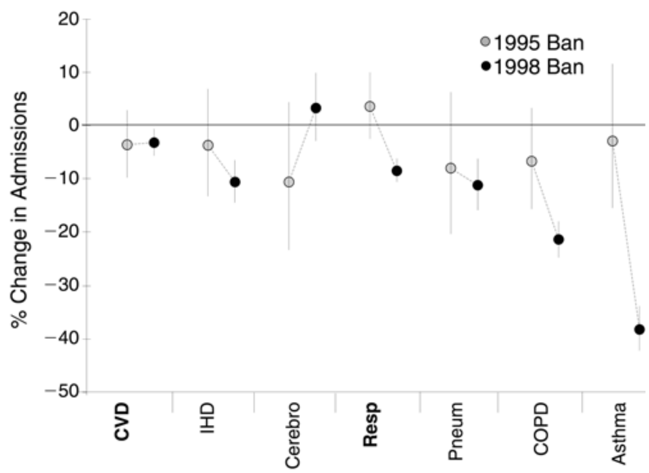


Figure 39. Estimated percentage changes (with 95% CIs) in directly standardized, normalized hospital admissions rates by cause for Cork after the 1995 coal ban and for Limerick, Louth, Wexford, and Wicklow (combined) after the 1998 ban compared with pre-ban admissions rates. Causes include cardiovascular (CVD), ischemic heart (IHD), cerebrovascular (Cerebro), and respiratory (Resp) disease as well as pneumonia (Pneum), COPD, and asthma. Boldfaced causes refer to principal categories; the remaining causes refer to subcategories.

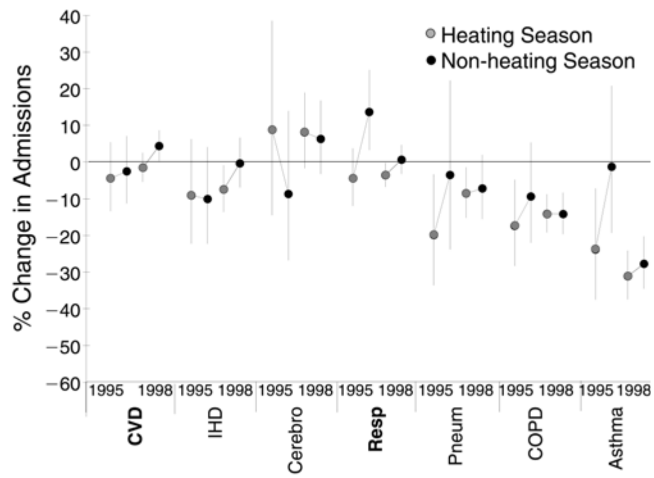


Figure 40. Estimated percentage changes (with 95% CIs) in directly standardized, normalized hospital admissions rates by cause for the heating and non-heating seasons for Cork after the 1995 coal ban and for Limerick, Louth, Wexford, and Wicklow (combined) after the 1998 ban compared with pre-ban admissions rates. Causes include cardiovascular (CVD), ischemic heart (IHD), cerebrovascular (Cerebro), and respiratory (Resp) disease as well as pneumonia (Pneum), COPD, and asthma. Boldfaced causes refer to principal categories; the remaining causes refer to subcategories.

was broadly consistent with the results of our mortality analyses. Admissions for cardiovascular disease decreased by about 4% in Cork after the 1995 ban and about 3% in the four counties affected by the 1998 ban (Figure 39). By comparison, mortality rates for cardiovascular disease decreased by approximately 4% after the 1995 ban and 1% after the 1998 ban (Table 18). We observed decreases in hospital admissions for ischemic heart disease (4% and 11% for the 1995 and 1998 bans, respectively) that were similar in magnitude to those for mortality rates for ischemic heart disease (11% and 10%, respectively). We found an 11% decrease in admissions for cerebrovascular disease after the 1995 ban and a 3% increase after the 1998 ban compared with substantial decreases in mortality rates for cerebrovascular disease associated with the 1995 (10%) and 1998 (13%) bans.

There was no decrease in hospital admissions rates for respiratory diagnoses associated with the 1995 ban, in contrast with the 9% decrease observed in mortality rates for respiratory disease (Table 18). On the other hand, the 1998 ban was associated with a 9% decrease in admissions for respiratory disease compared with a 3% decrease in mortality rates for respiratory disease. Admissions rates for COPD decreased substantially (7% and 21% for the 1995 and 1998 bans, respectively) as did mortality rates for COPD (19% and 30%, respectively).

Although the hospital admissions results were broadly consistent with the mortality results, it would be wrong to interpret them as confirmatory. As we have seen, there were substantial reporting problems with the hospital admissions data, particularly before the 1995 ban. Thus we had to apply an ad hoc adjustment for underreporting based on an internal reference, that is, admissions for digestive diagnoses.

The lack of external reference data, such as hospital admissions in the Coastal counties, or of comparison data, such as hospital admissions in the Midlands counties, used in the mortality analyses is a weakness. Indeed the adjustment for long-term trends in the mortality analyses removed much of the apparent effect on cardiovascular mortality rates. Our inability to adjust adequately for background cardiovascular disease rates therefore calls into question the observed decreases in admissions for cardiovascular disease associated with the 1995 and 1998 coal bans. In the case of respiratory admissions, we found substantial and comparable decreases in mortality from COPD associated with each of the bans in both the affected and the unaffected counties. Therefore, we cannot conclude that the similar decreases in admissions for COPD were specifically linked to the coal bans and not to other temporal factors. We must therefore be very circumspect in interpreting these changes in hospital admissions.

COMPARISON WITH OTHER STUDIES

There have been other national- or regional-scale air pollution reductions in which either a policy was implemented to directly reduce air pollution concentrations or composition (Hedley et al. 2002) or a national political realignment, an employee strike at an industrial facility, a congestion-charging scheme intended to reduce traffic, or a large-scale sporting event resulted in changes in point and non-point source emissions and therefore in ambient pollutant concentrations (Pope 1989; Friedman et al. 2001; Lee et al. 2007; Pope et al. 2007; Tonne et al. 2008; Peel et al. 2010). Each of these studies found that documented large-scale air pollution reductions were associated with a beneficial public health effect, including reductions in total or cause-specific mortality rates (Hedley et al. 2002; Pope et al. 2007), bronchitis prevalence (Heinrich et al. 2000), childhood hospital admissions for respiratory disease (Pope 1989), asthma acute-care events (Friedman et al. 2001), and hospital admissions for childhood asthma (Lee et al. 2007) as well as estimated improvements in life expectancy (Tonne et al. 2008). Our analyses add to this important but limited group of "natural experiments" showing reductions in respiratory morbidity or mortality associated with large-scale air pollution reductions.

CONCLUSIONS

In summary, there was clear evidence that the Irish coal bans led to substantial local improvements in air quality. We found no evidence for a decrease in total or cardiovascular mortality rates after the bans. There was a suggestion of decreases in mortality rates for respiratory disease after the bans in regression analyses and also when compared with those of unaffected counties. Hospital admissions for diagnoses of cardiovascular disease, specifically ischemic heart disease, and of respiratory disease, specifically pneumonia, COPD, and asthma, decreased after the bans in our analyses. However, confidence in these observations is diminished by the weaknesses in the hospital data, including incomplete reporting, inadequate data to control for secular trends, and lack of data for comparison with unaffected counties. Detecting improvements in public health indicators associated even with clear improvements in air quality, as in this case in Ireland, remains challenging.

IMPLICATIONS OF FINDINGS

Our analysis shows that simple regulatory interventions to reduce air pollution can be very effective in reducing exposures. In this case the simple prohibition of the marketing, sale, and distribution of coal led to immediate and substantial reductions (50% or more) in ambient particulate (BS) concentrations in multiple cities and towns in Ireland. In contrast, no consistent reductions were seen in ambient concentrations of SO_2 measured as total gaseous acidity.

Previous studies have shown the deleterious effects of episodes of high particulate air pollution in acute increases in hospital admissions and mortality rates for cardiovascular and respiratory disease. In the two cities and four counties affected by coal bans in 1990 (Dublin), 1995 (Cork), and 1998 (counties Limerick, Louth, Wexford, and Wicklow), the improvements in air quality were associated with decreased mortality rates for respiratory disease and decreased hospital admissions for cardiovascular and respiratory disease.

A strength of this study is the intrinsic design, in which we evaluated the effects of a specific intervention in producing a step-change in air pollution exposures and consequent changes in mortality and hospital admissions. This quasi-experimental design provided important evidence for a causal relationship in epidemiologic studies (Hill 1965). Second, the experience in Ireland with the sequential introduction of coal bans in various cities and towns in 1990, 1995, 1998, and 2000 provided evidence of the consistency of these associations in different times and locations, another key element in assessing causality (Hill 1965). Third, the coherence of the parallel analyses of cause-specific mortality and hospital admissions also informs the evaluation of causality. In those analyses, however, this evidence of coherence was tempered by the weakness of the hospital admissions data.

It remains challenging to detect the public health benefits even of clear improvements in air quality in the presence of long-term secular improvements in health.

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APPENDIX A. Population

The Central Statistics Office of Ireland is responsible for "the collection, compilation, extraction and dissemination for statistical purposes of information relating to economic, social and general activities and conditions in the State." It is also responsible for coordinating official statistics of other public authorities and for developing the statistical potential of administrative records. In 2005 the Central Statistics Office Web site (*www.cso.ie*) became the main vehicle for the dissemination of information and data.

In Ireland a census is normally taken every 5 years on census night. The last census in this study was on Sunday, April 23, 2006. The previous census, originally planned for April 29, 2001, was postponed to April 28, 2002, because of the 2001 outbreak of foot-and-mouth disease. The 1976 census was delayed repeatedly because of economic conditions and ultimately completed in 1979. For these analyses, we restricted our attention to the years from 1981 to 2004, which correspond to the years with available air pollution data.

POPULATION TRENDS

The overall population of Ireland was stable over the decade of the 1980s, increasing by only 4.7% between the 1981 and 1991 censuses (Figure A.1). However, between the 1996 and 2006 censuses, total population increased by 16.9%.

Figure A.2 shows the total Irish population distribution by age for the 1979 and 1996 censuses, the latter being a middle year in our period of analyses. For comparison, the age distribution of the U.S. population from the 2000 census is also shown. The 1979 Irish population shows a typical high-fertility pattern, with a monotonically decreasing frequency with age. By 1996, there had been a shift, with a peak in the teen years. This shift suggests a population with decreasing fertility, similar to the pattern in the 2000 U.S. population with a peak in the years from the late 30s to early 40s.

There were substantial shifts in the age distribution of the Irish population during the last 25 years. Figure A.3 shows the changes in the total Irish population in 15-year age groups across the census years. There was a substantial decrease in the number of children (0–14 years) and a substantial increase in the middle-aged population (30–44 and 45–59 years). Although the total number of people 75 years and older remained a small fraction of the total population (4.8% in 1996) in all census years between 1981 and 2006, the absolute number increased substantially during this time (59% increase, from n = 131,897 to n = 202,378).

Another method by which to examine population changes and shifts over these same years is by use of birth cohorts, that is, following the same group forward as they age and examining the change in the size of each birth cohort across the time period. For example, because of the 5-year interval between censuses, those 0 to 9 years of age at the 1981 census would be 5 to 14 years old at the 1986 census. We could thus track groups defined by birth year

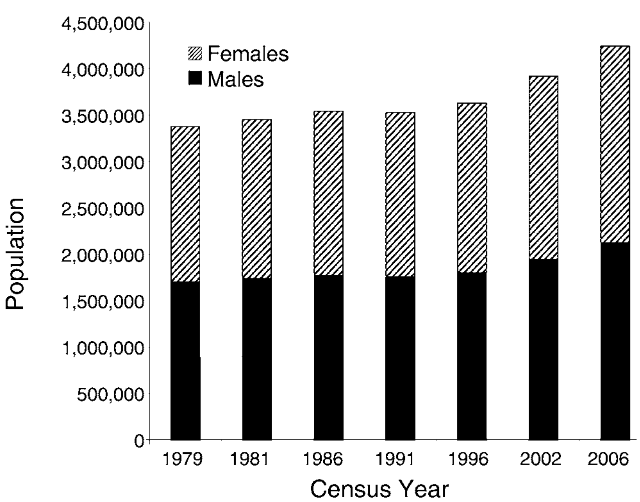


Figure A.1. Total Irish population by census year.

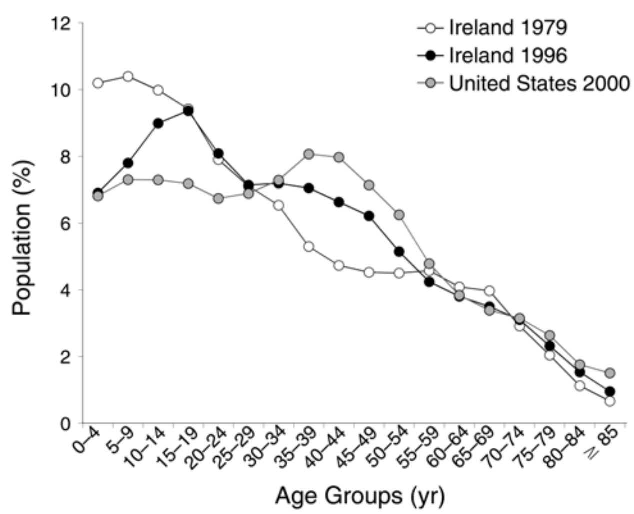


Figure A.2. Frequency distribution of Irish population by age groups for 1979 and 1996 census years compared with that of the 2000 U.S. census.

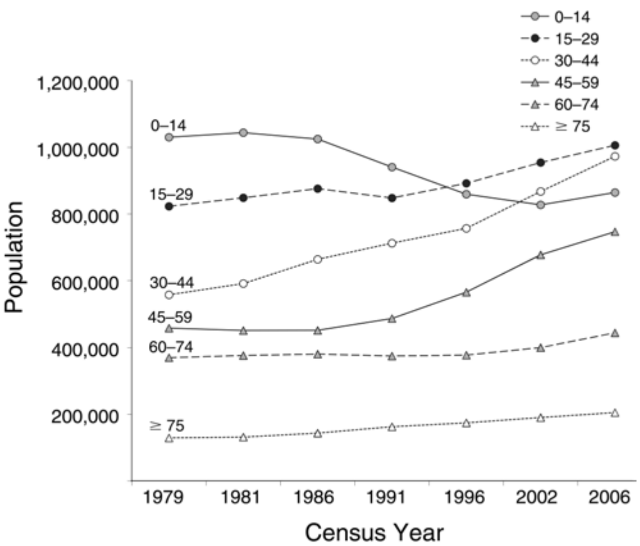


Figure A.3. Irish population by age groups and census year.

(birth cohort) as they aged across the census years. However, it should of course be noted that because the 2001 census was delayed for a year, the birth cohorts aged 6 years before the 2002 census and 4 years before the 2006 census.

Figure A.4 shows the population change for six birth cohorts followed over the censuses between 1981 and 2006. The ages of the 10-year birth cohorts at selected census years are indicated. For the oldest birth cohort (birth years 1922–1931; 50–59 years old in 1981) the population decreased as expected with increasing age and increasing rates of mortality across the census years. The three cohorts with ages from 20 to 49 years in 1981 remained fairly stable over this same period.

The most notable changes were in the two youngest cohorts, with ages from 0 to 19 years in 1981. These cohorts dropped substantially in the 1990s, as they entered their working years. This decrease reflected the emigration from Ireland during the late 1980s and early 1990s. In the late 1990s and early 2000, this population increased,

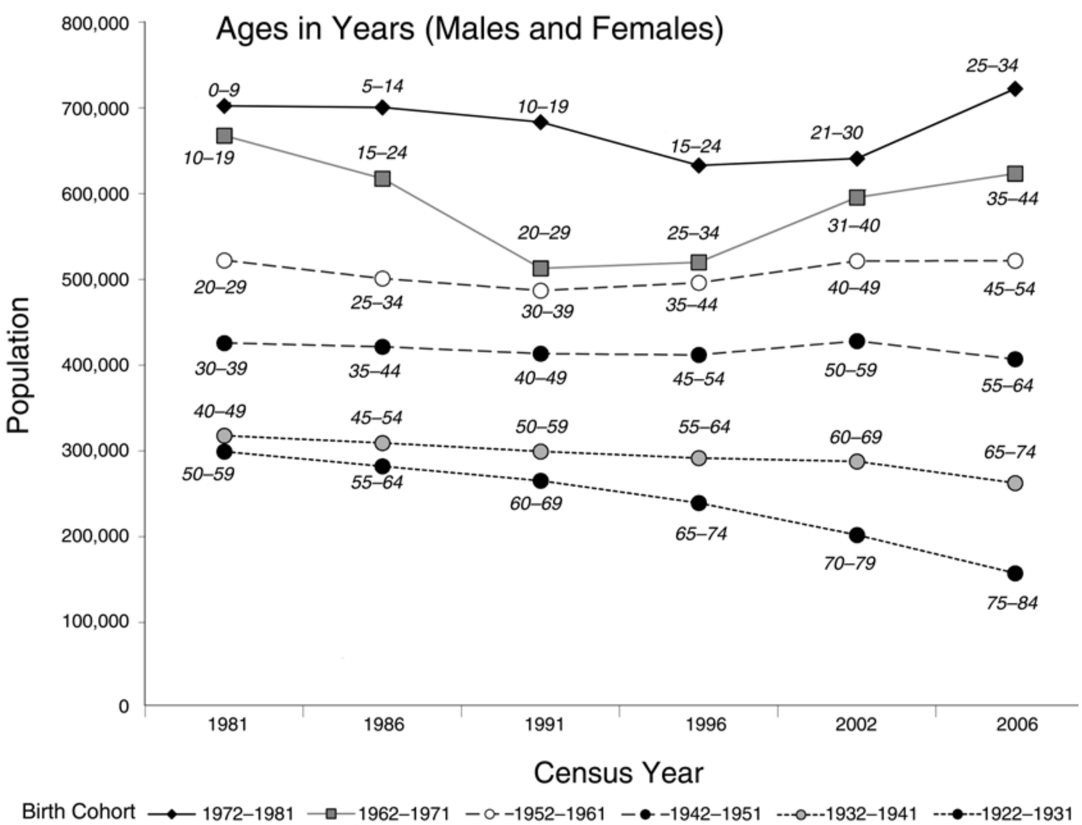


Figure A.4. Irish population by birth cohorts and census year.

reflecting immigration associated with the economic boom in Ireland known as the "Celtic Tiger."

These substantial shifts in age-specific total population illustrated the need to adjust carefully for age and sex (data not shown) in examining changes in rates of mortality and morbidity over this time period.

ADMINISTRATIVE DISTRICTS

The island of Ireland comprises four provinces (Ulster, Leinster, Munster, and Connaught) that are divided into 32 counties. The Republic of Ireland is made up of 26 of these counties and Northern Ireland of 6 counties. Figure A.5 shows the provinces and counties of Ireland.

Figure A.5. Irish counties and provincial boundaries.

The administrative and political districts of the Republic of Ireland are unique to the United Kingdom and might not be familiar to the general reader.

- A "borough" is an administrative district designating a self-governing township. In practice, however, the official use of the term varies widely.
- A "county borough" is a borough or city independent of county council control. The term was introduced in 1889 and is still used in Ireland. The Local Government Act 1972 (*https://en.wikipedia.org/wiki/Local_Government_Act_1972*) abolished them in England and Wales.
- An "urban district" is a type of local government district that covers an urbanized area. In Ireland, urban districts were created in 1898 by the Local Government (Ireland) Act 1898 (*https://en.wikipedia.org/wiki/Local_Government_%28Ireland%29_Act_1898*) and were renamed simply "towns" under the Local Government Act 2001 (*https://en.wikipedia.org/wiki/Local_Government_Act_2001*).

The number and boundaries of administrative counties in the Republic of Ireland were reformed in the 1990s.

- In 1994, county Dublin was broken into three administrative counties: Dun Laoghaire-Rathdown, Fingal, and South Dublin.
- The major urban centers of Cork, Galway, Limerick, and Waterford were separated from the towns and rural areas of their respective counties.

CITIES AND TOWNS AFFECTED BY COAL BANS

Coal sales were banned by a series of acts under the Air Pollution Control Act of 1987.

- On September 1, 1990, a ban was put into effect for the County Borough of Dublin (Air Pollution Act 1990).
- On October 1, 1995, a ban was put into effect for the County Borough of Cork (Air Pollution Act 1994).
- On October 1, 1998, a ban was put into effect for the County Borough of Limerick, the Urban District of Arklow, the Borough of Drogheda, the Urban District of Dundalk, the Borough of Wexford, and county Wexford (Air Pollution Act 1998).
- On October 1, 2000, a ban was put into effect in Celbridge in county Kildare, the County Borough of Galway, the Town of Leixlip, the Urban District of Naas, and the County Borough of Waterford (Air Pollution Act 2000).

Figure A.6 shows the locations of these cities and towns.

Figure A.6. Cities and towns affected by the coal bans of 1990 (Dublin), 1995 (Cork), 1998 (Dundalk, Drogheda, Arklow, Wexford, and Limerick), and 2000 (Leixlip, Celbridge, Naas, Waterford, and Galway).

POPULATIONS OF CITIES AND COUNTIES AFFECTED BY COAL BANS

For the current study, census population counts were abstracted from Central Statistics Office census documents and Web sites for the census years from 1981 to 2006 for the cities and towns affected by the bans and the surrounding counties (Table A.1). Table A.2 presents the codes used for each census to define the counties, county boroughs or cities, and towns. Table A.1 shows the total population of each of the county boroughs or cities and towns and their respective counties for each census. County boroughs are separate from the surrounding county, and the population of a county borough is not counted in the county population. On the other hand, the population of urban districts (including cities and towns) is included in the county population.

Table A.1. Population by Census Year of Cities, Towns, and Surrounding Counties Affected by the Coal Bans

Administrative District	1981	1986	1991	1996	2002	2006
1990 Ban						
Dublin County Borough	525,882	502,749	478,569	481,854	495,781	506,211
County Dublin	1,003,164	1,021,449	1,025,304	1,058,264	1,122,821	1,187,176
1995 Ban						
Cork County Borough	136,344	133,271	127,253	127,187	123,062	119,418
County Cork	402,465	412,735	410,369	420,510	447,829	481,295
1998 Ban						
Limerick City	60,736	56,279	52,083	52,039	54,023	52,539
County Limerick	161,661	164,569	161,956	165,042	175,304	184,055
Arklow	8,646	8,388	7,987	8,557	9,955	11,712
County Wicklow	87,449	94,542	97,265	102,683	114,676	126,194
Dundalk	25,663	26,669	25,843	25,762	27,385	29,037
Drogheda	23,247	24,086	23,848	24,460	28,333	28,973
County Louth	88,514	91,810	90,724	92,166	101,821	111,267
Wexford	15,364	15,365	15,393	15,862	17,235	18,163
County Wexford	99,081	102,552	102,069	104,371	116,596	131,749
2000 Ban						
Galway City	41,861	47,104	50,853	57,241	65,832	72,414
County Galway	172,018	178,552	180,364	188,854	209,077	231,670
Celbridge	4,583	7,135	9,629	12,289	16,016	17,262
Leixlip	9,306	11,938	13,194	13,451	15,016	14,676
Naas	8,345	10,017	11,141	14,074	18,288	20,044
County Kildare	104,122	116,247	122,656	134,992	163,944	186,335
Waterford	38,473	39,529	40,328	42,540	44,594	45,748
County Waterford	88,591	91,151	91,624	94,680	101,546	107,961

Table A.2. Census ID Codes of Cities, Towns, and Surrounding Counties Affected by the Coal Bans[a]

Census	1981	1986	1991	1996	2002	2006
1990 Ban						
Dublin County Borough	03	02	02	02	02	Dublin City
1995 Ban						
Cork County Borough	18	18	17	17	17	Cork City
County Cork	19	19	18	18	18	Cork
1998 Ban						
Limerick City	22	22	20	20	20	Limerick City
County Limerick	23	23	21	21	21	Limerick
Arklow	15–12	15–15	15–15	15–15	15–15	Arklow Legal Town
County Wicklow	15	15	15	15	15	Wicklow
Dundalk	10–11	10–11	10–11	10–11	10–11	Dundalk Legal Town
Drogheda	10–10	10–10	10–10	10–10	10–10	Drogheda Borough
County Louth	10	10	10	10	10	Louth
Wexford	14–15	14–18	14–18	14–18	14–18	
County Wexford	14	14	14	14	14	Wexford
2000 Ban						
Galway County Borough	29–05	37	26	26	26	Galway City
County Galway	29	29	27	27	27	Galway
Celbridge	06–07	06–07	06–07	06–07	06–07	Celbridge
Leixlip	06–10	06–10	06–10	06–10	06–10	Leixlip Legal Town
Naas	06–15	06–15	06–15	06–15	06–15	Naas Legal Town
County Kildare	06	06	06	06	06	Kildare
Waterford	27	27	24	24	24	Waterford City
County Waterford	25	25	25	25	25	Waterford

[a] Available from *www.cso.ie/en/census/*. Census ID Codes of Cities, Towns, and Surrounding Counties are subject to change as described in Appendix A.

APPENDIX B. Air Pollution

In each city or town affected by coal bans, BS and SO_2 concentrations were measured by the local authorities using the British Standards Institute methods. BS was measured by reflectometry (BS1747 method) (British Standards Institute 1969) and is an indirect measure of fine particle mass. SO_2 was measured by total gaseous acidity (British Standards Institute 1969, 1983). The Irish EPA compiled these observations and provided the data for these analyses.

Dublin and Cork, affected by the 1990 and 1995 bans, respectively, each had six monitors consistently measuring BS and SO_2 (Table B.1). Of the cities affected by the 1998 ban, Limerick had four monitors, Dundalk had two, and Drogheda and Arklow each had one. BS was measured at one monitor in Wexford before the 1998 ban, but these measurements were discontinued after the ban was introduced. No SO_2 measurements were made either before or after the introduction of the 1998 ban. Of the cities affected by the 2000 ban, Leixlip, Naas, and Celbridge each had one monitor, Waterford had two, and Galway had three.

Table B.1. Locations of BS and SO_2 Monitoring Sites[a]

1990 Ban
Dublin
Royal Dublin Society
Mountjoy Square
Clontarf
Herbert Street
Bluebell
Finglas
1995 Ban
Cork
Blackpool Fire Station
Environment Lab
St. Finbarrs Cemetery
St. Josephs Cemetery
Mahon House
Heatherton Park
1998 Ban
Limerick
Southill
Moyross
Todds
Ballykeeffe
Dundalk
Town Hall
Sports Centre
Drogheda
Drogheda (Fair Green)
Wexford
Wexford town
Arklow
Arklow
2000 Ban
Galway
Public Analyst's Laboratory
Waterworks
Sandy Road
Waterford
Tycor
The Palace
Naas
Naas
Leixlip
Leixlip
Celbridge
Celbridge

[a] SO_2 was measured as total gaseous acidity.

APPENDIX C. Deaths

DEATH REGISTRATION

Death data are collected in Ireland under the Vital Statistics Act of 1952 and Section 73 of the Civil Registration Act of 2004. Details on how deaths are registered can be found at the Citizens Information Board Web site (*www.citizensinformation.ie/en/death/after_a_death/death_cert.html*). Approximately 30,000 deaths occur in Ireland each year. It is required to register deaths within 3 months of the date of death. Written permission from the Registrar General is required to register deaths more than one year after the date of death. Approximately 400 deaths are registered late in Ireland each year.

A copy of a death certificate form is shown in Figure C.1. Principal information collected on the death certificate includes: date of death, residence address of deceased at time of death, place of death, cause of death based on ICD-9 code, occupation of deceased, age of deceased, sex of deceased, and marital status of deceased.

Stillbirths are registered separately under the Vital Statistics Act 1952 (Stillbirth Act 1995) and Section 73 of the Civil Registration Act 2004. Approximately 300 stillbirths occur in Ireland each year. For these analyses, we have not included stillbirths.

LOCATION CODING

Death certificates include the residence address of the deceased at the time of death. The residence address is reported as a three-character code indicating the city, town, or county (Table C.1). The Registration Stamp (REGSTMP in Figure C.1; two- and four-digits Registry Stamps are shown in Table C.1) identifies the office where the death was registered and recorded. Because a death can be registered with any Registrar, irrespective of where the death occurred, we used address codes to establish the locations of deaths.

TRENDS IN DEATHS

Figure C.2 shows the total number of deaths and the death rate (per 1,000 population of the estimated population) in Ireland between 1990 and 2006. Note in particular the substantial decrease in the death rate since the mid-1990s.

CAUSE OF DEATH

Primary and contributing cause of death are reported on the death certificates. Cause of death is coded according to the ICD-9. Table C.2 shows the number of deaths from 1998 to 2006 for general and specific causes of death as reported by the Central Statistics Office (*www.CSO.ie/en/statistics/birthsdeathsandmarriages/deathsfromprincipalcausesintheyears1998to2006/*). The leading causes of death were circulatory diseases, malignant neoplasms, and respiratory diseases. Of deaths from circulatory disease, the subcategories with the largest number of deaths were ischemic heart and cerebrovascular disease. Of deaths from malignant neoplasms, the subcategories with the largest number of deaths were cancers of the lung, trachea, and bronchus. Of deaths from respiratory disease, the subcategories with the largest number of deaths were pneumonia and COPD.

Death Registration Form

To register a death and obtain a Death Certificate, Part 1 and Part 2 (overleaf) of this form must be completed and brought by the qualified informant to their nearest Registrar's Office.

PART 1

Medical Certificate of Cause of Death - To be completed by a Registered Medical Practitioner

DETAILS OF DECEASED

Forename(s):.. Home Address: ....

Surname:.. ....

Date of Birth: ☐ / ☐ / ☐ Age...................... ....

Date of Death: ☐ / ☐ / ☐

Place of Death (in full): ....

Last seen alive by me on: / /

Whether seen after death by me (Answer "yes" or "no" in all cases) ☐ yes ☐ no

If the deceased was female, was she known to have been pregnant at the time of death, or within the previous 42 days ? (Answer "yes" or "no" in all cases) ☐ yes ☐ no

● *Please use BLOCK CAPITALS*

MEDICAL CAUSE OF DEATH DETAILS

		Approximate interval between onset and death
	I	
Disease or Condition directly leading to death (This does not mean the mode of dying, e.g. heart failure, asthenia etc. It means the disease which caused death.)	(a) .... due to (or as consequence of)	
Antecedent Causes (morbid conditions if any, giving rise to the above cause, stating the underlying condition last.)	(b) .... due to (or as consequence of)	
	(c)..	
	II	
Other Significant Conditions contributing to the death, but not related to the disease or condition causing it.	....	

DETAILS OF REGISTERED MEDICAL PRACTITIONER

Forename:.. Business Address ....

Surname ....

Registered Qualification: ....

Signature:.. Date .... Telephone No......................................

Figure C.1. An Irish death registration form. (*Figure continues next page.*)

To register a death and obtain a Death Certificate, Part 1 (overleaf) and Part 2 of this form must be completed and brought by the qualified informant to their nearest Registrar's Office.

PART 2

PERSONAL DETAILS OF DECEASED – To be completed by the Qualified Informant – (see note below)

For Official Use

Forename(s):.. Home Address: .... ☐☐☐ home

Surname:.. ....

Birth Surname:.. .... ☐☐☐ age

Date of birth: ☐☐ / ☐☐ / ☐☐☐☐ ....

Age:.. PPS Number: ☐☐☐☐☐☐☐ - ☐☐ ☐☐ infant

(Note: If age at death is less than 1 year insert age in hours, days, weeks, months, as appropriate).

Date of Death: ☐☐ / ☐☐ / ☐☐☐☐ Male ☐ Female ☐ ☐ sex

Place of Death (in full): .... ☐ plocc

Marital Status: Never Married ☐ Married ☐ Married - Separated ☐ Widowed ☐ Divorced ☐ ☐ mar

Occupation: .... Retired ☐ ☐☐ occ

Occupation of spouse if married or widowed:.. Retired ☐

If under 15 years,

Occupation of Parent / Guardian 1.. Retired ☐ cod

Occupation of Parent / Guardian 2.. Retired ☐

Details of Qualified Informant (see note below)

Forename:.. Address:..

Surname:.. ....

Qualification to Act as Informant see note below:.. ....

....

I hereby declare that the above details are to the best of my knowledge correct.

Signature: ....

Note: A Qualified Informant is a person who has knowledge of the particulars required to register a death **(a)** the nearest relative present at death or in attendance during the last illness of the deceased **(b)** other relatives living in the district **(c)** each person present at death **(d)** the occupier of the house or administrator of the hospital in which the death occurred **(e)** the person finding the body or the person arranging for the funeral.

For Registrar's Use Only

State whether certified ☐ or uncertified ☐ inquest ☐ or post mortem ☐

Complete Part A or B

A : Computerised Offices: If notification is to be entered electronically enter the system notification number in the adjacent box: ☐

B : Non-Computerised Offices: If the notification in not being entered electronically then the Information in the section below should be completed, and this form should then be sent to the Central Statistics Office

Date of Registration:..

Entry Number in Register:.. **Signature of Registrar:** ....

REGSTMP

Figure C.1 (*Continued*).

Table C.1. City, Town, and County Address Codes and Registration Stamps for Death Certificates

			Registration Stamp	
City or Town (County)	Regulation Language	Address Code	2 Digit	4 Digit
1990 Ban				
Dublin (Dublin)	"County Borough of Dublin"	0 Dublin 00 Dublin (City) 000 Dublin (City)	0 1 2 3 4	00&&, 00--, Etc to 0429
1995 Ban				
Cork (Cork)	"County Borough of Cork"	21 Cork (City) 210 Cork (City) 22 County Cork	21	2100 : 2133
1998 Ban				
Limerick (Limerick)	"County Borough of Limerick"	26 Limerick (City) 260 Limerick (City)	26	2600 : 2604
Arklow (Wicklow)	"Urban District of Arklow"	1- County Wicklow 1-0 Arklow		Jan-41
Drogheda (Louth)	"Borough of Drogheda"	15 County Louth 150 Drogheda		1520 : 1521
Dundalk (Louth)	"Urban District of Dundalk"	15 County Louth 151 Dundalk		1542 and 1545
Wexford (Wexford)	"Borough of Wexford and County of Wexford"	19 County Wexford 192 Wexford		1965 : 1966

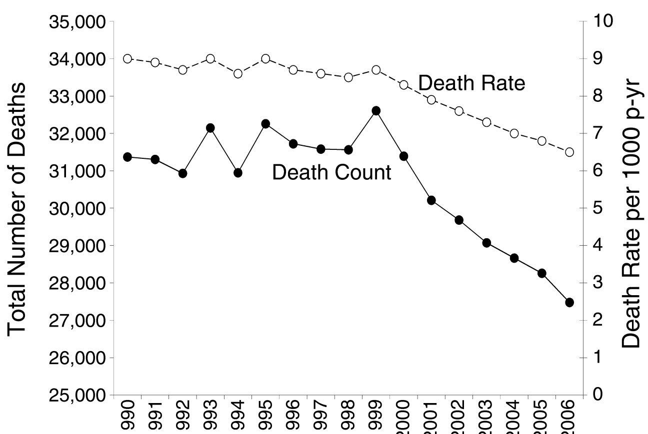


Figure C.2. Total number of deaths and death rate in Ireland between 1990 and 2006 (Central Statistics Office, *www.cso.ie/en/statistics/births deathsandmarriages*).

Table C.2. Deaths by Cause and Year as Reported by the Central Statistical Office

Causes[a]	1998	1999	2000	2001	2002	2003	2004	2005	2006
Malignant Neoplasms									
Stomach	357	352	352	336	335	324	305	337	325
Other digestive organs and peritoneum	1924	2022	1975	2021	1992	2003	2078	1988	2044
Trachea, bronchus, and lung	1523	1449	1568	1478	1469	1574	1609	1587	1608
Breast	608	649	669	677	608	647	666	699	674
Genitourinary organs	1198	1192	1234	1281	1267	1267	1307	1339	1382
Lymphatic and hematopoietic tissue	676	673	687	665	661	644	688	656	687
Other	1194	1204	1181	1174	1171	1144	1175	1143	1148
Total	7480	7541	7666	7632	7503	7603	7828	7749	7868
Diseases of the Circulatory System									
Hypertensive disease	259	289	266	239	267	293	317	348	365
Ischemic heart disease	7240	7059	6589	6163	6107	5583	5485	5141	4860
Cerebrovascular disease	2572	2807	2738	2584	2394	2276	2106	2037	1903
Other diseases of the circulatory system	3170	3225	3073	2900	2884	2886	2758	2623	2534
Total	13241	13380	12666	11886	11652	11038	10666	10149	9662
Diseases of Respiratory System									
Pneumonia	2268	2697	2474	2240	2182	2209	1968	1943	1913
Bronchitis, emphysema, and asthma, including COPD	1902	1910	1645	1477	1436	1450	1384	1323	1259
Other diseases of the respiratory system	664	784	744	755	726	795	727	782	806
Total	4834	5391	4863	4472	4344	4454	4079	4048	3978
Injury and Poisoning									
Motor vehicle accidents including non-traffic accidents	448	414	407	391	363	309	319	344	285
Other injury and poisoning	1166	1189	1171	1257	1240	1292	1275	1235	1007
Total	1614	1603	1578	1648	1603	1601	1594	1579	1292
Other									
Diabetes mellitus	412	455	412	398	418	418	459	471	516
Diseases of the digestive system	990	1044	1050	1047	1025	1002	1008	1033	1012
Congenital anomalies	202	199	200	192	202	211	165	181	162
Certain causes of perinatal mortality	122	129	125	124	111	109	131	87	110
Remainder	2668	2866	2831	2813	2825	2638	2735	2963	2879
Total	4394	4693	4618	4574	4581	4378	4498	4735	4679
Total Number of Deaths	31563	32608	31391	30212	29683	29074	28665	28260	27479

[a] Causes in **boldface** are principal categories; the rest are subcategories.

DIRECTLY STANDARDIZED MORTALITY RATES

Because of the changing age and sex distribution over time described above, any comparison between mortality rates might be confounded by age and sex. Therefore, we calculated directly standardized cause-specific mortality rates using the total population of Ireland in 1996 as the age standard. It should be noted that there were up to 18 5-year age groups (0–4, 5–9, 10–14, 15–19, … 70–74, 75–79, 80–84, and ≥85). The age standardization can include all 18 age groups, that is, the total or any subset, for example, 0–74 and ≥75 years).

$$RATE_d^{Cause} = \sum_{j=1}^{2}\sum_{i=1}^{N}(N_{i,j,d}^{Cause} / POP_{i,j,d}^{City}) \times (POP_{i,j}^{Ireland} / POP_{Total}^{Ireland})$$

where

$RATE_d^{Cause}$ = admission rate for *Cause* on date d;

$N_{i,j,d}^{Cause}$ = number of deaths for *Cause* for sex i, age group j, and date d;

$POP_{i,j,d}^{City}$ = interpolated census population for *City* for sex i, age group j, and date d;

$POP_{i,j}^{Ireland}$ = Irish population for sex i, age group j, for 1996 census; and

$POP_{Total}^{Ireland}$ = total Irish population for age groups being considered $(j = 1 \text{ to } N)$, such that

$$= \sum_{i=1}^{2}\sum_{j=1}^{N} POP_{i,j}^{Ireland}$$

APPENDIX D. Hospital Admissions

HOSPITAL IN-PATIENT ENQUIRY SCHEME

The Hospital In-Patient Enquiry (HIPE) scheme is a computer-based system designed to collect demographic, clinical, and administrative data on discharges and deaths from acute-care hospitals nationally in Ireland. HIPE is the only source of morbidity data available nationally for acute-care hospital services in Ireland. As of 1992, 53 acute-care public hospitals participated in the HIPE system; in 2001 this number had increased to 62 hospitals.

The HIPE scheme was started on a pilot basis in 1969 and then expanded and developed as a national database of coded discharge summaries from the 1970s onward. In 1990 the management of the HIPE scheme was transferred from the Health Research Board to the Economic and Social Research Institute (ESRI, *www.esri.ie*). ESRI and the Health Service Executive (*www.hse.ie*) manage this national database.

DATA COLLECTED BY THE HIPE SYSTEM

The data collected by the HIPE system (see sample form, Figure D.1) can be logically grouped into demographic, clinical, and administrative data or variables.

Demographic data:

- Date of birth, sex, marital status, and area of residence by county or country

Clinical data:

- One principal diagnosis and up to five secondary diagnoses
- One principal procedure and up to three (optional) additional procedures

Administrative data:

- Patient's name (not exported outside the hospital)
- Hospital number or chart number (unique to hospital of discharge)
- Dates of admission and discharge
- Dates of principal and first operation; day case (elective admission, not overnight) indicator
- Source of admission: booked, emergency by type or transfer
- Discharge destination: home, transfer, self-discharge, or death
- Public or private status of patient on admission and discharge
- General Medical Service status (medical cardholder or not)
- Admitting consultant

Each HIPE discharge record represents one episode of care and patients might have been admitted to hospital(s) more than once with the same or different diagnoses. HIPE records therefore facilitate analyses of hospital activity rather than incidence or prevalence of disease. All of the data collected are coded in a standardized format for computer input and for subsequent analysis of the data. The most specialized aspect of this process is the coding of the diagnoses and procedures performed.

CODING OF DIAGNOSES AND PROCEDURES

As of January 1, 1990, the clinical modification version of the ninth revision of the International Classification of Diseases, known as ICD-9-CM, has been in use in Ireland for coding both diagnoses and procedures in HIPE. The October 1, 1988, version of ICD-9-CM was in effect from 1990 through 1994. The October 1, 1994, version of ICD-9-CM was in effect from 1995 through 1998. The October 1, 1998, version of the ICD-9-CM was in effect beginning in 1999.

The source document for coding for the HIPE system is the medical record or chart, which is reviewed in full. Each hospital admission is reported to HIPE. ESRI took over management of HIPE in 1990.

Data on daily hospital admissions for cardiovascular (ICD-9 390–459), respiratory (ICD-9 460–519), and digestive (ICD-9 520–579) discharge diagnoses, based on HIPE reports, was obtained from ESRI. The data obtained from ESRI included up to three diagnoses coded in accordance with ICD-9. Table D.1 presents a summary of the counts by diagnoses codes for the admissions data provided by ESRI.

ESRI

Hospital In-Patient Enquiry (HIPE)

Summary Sheet

For use with W-HIPE data entry software - **for discharges up to the 31st December 2001**

Basic Patient Discharge Information

Medical Record Number		**Source of Admission**		
Admission Date	/ /	**Transfer From**		**Em.**
Discharge Date	/ /	**Discharge Code**		
Date of Birth	/ /	**Transfer To**		**Em.**
Sex				

Patient Details

Name		**Marital Status**	
Medical Card		**GMS Number**	
Area of Residence		**Discharge Status**	
Admission Status		**Day Case**	
		Admitting Consultant	

For use on discharges up to 31st December 2001

PDX = That condition established after study to be chiefly responsible for occasioning admission to hospital for care

	Diagnosis Code	**Description**	**Consultant**	**Specialty**
(1)		Principal		
(2)				
(3)				
(4)				
(5)				
(6)				

Procedures / Operations

	Code	**Description**	**Consultant**
(1)		Principal	
(2)			
(3)			
(4)			

Date of 1st Procedure / / **Date of Principal Procedure** / /

HIPE Unit, ESRI, Feb '01

Case Entered on pc Comment: ____________

Source: HIPE Unit, ESRI, 4 Burlington Road, Dublin 4. Tel 01-6671525 Fax 01-6686231

Figure D.1. A HIPE data collection form.

Table D.1. Primary Discharge Diagnosis Codes for ESRI Hospital Admissions Data

ICD-9 Code	Disease Category	Counts	Percentage of Total
390–459	**Diseases of the Circulatory System**	**105,359**	**33**
390–392	Acute rheumatic fever	36	0
393–398	Chronic rheumatic heart disease	195	0
401–405	Hypertensive disease	4,455	4
410–414	Ischemic heart disease	37,309	35
415–417	Diseases of pulmonary circulation	2,237	2
420–429	Other forms of heart disease	30,357	29
430–438	Cerebrovascular disease	18,823	18
440–448	Arteries, arterioles, and capillaries	3,920	4
451–459	Veins and lymphatics, and other diseases of the circulatory system	8,027	8
460–519	**Diseases of the Respiratory System**	**126,302**	**39**
460–466	Acute respiratory infections	33,492	27
470–478	Other diseases of the upper respiratory tract	2,632	2
480–487	Pneumonia and influenza	23,239	18
490–496	Chronic obstructive pulmonary disease and allied conditions	40,323	32
500–508	Pneumoconioses and other lung diseases due to external agents	884	1
510–519	Other diseases of respiratory system	25,732	20
520–579	**Diseases of Digestive System (520–579)**	**90,882**	**28**
520–529	Diseases of oral cavity, salivary glands, and jaws	1,525	2
530–537	Diseases of esophagus, stomach, and duodenum	17,495	19
540–543	Appendicitis	14,103	16
550–553	Hernia of abdominal cavity	3,366	4
555–558	Noninfectious enteritis and colitis	16,380	18
560–569	Other diseases of intestines and peritoneum	19,300	21
570–579	Other diseases of digestive system	18,713	21

CODING OF RESIDENCE

The patient's residence address is not recorded in HIPE. The area of residence is coded only at the county or county borough level (see Figure D.1).

COMPLETENESS OF REPORTING

As noted above, ESRI took responsibility for collecting the HIPE hospital admissions data in 1990. In 2007, ESRI reported that admissions were underreported before 1995 (ESRI 2007). Figure D.2 shows a comparison of two estimates of the numbers of hospital admissions reported in Cork City hospitals from 1991 to 2006 and illustrates the underreporting by the HIPE system before 1995 (ESRI 2007). By 1995, coverage of HIPE records was estimated to be more than 90% (Figure D.3). ESRI recommended not using HIPE data for trends analyses before 1995. This recommendation precluded using HIPE records to assess the effect of the 1990 coal ban in Dublin and the 1995 coal ban in Cork. Our interest in assessing the effects of the 1995 and 1998 coal bans on hospital admissions required us to consider approaches to adjust for underreporting.

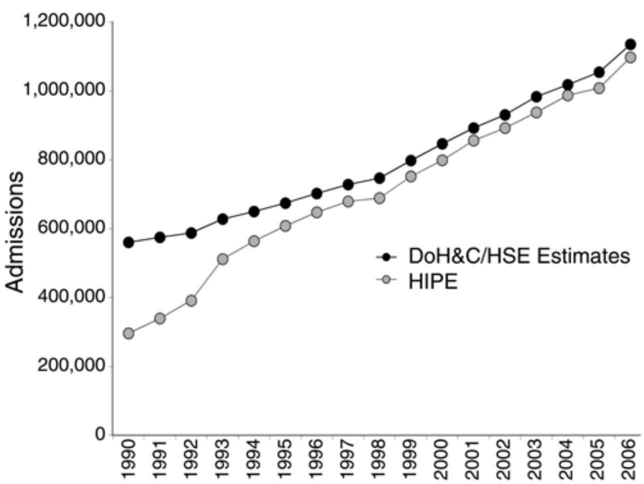


Figure D.2. Hospital admissions by year for Cork County Borough hospital as estimated by the Department of Health and Children/Health Service Executive (DoH&C/HSE) and as reported to HIPE (ESRI 2007).

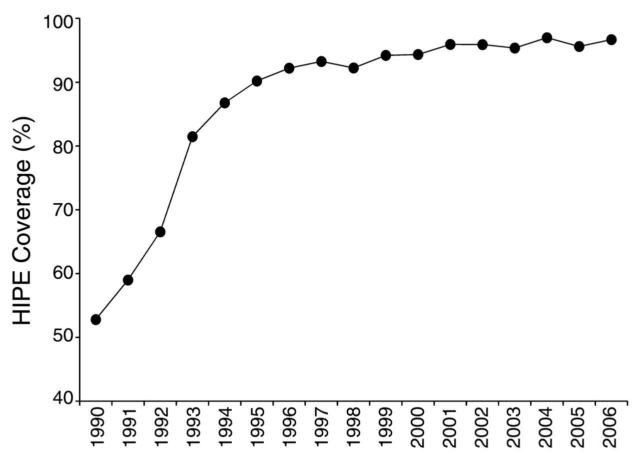


Figure D.3. Estimated HIPE percentage coverage of hospital records by year (ESRI 2007).

APPENDIX E. Influenza Outbreaks

We identified outbreaks of influenza and pneumonia infections in accordance with the surveillance methods of the U.S. Centers for Disease Control and Prevention (Serfling 1963; Serfling et al. 1967). For each week of the year, we calculated the percentage of total deaths attributed to pneumonia and influenza. A seasonal pattern (annual and semiannual sines and cosines) was fitted to this overall weekly pattern plus sine and cosine terms for the 24-year trend in the means (see Figure E.1). The 95th percentile was defined by the estimated weekly mean plus 1.645 times the standard deviation of the residuals. Influenza episodes were defined as a period of at least 2 weeks in

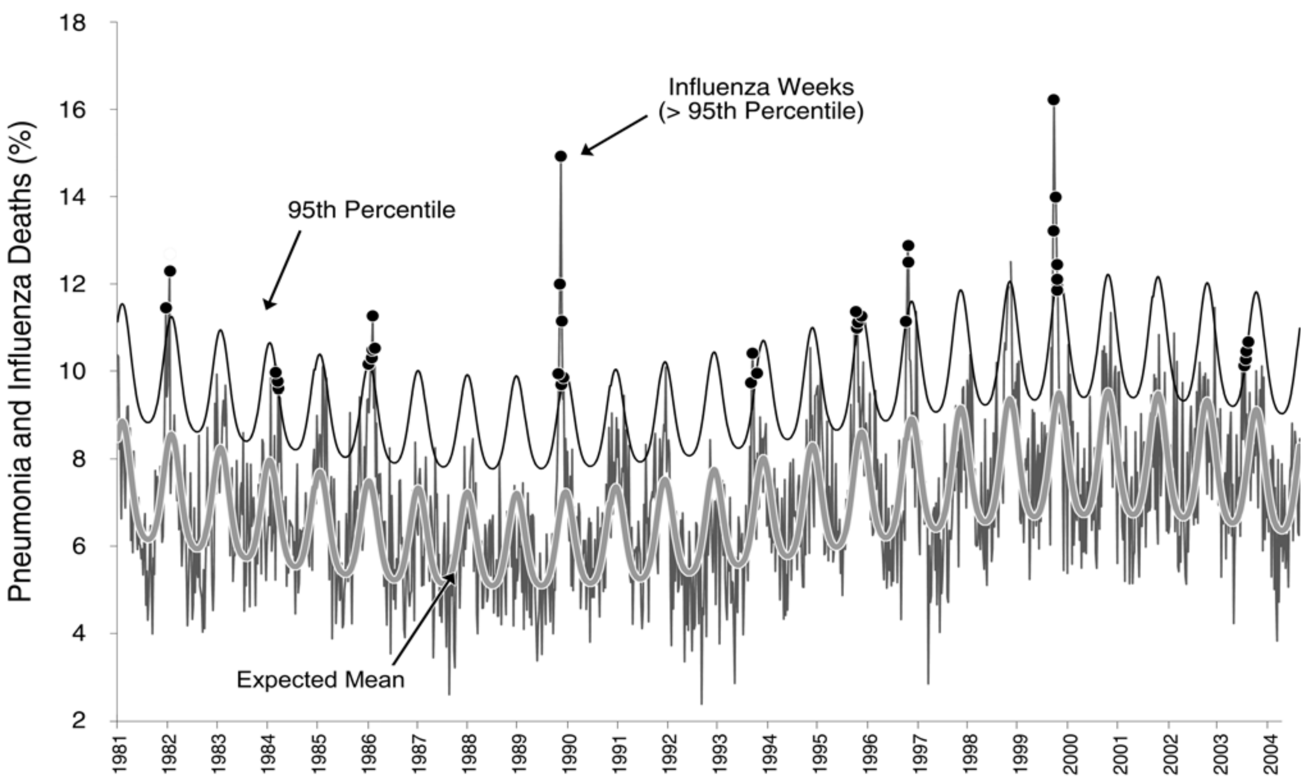


Figure E.1. Weekly percentage of deaths from pneumonia and influenza in Ireland.

which the percentages of deaths in Ireland from pneumonia and influenza were greater than the 95th percentile of expected deaths. Using this approach, nine influenza outbreak episodes were identified (Table E.1).

Table E.1. Influenza Outbreaks[a]

Begin	End	Number of Weeks
Jan. 18, 1982	Jan. 31, 1982	2
April 9, 1984	April 29, 1984	3
Feb. 24, 1986	March 30, 1986	5
Dec. 18, 1989	Jan. 28, 1990	6
Nov. 15, 1993	Dec. 5, 1993	3
Dec. 18, 1995	Jan. 14, 1996	4
Jan. 6, 1997	Jan. 26, 1997	3
Dec. 27, 1999	Feb. 6, 2000	6
Oct. 27, 2003	Nov. 23, 2003	4

[a] Outbreaks were identified as 2-week periods with percentage of pneumonia and influenza deaths above the expected 95% percentile.

Influenza epidemics in Ireland are currently monitored as part of the European Influenza Surveillance Scheme. However, this surveillance system only began in Ireland during the 1999–2000 season and thus was not helpful for the analyses of mortality and morbidity in the period of interest, that is, the 1980s and 1990s. The European Influenza Surveillance Scheme reported “Low” influenza reporting since 1999 and only two periods of “Medium” influenza (February 17 to March 2, 2003, and October 20 to December 14, 2003). These reports are consistent with the low level of influenza activity detected by the expected 95th percentile method and match the October–November 2003 episode. The episode identified by the European Influenza Surveillance Scheme in late February 2003 did not meet our definition of an influenza episode (described above).

The influenza epidemics identified before 1999 were found to match influenza periods in England and Wales identified by surveillance data from sentinel general practices (Fleming et al. 1999).

APPENDIX F. Weather

The Irish Meteorological Service (Met Éireann) measures daily maximum and minimum temperatures (°C), mean daily relative humidity (%), and mean daily barometric pressure at five meteorologic stations (Cork, Dublin, Knock, Rosslare, and Shannon) in Ireland (Figure F.1).

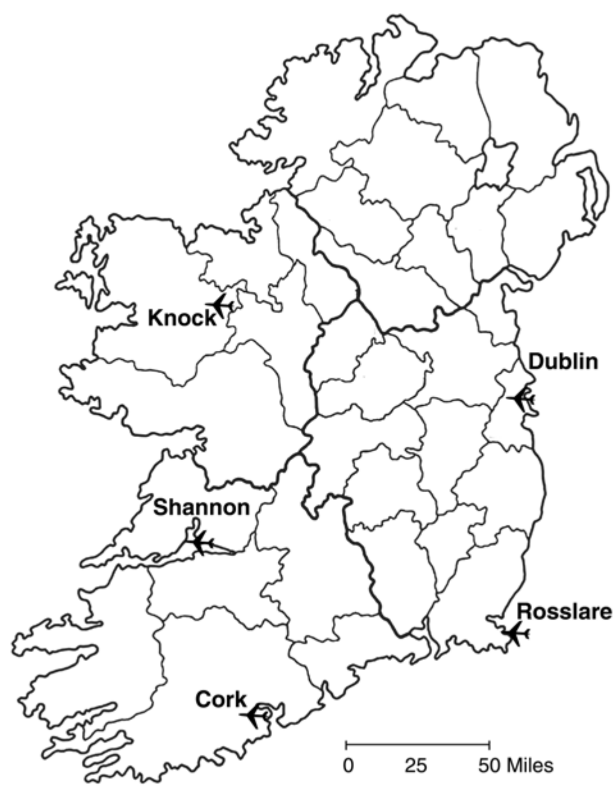


Figure F.1. Locations (indicated by airplane icons) of Irish Meteorological Service (Met Éireann) stations.

APPENDIX G. Simulation Analysis: Control of Long-Term Trends

Quantifying the health benefits associated with the introduction of air pollution controls in the presence of substantial long-term trends in health indicators can be a challenge. In our previous analyses of the effects of the 1990 coal ban in Dublin (Clancy et al. 2002) we adjusted in Poisson regression for mortality rates in the rest of Ireland to adjust for secular trends in mortality. In our initial analyses of the effects of the subsequent coal bans in the Midlands counties, we unexpectedly found effects of each of the coal bans in these presumably unaffected counties, after adjusting for mortality in the Coastal counties. To investigate the potential for bias in these regressions we undertook a simulation analysis of the possibility of bias in the assessment of the effects of an intervention by long-term secular trends in the mortality data.

SIMULATED MORTALITY TIME SERIES

We assumed a daily time series of mortality rates over 8 years with a mean of 10 deaths per 1000 p-yr with a sinusoidal annual pattern, Poisson variation about the expected value, and no trend over time. We then assumed that after 4 years there was a 20% decrease in deaths, that is, effect of the ban ("Ban, No Trend," Figure G.1). Further, we assumed a time series from a comparable area, with the same characteristics but no step-change, which we used as a reference for adjusting the underlying temporal patterns ("Reference, No Trend," Figure G.1).

ADJUSTMENT OF REFERENCE TIME SERIES (COVARIATE MODEL)

Applying the Poisson regression model to the "No Ban" series estimating the effect of a posited ban after 4 years, adjusting for the "Reference" series as a covariate (that is, on the right side of the equation), we got a coefficient of effectively 1.0, that is, no effect or no change (0%). Repeating this simulation 100 times, we found a mean effect of the "Non-Ban" of 0% ($P = 0.96$, Table G.1). Applying the Poisson model to the "Ban" time series, adjusting for the "Reference" time series as a covariate, we found the expected 20% decrease in mortality averaged over 100 simulations ($P < 0.00001$, Table G.1).

Alternatively, we assumed that we had a long-term linear decline in these time series, for example, −0.001 death/1000 person/year/day (Figure G.1). Applying the Poisson regression to the "Non Ban" with trend, we found a statistically significant decrease associated with the "Non-Ban" event (−10.8%, $P < 00001$, Table G.1). Similarly, when we applied the Poisson regression model to the simulated "Ban" time series with trend, adjusting for the "Reference" time series as a covariate, we found an estimated decrease of −28.7% in mortality (Table G.1), that is, more than the true value of 20%. If we assumed a larger trend in the time series (−0.002), there was larger bias for both the "No Ban" and "Ban" series (Table G.1). Thus it appeared that there was a bias in the covariate regression approach proportional to the long-term time trend in the underlying time series. Note that there was a substantial decrease in Irish mortality rates over the course of these analyses (see, for example, Figure 6 in the Investigators' Report). This time trend was largest for cardiovascular deaths and smaller for respiratory and other causes of death. The trend implied the greatest bias would be seen in the cardiovascular event analyses.

FIXED ASSOCIATION WITH REFERENCE TIME SERIES (OFFSET MODEL)

An alternative approach is to assume a fixed relationship with the reference mortality rates. This can be accomplished by specifying the reference death rate as an "Offset" in the Poisson regression. When we repeated the simulations using the offset approach (Table G.1), we found no bias in either the case with no trend (−19.9%) nor with a time trend in the mortality data (−20.3%).

SMOOTHING THE REFERENCE TIME SERIES

We assessed the effect of applying a LOESS smooth to the reference data in the simulated data. We adjusted for the reference time series with the covariance and the offset models in the Poisson regression for the effects of assumed bans with no smooth (0.00) and various levels of smoothing (0.01, 0.05, and 0.10). Table G.2 shows the average results from 100 repetitions of the simulation for the covariance and offset adjustments with increasing assumed secular trends in the underlying rates and the various degrees of smoothing.

For the covariate model, in the absence of a secular trend, there was no bias in the estimated effect for no ban effect (0%) or an assumed 20% ban effect. This was true irrespective of the amount of smoothing. There was a very slight increase in the estimated standard errors with increasing smoothing.

In the presence of a secular trend, there was the previously observed positive bias in the estimated ban effect with covariate adjustment of the raw (not smoothed)

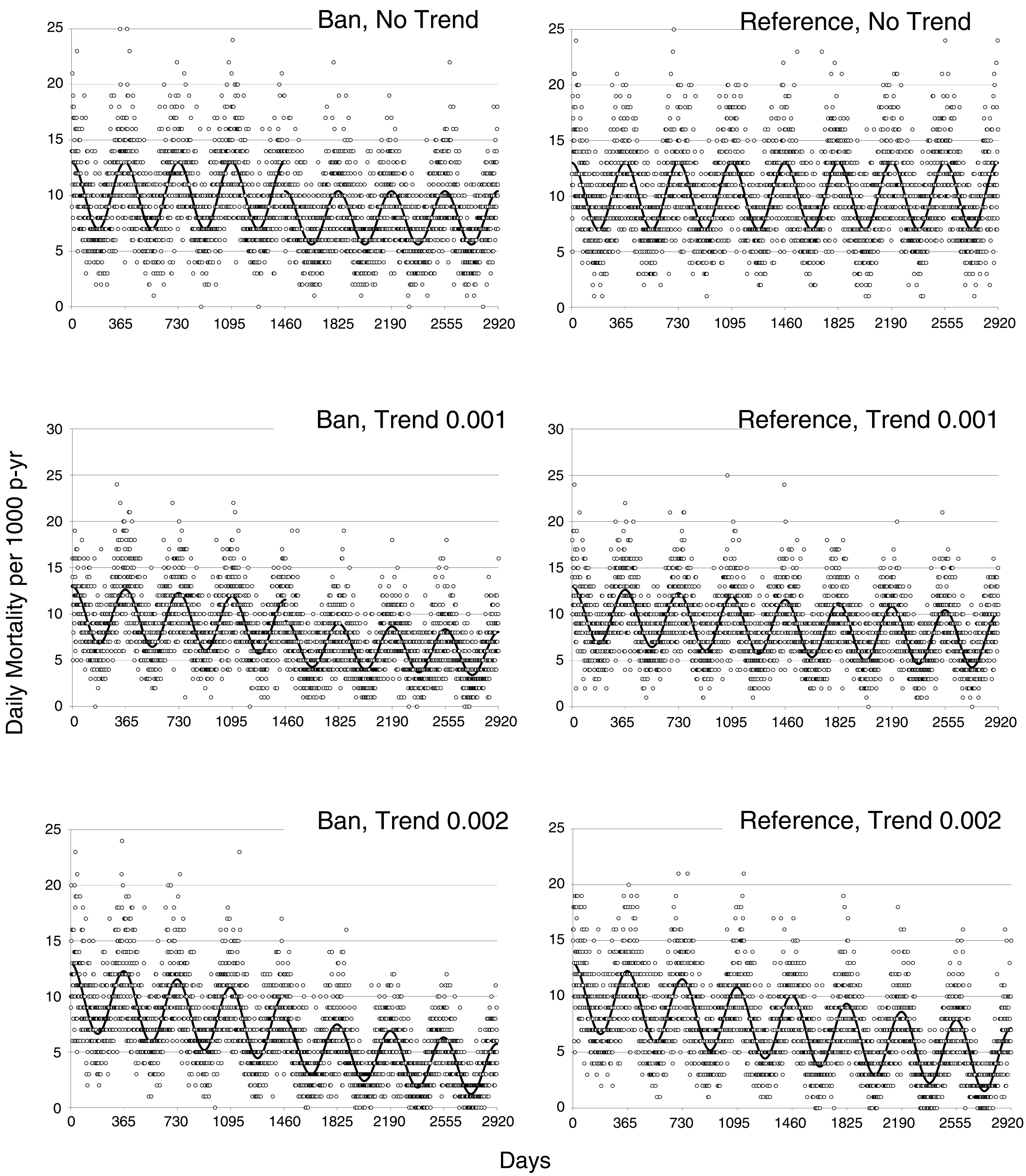


Figure G.1. Simulated daily mortality rates over 8 years, assuming Poisson distributions (dots) around assumed truths (lines). Left panels show an assumed 20% ban effect with either no trend over time or a linear decrease over time with trends = 0.001 and 0.002. Right panels show the same assumptions but in a comparison community with no effect of the ban.

Table G.1. Estimated Percentage Changes in Daily Mortality After a Hypothetical Coal Ban in the Middle of a Daily Mortality Time Series Simulated by Poisson Regression, Adjusting for Reference Mortality as a Covariate (Covariance Model) or as an Offset Term (Offset Model)[a]

Ban Effect[b]	Trend	Estimate (%)	95% CI	*P*
Covariance Model				
0%	0	0	−3 to 3	0.96
0%	0.001	−10.8	−13 to −8	< 0.00001
0%	0.002	−22	−25 to −20	< 0.00001
Covariance Model				
20%	0	−20	−22 to −18	< 0.00001
20%	0.001	−28.7	−31 to −27	< 0.00001
20%	0.002	−38	−40 to −36	< 0.00001
Offset Model				
0%	0	0	−3 to 3	0.91
0%	0.001	−1	−4 to 3	0.78
0%	0.002	−1	−5 to 3	0.63
Offset Model				
20%	0	−19.9	−22 to −17	< 0.00001
20%	0.001	−20.3	−23 to −18	< 0.00001
20%	0.002	−21	−24 to −18	< 0.00001

[a] The effects of the ban were simulated as a 0% or 20% decrease in daily mortality in the presence of no time trend or linear trends of 0.001 or 0.002 deaths per 1000 p-yr per day. Results are the means of estimates from 100 simulations.

[b] Ban Effect of 0% corresponds to “Reference” and Ban Effect of 20% to “Ban” in Figure G.1.

reference data. With covariate adjustment using the smoothed data, the bias was substantially reduced for 0.01 and 0.05 smoothing, although not completely removed as in the offset model. For the largest amount of smoothing (0.10) there was actually bias in the opposite direction. Optimal smoothing was between 0.01 and 0.05 (a window of 29 to 146 days), that is, a window of 1 to 5 months that removed the extreme values but left the season pattern along with the long-term trend.

The implication of these simulations is that the covariate adjustment for weekly mortality rates in the reference population produces a bias attributable to uncontrolled confounding in the presence of long-term trends. This could be avoided by assuming a fixed association with the weekly mortality rates in the reference population, that is, assuming the underlying expected rates equaled those observed in the reference population or a regression coefficient of one. Although we assumed that the mortality rates in the reference population were predictive of those observed in the study population, we were not prepared to assume they were equal. Therefore, we elected to use the alternative of adjusting for the smoothed weekly mortality rates in the reference population, with a smoothing window of 25 weeks (approximately 6 months).

Table G.2. Estimated Percentage Changes in Daily Mortality After a Hypothetical Coal Ban in the Middle of a Daily Mortality Time Series Simulated by Poisson Regression, Adjusting for Smoothed Reference Mortality as a Covariate (Covariance Model)[a]

Ban Effect	Trend	Smooth	Estimate (%)	95% CI	*P*
0%	0	0	0	−2 to 2	0.94
	0	0.01	0	−2 to 2	0.99
	0	0.05	0	−2 to 2	1
	0	0.10	0	−2 to 2	0.97
0%	0.001	0	−11	−13 to −8	< 0.00001
	0.001	0.01	−1	−4 to 1	0.38
	0.001	0.05	2	−2 to 6	0.32
	0.001	0.10	10	7 to 13	< 0.00001
0%	0.002	0	−22	−25 to −20	< 0.00001
	0.002	0.01	−3	−6 to 0	0.08
	0.002	0.05	3	0 to 7	0.05
	0.002	0.10	17	13 to 22	< 0.00001
20%	0	0	−20	−22 to −18	< 0.00001
	0	0.01	−20	−22 to −18	< 0.00001
	0	0.05	−20	−22 to −18	< 0.00001
	0	0.10	−20	−22 to −18	< 0.00001
20%	0.001	0	−29	−31 to −27	< 0.00001
	0.001	0.01	−21	−23 to −19	< 0.00001
	0.001	0.05	−19	−21 to −16	< 0.00001
	0.001	0.10	−12	−15 to −10	< 0.00001
20%	0.002	0	−38	−40 to −36	< 0.00001
	0.002	0.01	−23	−26 to −20	< 0.00001
	0.002	0.05	−18	−21 to −15	< 0.00001
	0.002	0.10	−7	−11 to −4	< 0.00001

[a] The effects of the ban were simulated as a 0% or 20% decrease in daily mortality in the presence of no time trend or linear trends of 0.001 or 0.002 deaths per 1000 p-yr per day, with smoothing parameters of 0.0, 0.01, 0.05, and 0.10. Results are the means of estimates from 100 simulations.

APPENDIX H. Effects of the 1995 Coal Ban on Mortality Rates in County Cork

This appendix provides more detailed presentations of the analyses of mortality rates in county Cork and the estimated effects of the 1995 coal ban. Season-specific directly standardized mortality rates are presented for all cardiovascular causes and two major subcategories (Figure H.1), all respiratory causes and two major subcategories (Figure H.2), and all other causes and two major subcategories (Figure H.3). Table H.1 presents the estimated effects of the 1995 ban stratified by heating versus non-heating seasons. Table H.2 similarly presents estimated effects stratified by two age groups (<75 versus ≥75 years).

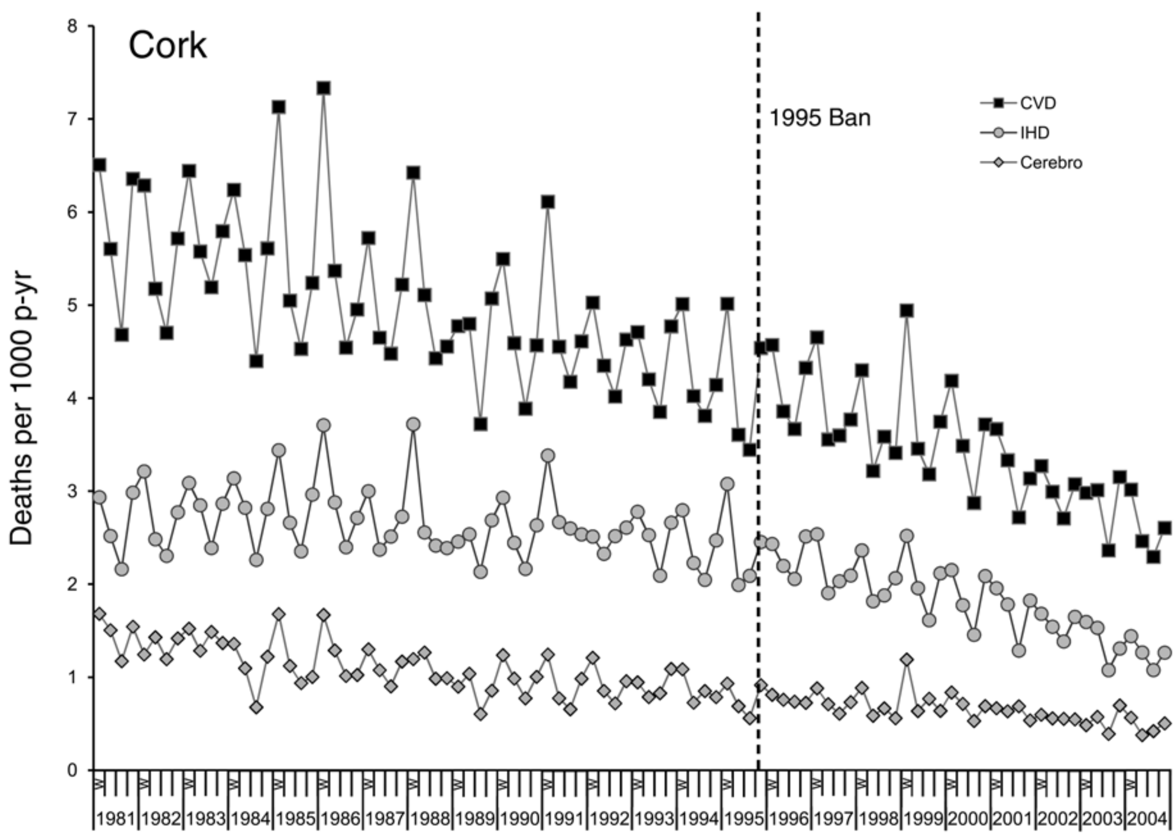


Figure H.1. Cork County Borough mortality rates by cause and season, directly standardized for age and sex. Causes include all cardiovascular disease (CVD) and two subcategories, ischemic heart (IHD) and cerebrovascular (Cerebro) disease. W indicates winter.

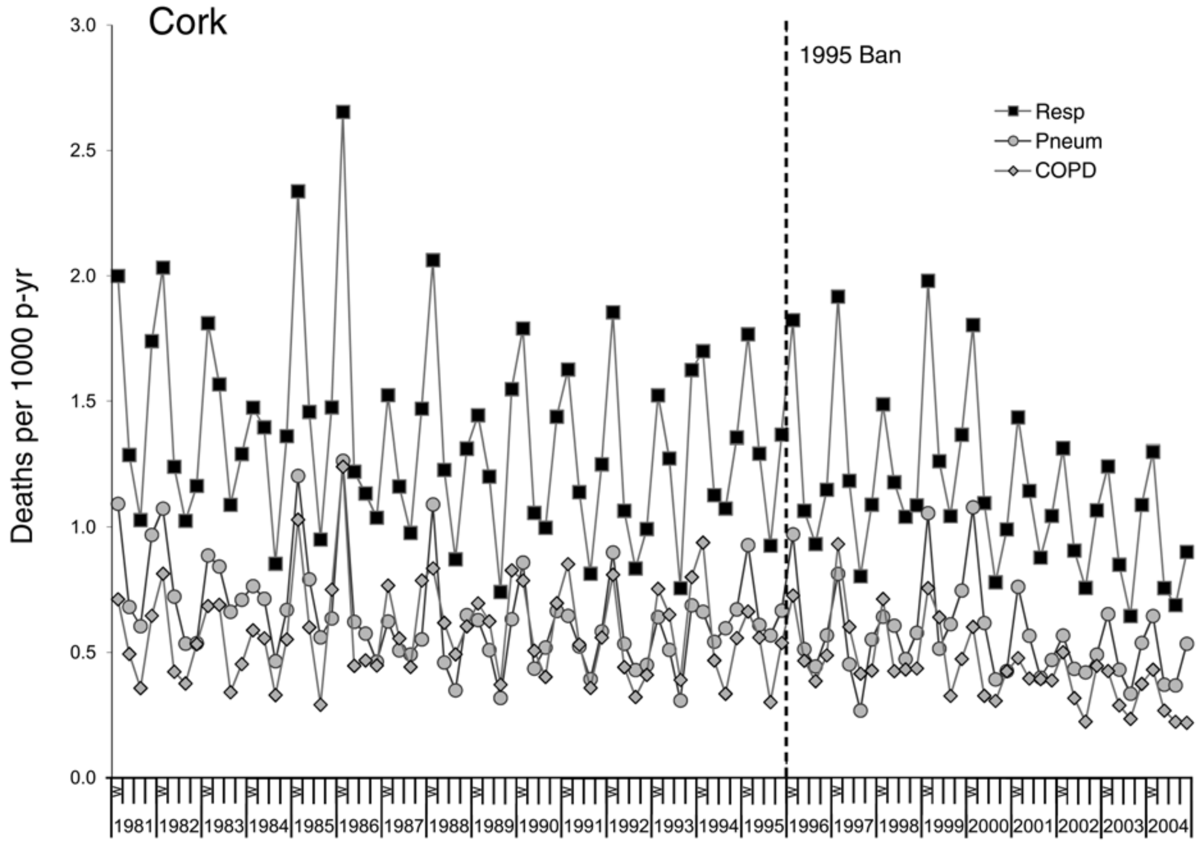


Figure H.2. Cork County Borough mortality rates by cause and season, directly standardized for age and sex. Causes include all respiratory disease (Resp) and two subcategories, pneumonia (Pneum) and COPD. W indicates winter.

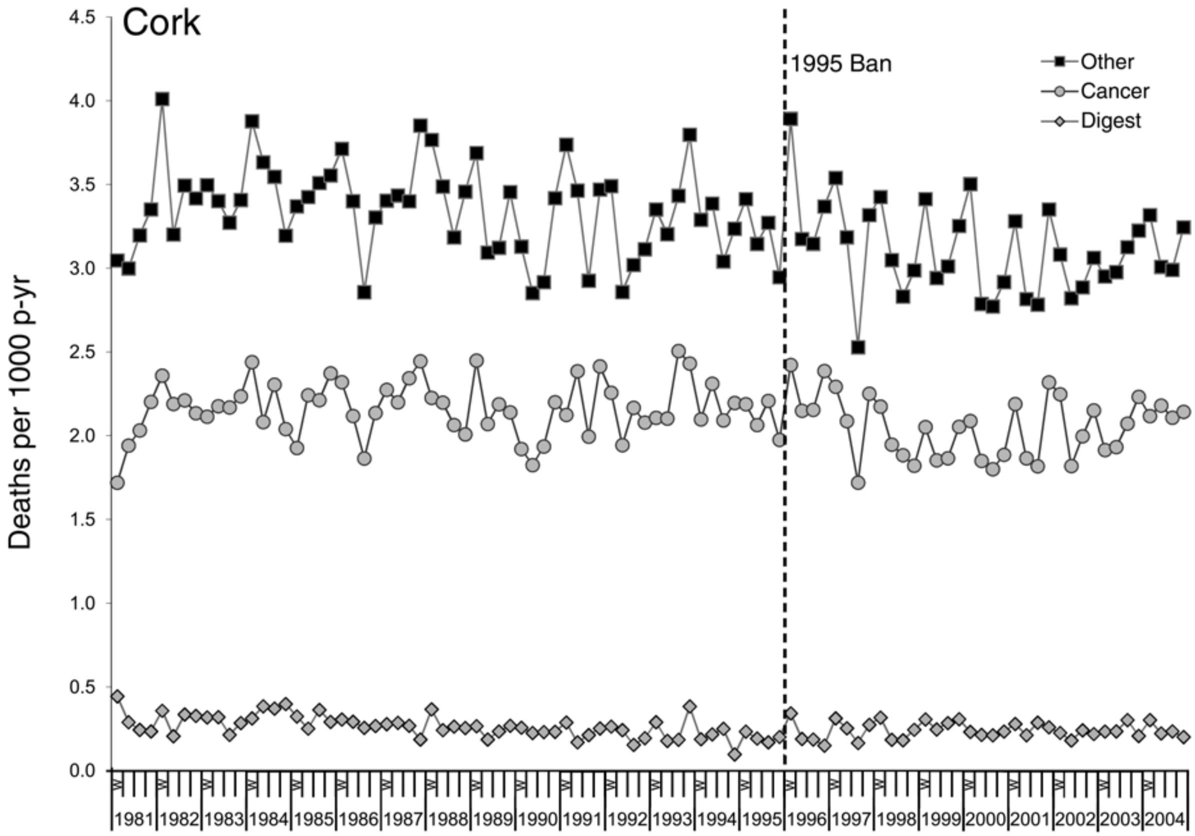


Figure H.3. Cork County Borough mortality rates by cause and season, directly standardized for age and sex. Causes include all other (not cardiovascular or respiratory) disease and two subcategories, cancer and digestive (Digest) disease. W indicates winter.

Table H.1. Estimated Percentage Changes in Cork Mortality Rates by Cause for the Heating and Non-Heating Seasons After the 1995 Coal Ban Compared with Pre-Ban Rates[a]

	Heating Season			Non-Heating Season		
Cause[b]	Change (%)	95% CI	P	Change (%)	95% CI	*P*
Total	−4.3	−11.2 to 3.0	0.24	−4.7	−12.9 to 4.3	0.29
Cardiovascular Disease	−2.7	−14.3 to 10.5	0.67	−4.2	−16.8 to 10.4	0.56
Ischemic heart disease	−8.9	−23.0 to 7.8	0.28	−13.1	−27.9 to 4.8	0.14
Cerebrovascular disease	−14.8	−34.5 to 10.9	0.23	−4.2	−27.4 to 26.4	0.76
Respiratory Disease	−11.9	−23.0 to 0.9	0.066	−6.1	−20.5 to 11.0	0.46
Pneumonia	−4.4	−21.5 to 16.5	0.66	−8.4	−27.9 to 16.5	0.48
COPD	−23.9	−38.3 to −6.1	0.011	−11.9	−32.3 to 14.8	0.35
Other	−4.0	−12.6 to 5.4	0.39	−10.0	−18.4 to −0.7	0.035
Cancer	−1.2	−11.7 to 10.5	0.84	−10.3	−20.1 to 0.8	0.067
Lung cancer	−9.6	−30.1 to 16.9	0.44	−23.1	−40.8 to −0.1	0.049
Digestive disease	−11.3	−35.2 to 21.4	0.45	−4.2	−32.4 to 35.8	0.81

[a] Adjusted for mortality rates by cause in Coastal counties, influenza weeks, and temperature.

[b] Causes in **boldface** are principal categories; the rest are subcategories.

Table H.2. Estimated Percentage Changes in Cork Mortality Rates by Cause for Two Age Groups (<75 and ≥75 years) After the 1995 Coal Ban Compared with Pre-Ban Rates[a]

		Deaths per 1000 p-yr		Adjusted Effect of Ban		
Cause[b]	Age	Pre-Ban	Post-Ban	Change (%)	95% CI	*P*
Total	< 75	4.39	3.16	−7.9	−16.3 to 1.4	0.09
	≥75	114.85	97.45	−3.0	−4.4 to −1.7	0.000011
Cardiovascular Disease	< 75	1.98	1.17	−10.4	−23.5 to 4.9	0.17
	≥75	64.82	48.52	−1.8	−4.1 to 0.6	0.14
Ischemic heart disease	< 75	1.32	0.69	−15.3	−31.2 to 4.4	0.12
	≥75	28.90	24.47	−5.7	−8.4 to −2.9	0.00009
Cerebrovascular disease	< 75	0.33	0.18	−20.5	−44.2 to 13.2	0.20
	≥75	16.02	10.21	−10.7	−14.7 to −6.4	0.00000
Respiratory Disease	< 75	0.42	0.29	−12.0	−30.2 to 10.9	0.28
	≥75	19.70	18.19	−8.2	−10.6 to −5.8	0.00000
Pneumonia	< 75	0.13	0.09	−10.2	−39.8 to 34.0	0.60
	≥75	11.03	10.00	−5.0	−8.3 to −1.6	0.0046
COPD	< 75	0.26	0.15	−22.7	−43.4 to 5.6	0.11
	≥75	7.12	6.30	−17.4	−21.1 to −13.5	0.00000
Other	< 75	1.99	1.71	−12.4	−21.5 to −2.3	0.018
	≥75	30.33	30.75	0.7	−1.5 to 2.9	0.55
Cancer	< 75	1.39	1.22	−12.8	−22.1 to −2.5	0.016
	≥75	17.43	18.52	5.4	2.3 to 8.6	0.0006
Lung cancer	< 75			−24.0	−39.8 to −4.1	0.021
	≥75			−4.2	−11.4 to 3.5	0.28
Digestive disease	< 75	0.12	0.11	−7.4	−34.3 to 30.5	0.66
	≥75	3.09	2.83	−6.7	−13.0 to 0.0	0.050

[a] Adjusted for mortality rates by cause in Coastal counties, influenza weeks, and temperature.

[b] Causes in **boldface** are principal categories; the rest are subcategories.

APPENDIX I. Effects of the 1998 Coal Ban on Mortality Rates in Affected Counties

This appendix provides more detailed presentations of the analyses of mortality rates in the four affected counties and the estimated effects of the 1998 coal ban. Season- and county-specific directly standardized mortality rates are presented for all cardiovascular causes and two major subcategories (Figure I.1), all respiratory causes and two major subcategories (Figure I.2), and all other causes and two major subcategories (Figure I.3). Table I.1 presents the county-specific and combined estimated effects of the 1998 ban. Table I.2 presents the combined estimated effects of the 1998 ban stratified by heating versus non-heating seasons.

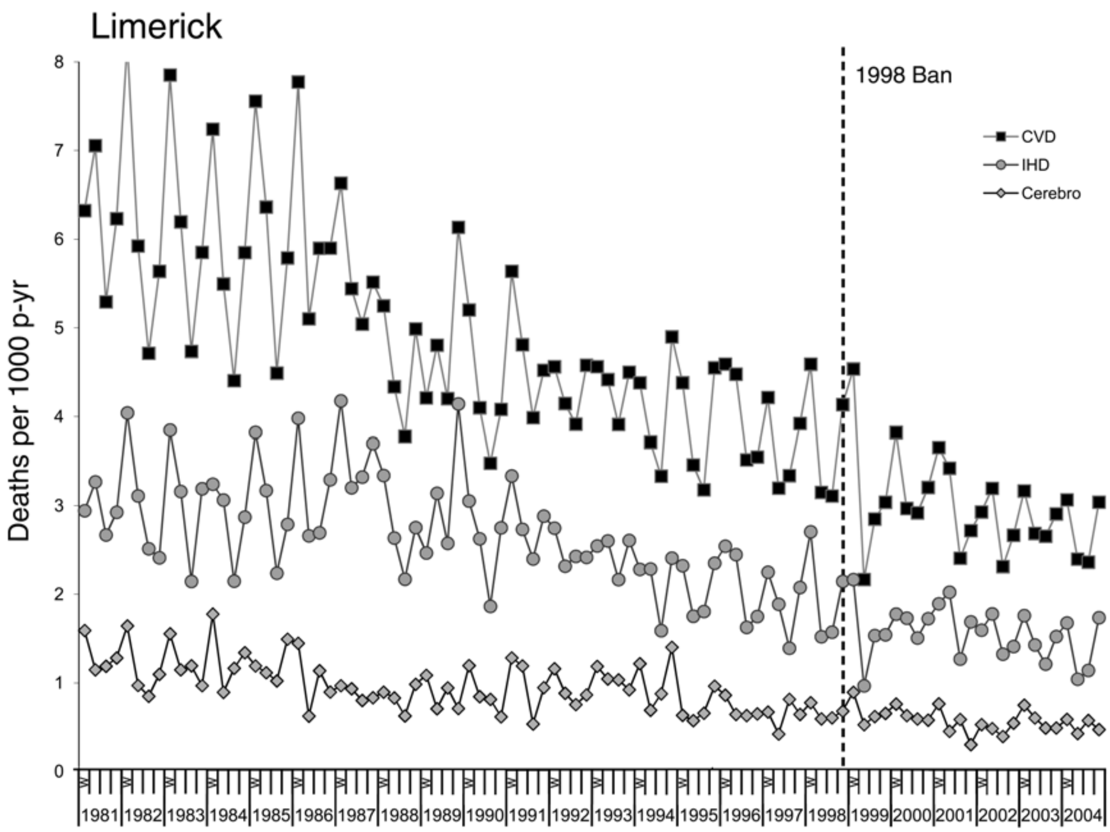
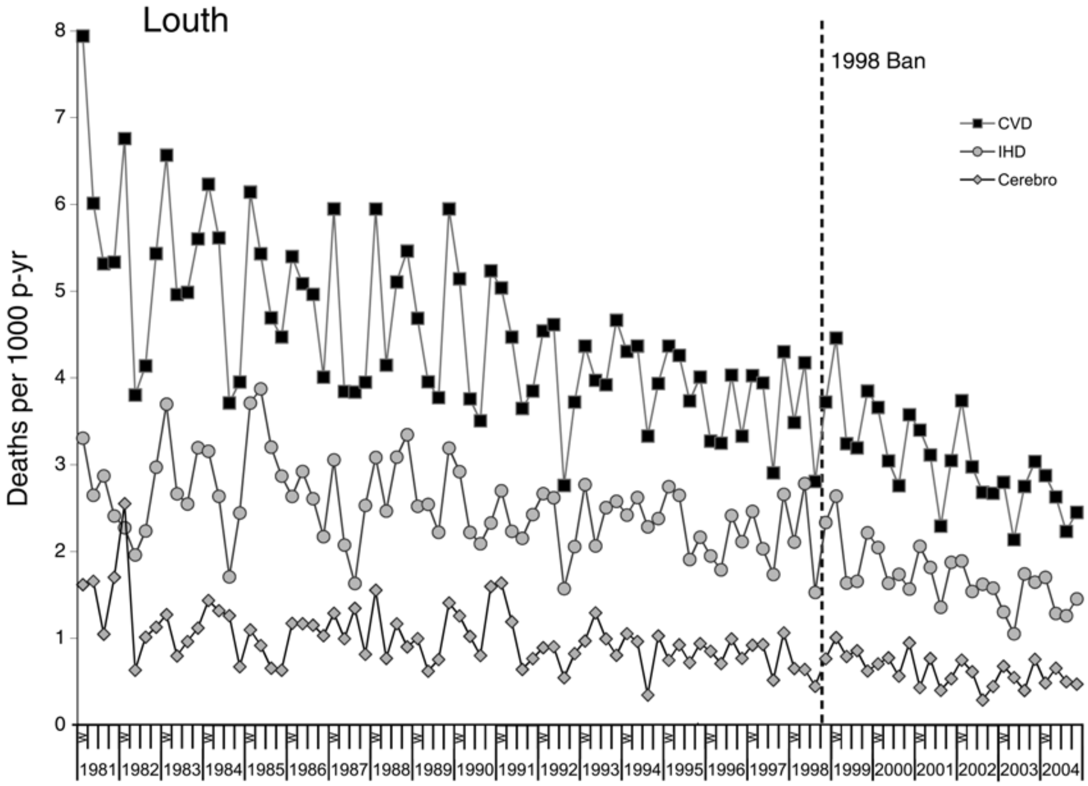


Figure I.1. Mortality rates by cause and season, directly standardized for age and sex, for each of the four counties affected by the 1998 coal ban. Causes include all cardiovascular disease (CVD) and two subcategories, ischemic heart (IHD) and cerebrovascular (Cerebro) disease. W indicates winter. (*Figure continues next page.*)



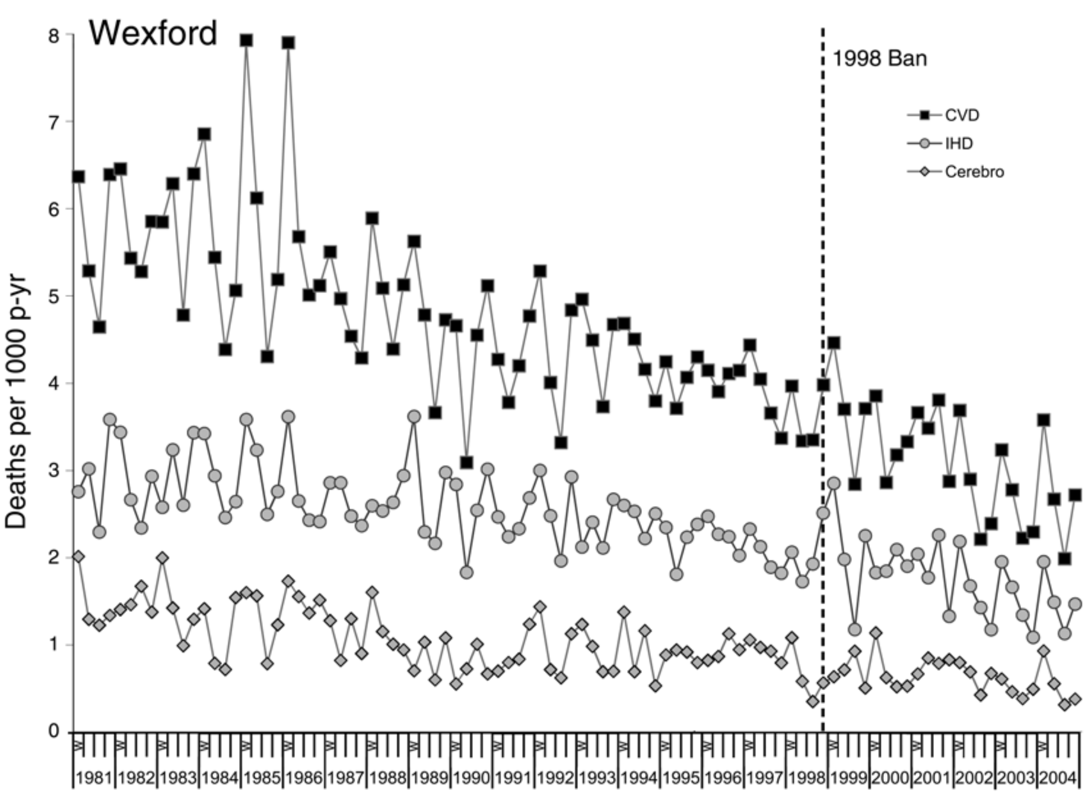


Figure I.1 (*Continued*). (*Figure continues next page.*)

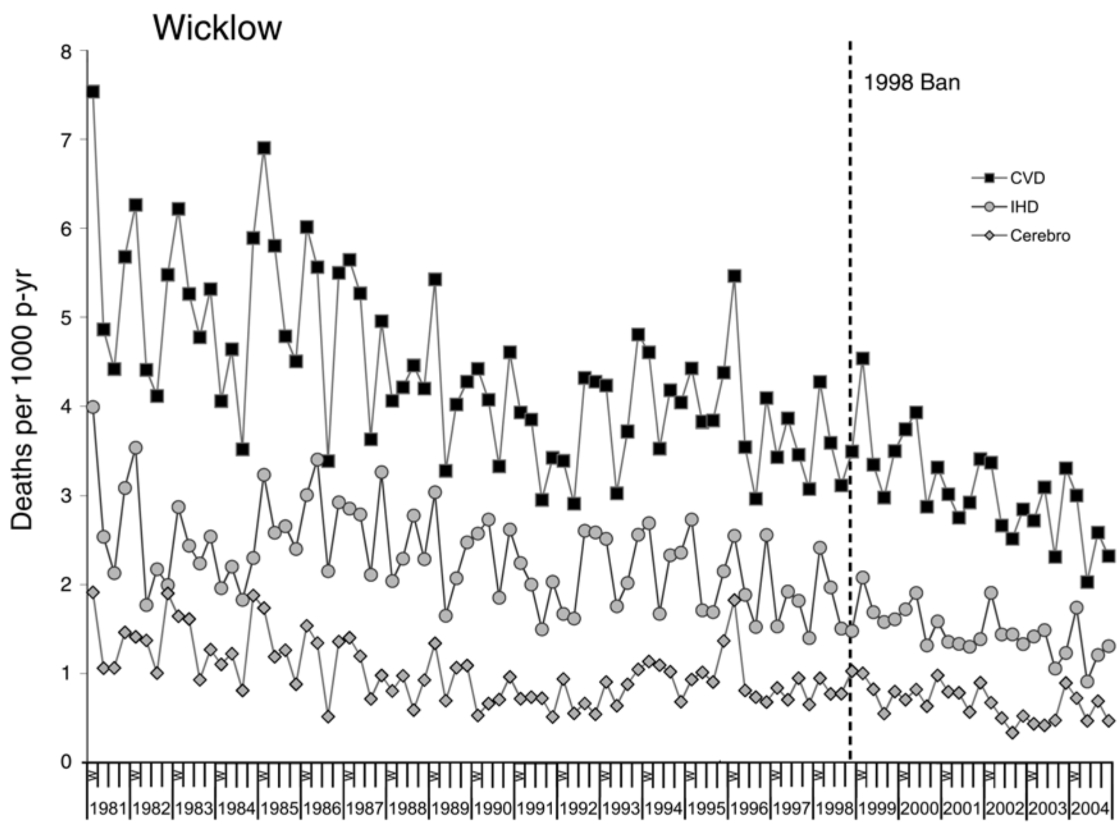
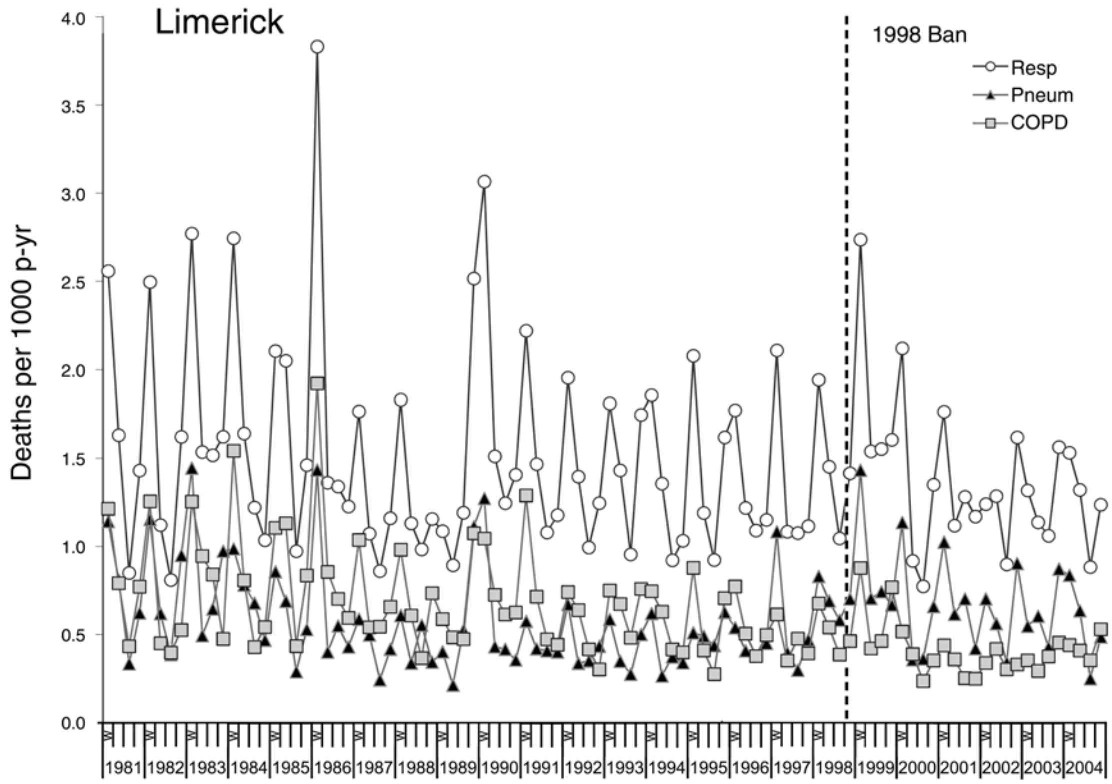


Figure I.1 (*Continued*).



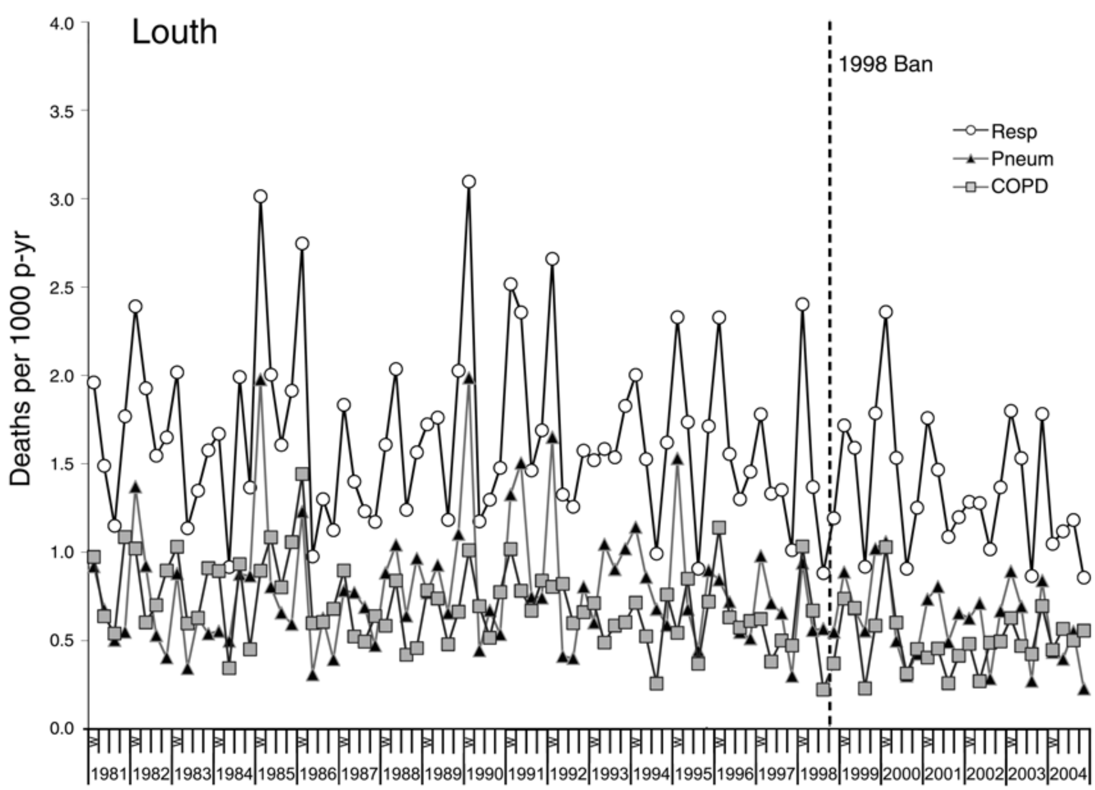


Figure I.2. Mortality rates by cause and season, directly standardized for age and sex, for each of the four counties affected by the 1998 coal ban. Causes include all respiratory disease (Resp) and two subcategories, pneumonia (Pneum) and COPD. W indicates winter. (*Figure continues next page.*)

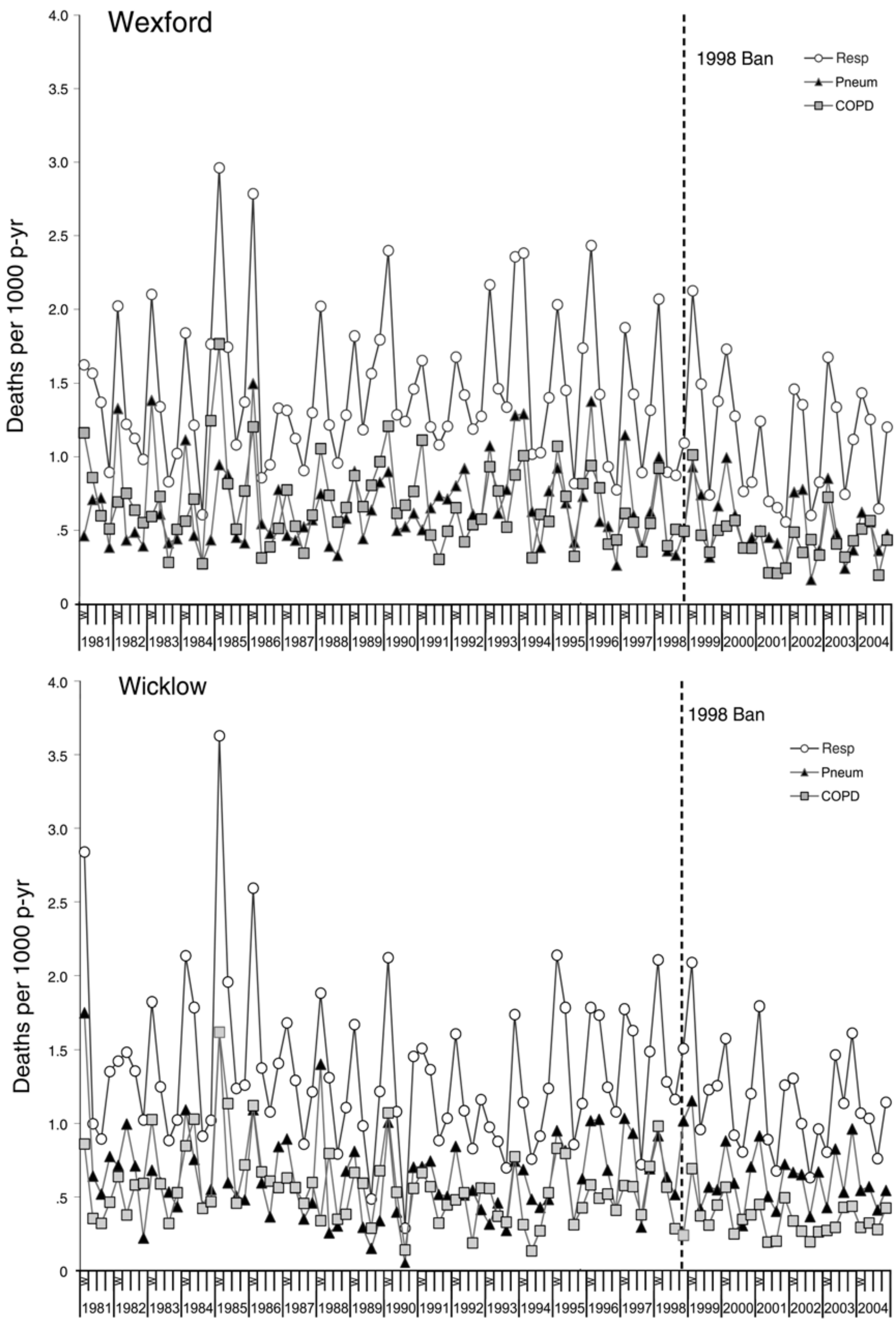


Figure I.2 (*Continued*).

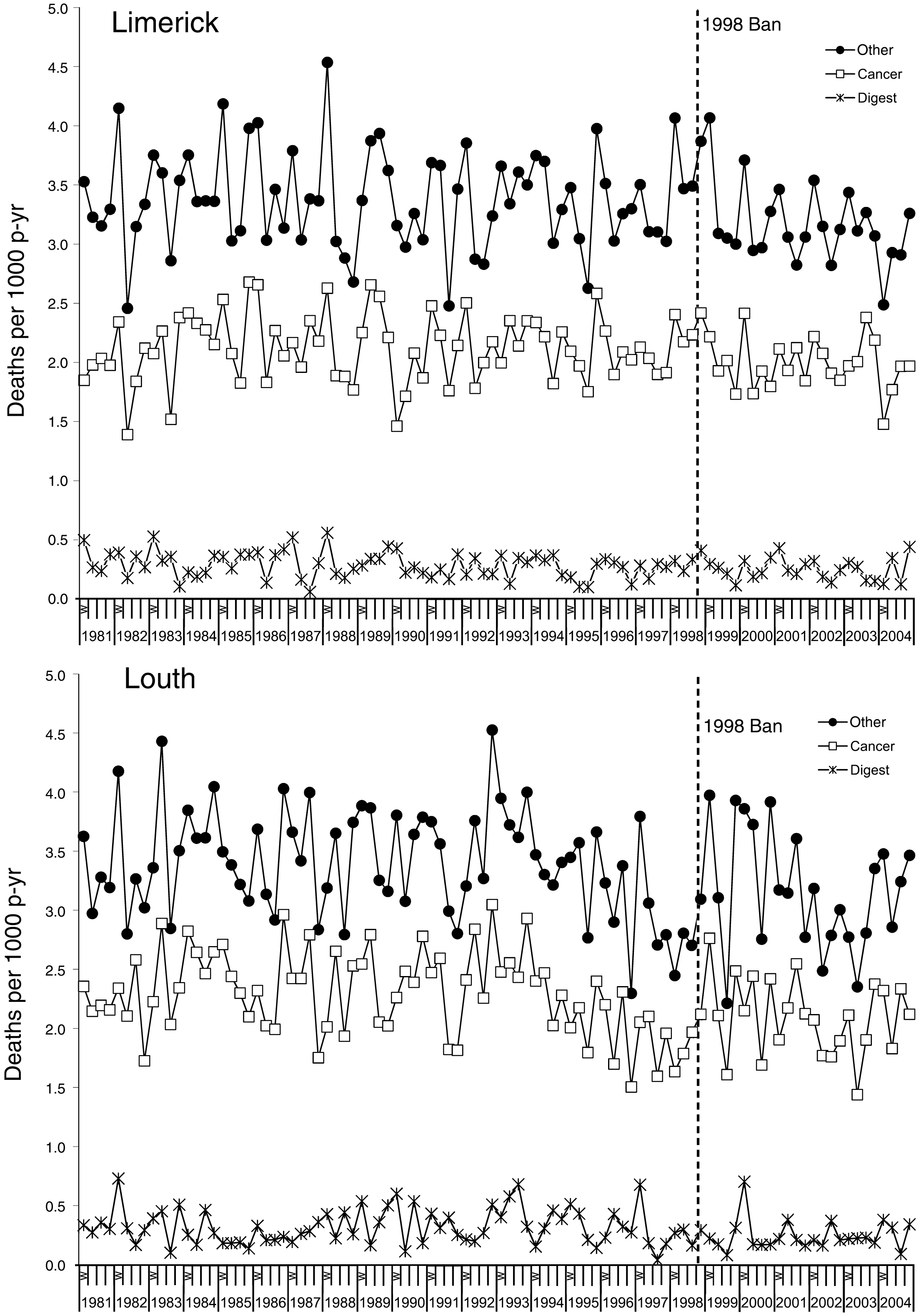
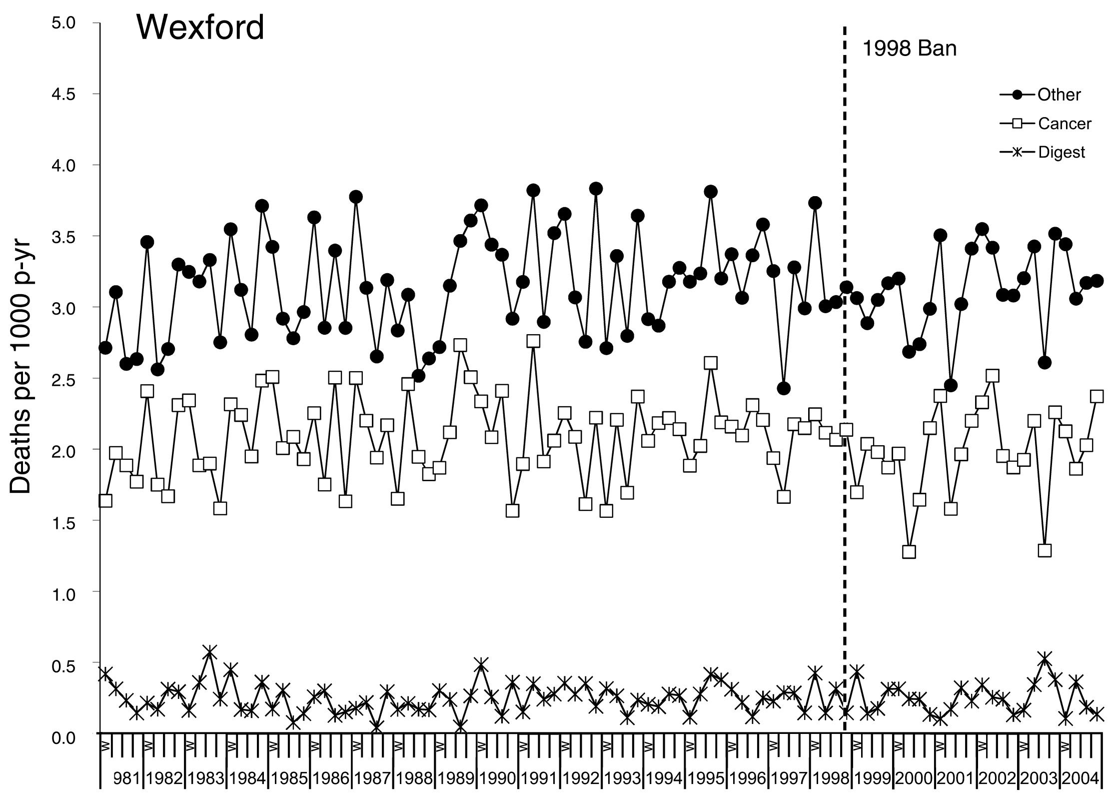


Figure I.3. Mortality rates by cause and season, directly standardized for age and sex, for each of the four counties affected by the 1998 coal ban. Causes include all other (not cardiovascular or respiratory) disease and two subcategories, cancer and digestive (Digest) disease. W indicates winter. (*Figure continues next page.*)



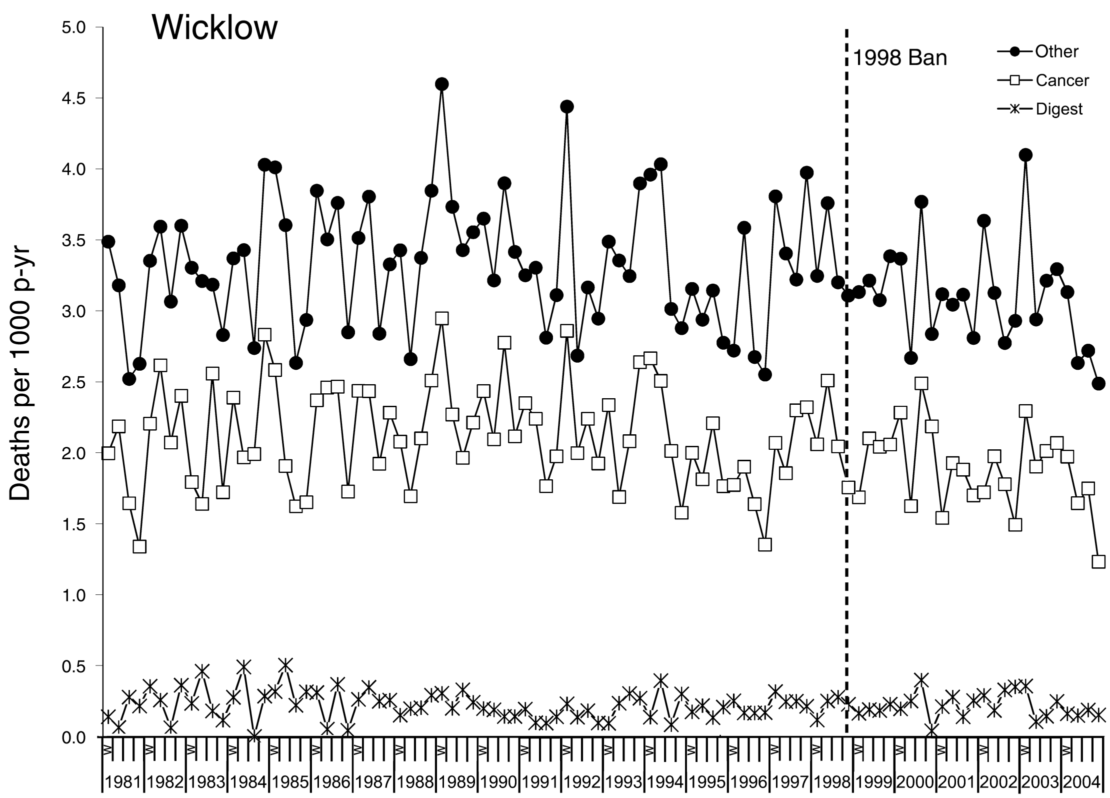


Figure I.3 (*Continued*).

Table I.1. Estimated Percentage Changes in County and Combined Mortality Rates After the 1998 Coal Ban Compared with Pre-Ban Rates[a]

	Deaths per 1000 p-yr		Adjusted Effect of 1998 Ban		
Cause[b] / County	Pre-Ban	Post-Ban	Change (%)	95% CI	*P*
Total					
Limerick	9.81	7.56	3.4	−3.1 to 10.4	0.32
Louth	9.57	7.57	1.9	−4.7 to 9.0	0.58
Wexford	9.41	7.39	−4.0	−10.2 to 2.7	0.24
Wicklow	9.09	7.34	−0.5	−7.1 to 6.5	0.87
Combined	9.47	7.47	0.2	−3.1 to 3.6	0.90
Cardiovascular Disease					
Limerick	4.93	3.01	−3.0	−12.4 to 7.3	0.55
Louth	4.54	3.05	2.0	−8.1 to 13.2	0.71
Wexford	4.82	3.14	−2.2	−11.7 to 8.3	0.67
Wicklow	4.41	3.06	−1.0	−10.8 to 10.0	0.86
Combined	4.68	3.07	−1.1	−6.1 to 4.1	0.67
Ischemic heart disease					
Limerick	2.67	1.59	−13.5	−25.0 to −0.2	0.047
Louth	2.52	1.70	−7.9	−20.2 to 6.3	0.26
Wexford	2.58	1.78	−2.4	−15.3 to 12.4	0.73
Wicklow	2.32	1.47	−15.3	−27.2 to −1.4	0.032
Combined	2.52	1.64	−9.7	−16.0 to −2.9	0.006
Cerebrovascular disease					
Limerick	0.97	0.58	−13.8	−29.9 to 6.0	0.16
Louth	1.01	0.63	−12.4	−28.3 to 7.1	0.2
Wexford	1.08	0.64	−14.2	−29.4 to 4.4	0.13
Wicklow	1.03	0.68	−10.3	−26.2 to 8.9	0.27
Combined	1.02	0.63	−12.6	−20.9 to −3.5	0.008

Table continues next page

[a]Adjusted for smoothed mortality rates by cause in Coastal counties, influenza weeks, and temperature.

[b] Causes in **boldface** are principal categories; the rest are subcategories.

Table I.1 (*Continued*). Estimated Percentage Changes in County and Combined Mortality Rates After the 1998 Coal Ban Compared with Pre-Ban Rates[a]

	Deaths per 1000 p-yr		Adjusted Effect of 1998 Ban		
Cause[b] / County	Pre-Ban	Post-Ban	Change (%)	95% CI	*P*
Respiratory Disease					
Limerick	1.51	1.38	9.6	−2.1 to 22.6	0.11
Louth	1.65	1.35	−8.5	−18.5 to 2.7	0.13
Wexford	1.44	1.13	−12.0	−22.2 to −0.5	0.041
Wicklow	1.35	1.17	0.6	−10.9 to 13.7	0.92
Combined	1.49	1.26	−2.6	−8.1 to 3.4	0.39
Pneumonia					
Limerick	0.58	0.67	51.9	28.0 to 80.4	0
Louth	0.79	0.61	−13.4	−27.1 to 2.9	0.1
Wexford	0.67	0.53	−13.0	−27.5 to 4.3	0.13
Wicklow	0.64	0.64	19.7	0.9 to 42.0	0.04
Combined	0.67	0.61	8.9	−0.2 to 18.8	0.055
COPD					
Limerick	0.69	0.42	−33.2	−45.1 to −18.9	0.00005
Louth	0.7	0.5	−27.9	−40.2 to −13.1	0.0006
Wexford	0.68	0.44	−27.1	−39.8 to −11.8	0.0012
Wicklow	0.57	0.35	−33.2	−46.0 to −17.3	0.00022
Combined	0.66	0.43	−30.2	−36.7 to −23.0	0
Other					
Limerick	3.38	3.18	−3.4	−10.8 to 4.5	0.39
Louth	3.38	3.16	−2.7	−10.2 to 5.6	0.51
Wexford	3.15	3.12	0.3	−7.5 to 8.7	0.95
Wicklow	3.33	3.11	−5.4	−12.7 to 2.5	0.17
Combined	3.31	3.14	−2.8	−6.7 to 1.1	0.16
Cancer					
Limerick	2.12	2.12	−5.8	−14.0 to 3.2	0.2
Louth	2.29	2.1	−7.1	−15.0 to 1.5	0.1
Wexford	2.09	1.98	−5.7	−13.9 to 3.4	0.21
Wicklow	2.12	1.88	−10.1	−18.2 to −1.4	0.025
Combined	2.16	2.02	−7.2	−11.3 to −2.8	0.001
Lung cancer					
Limerick	0.43	0.42	−3.0	−20.1 to 17.7	0.76
Louth	0.56	0.47	−15.8	−29.7 to 0.9	0.062
Wexford	0.45	0.43	−3.5	−20.3 to 16.8	0.71
Wicklow	0.55	0.43	−22.1	−35.5 to −6.0	0.009
Combined	0.50	0.44	−11.8	−19.7 to −3.1	0.009
Digestive disease					
Limerick	0.29	0.26	−9.9	−29.6 to 15.2	0.41
Louth	0.32	0.25	−22.4	−39.3 to −0.7	0.044
Wexford	0.25	0.25	0.1	−22.4 to 29.1	1
Wicklow	0.22	0.22	−0.7	−24.3 to 30.2	0.96
Combined	0.27	0.25	−9.2	−20.0 to 3.1	0.14

[a]Adjusted for smoothed mortality rates by cause in Coastal counties, influenza weeks, and temperature.

[b] Causes in **boldface** are principal categories; the rest are subcategories.

Table I.2. Estimated Combined Percentage Changes in Mortality Rates for the Heating and Non-Heating Seasons in Limerick, Louth, Wexford, and Wicklow After the 1998 Coal Ban Compared with Pre-Ban Rates[a]

	Heating Season			Non-Heating Season		
Cause[b] / County	Change (%)	95% CI	*P*	Change (%)	95% CI	*P*
Total						
Limerick	5.8	−3.0 to 15.3	0.20	0.7	−9.7 to 12.3	0.90
Louth	5.3	−3.6 to 15.0	0.25	−2.3	−12.4 to 9.1	0.68
Wexford	−3.3	−11.6 to 5.7	0.46	−6.0	−15.9 to 5.0	0.27
Wicklow	0.4	−8.2 to 9.9	0.92	−2.1	−12.5 to 9.6	0.71
Combined	2.1	−2.3 to 6.7	0.36	−2.4	−7.6 to 3.1	0.39
Cardiovascular Disease						
Limerick	1.5	−11.5 to 16.5	0.83	−5.5	−19.1 to 10.3	0.47
Louth	9.1	−5.2 to 25.6	0.23	−7.7	−21.3 to 8.1	0.32
Wexford	2.2	−11.0 to 17.5	0.75	−7.4	−20.5 to 7.9	0.33
Wicklow	4.5	−9.3 to 20.5	0.54	−7.4	−20.9 to 8.5	0.34
Combined	4.2	−2.8 to 11.8	0.24	−7.0	−14.0 to 0.6	0.07
Ischemic heart disease						
Limerick	−13.9	−29.1 to 4.5	0.13	−9.3	−27.0 to 12.8	0.38
Louth	−3.3	−20.3 to 17.3	0.73	−14.9	−31.6 to 5.9	0.15
Wexford	4.2	−14.0 to 26.3	0.67	−10.9	−28.0 to 10.1	0.29
Wicklow	−16.0	−31.6 to 3.2	0.10	−13.4	−31.1 to 8.9	0.22
Combined	−7.3	−16 to 2.3	0.13	−12	−21.2 to −1.9	0.02
Cerebrovascular disease						
Limerick	−9.2	−31.3 to 20.0	0.50	−21.2	−42.1 to 7.3	0.13
Louth	−8.8	−30.8 to 20.2	0.51	−14.7	−36.4 to 14.5	0.29
Wexford	−13.3	−33.7 to 13.5	0.30	−14.5	−35.9 to 14.1	0.29
Wicklow	−5.6	−27.3 to 22.6	0.66	−16.9	−38.0 to 11.4	0.22
Combined	−9.2	−20.7 to 3.9	0.16	−16.7	−28.2 to −3.4	0.02

Table continues next page

[a] Adjusted for smoothed mortality rates by cause in Coastal counties, influenza weeks, and temperature.

[b] Causes in **boldface** are principal categories; the rest are subcategories.

Table I.2 (*Continued*). Estimated Combined Percentage Changes in Mortality Rates for the Heating and Non-Heating Seasons in Limerick, Louth, Wexford, and Wicklow After the 1998 Coal Ban Compared with Pre-Ban Rates[a]

	Heating Season			Non-Heating Season		
Cause[b] / County	Change (%)	95% CI	*P*	Change (%)	95% CI	*P*
Respiratory Disease						
Limerick	5.3	−8.9 to 21.6	0.49	13.0	−7.0 to 37.3	0.22
Louth	−6.0	−18.9 to 8.9	0.41	−20.5	−34.6 to −3.3	0.02
Wexford	−10.3	−23.3 to 4.9	0.17	−21.2	−36.2 to −2.6	0.03
Wicklow	−2.9	−17.1 to 13.6	0.71	4.6	−15.2 to 29.0	0.68
Combined	−3.4	−10.4 to 4.2	0.37	−7.0	−16.0 to 2.9	0.16
Pneumonia						
Limerick	53.8	23.3 to 91.9	0.00	45.7	9.8 to 93.3	0.01
Louth	−3.3	−22.2 to 20.2	0.77	−31.8	−48.6 to −9.5	0.008
Wexford	−12.0	−30.6 to 11.5	0.29	−19.2	−39.6 to 8.0	0.15
Wicklow	15.4	−7.9 to 44.5	0.21	24.5	−5.3 to 63.5	0.12
Combined	11.5	−0.4 to 24.8	0.06	0.7	−12.6 to 15.9	0.93
COPD						
Limerick	−34.0	−48.6 to −15.2	0.0012	−34.1	−52.2 to −9.0	0.011
Louth	−25.9	−41.8 to −5.6	0.015	−35.0	−51.6 to −12.7	0.0041
Wexford	−22.1	−38.8 to −0.9	0.042	−37.4	−54.8 to −13.4	0.0047
Wicklow	−33.4	−49.2 to −12.7	0.0032	−34.9	−54.6 to −6.6	0.020
Combined	−28.7	−37.1 to −19.2	< 0.00001	−35.3	−45.0 to −24.0	< 0.00001
Other						
Limerick	−2.7	−13.1 to 9.0	0.64	−5.0	−15.3 to 6.6	0.39
Louth	1.0	−10.0 to 13.3	0.87	−6.2	−16.4 to 5.3	0.28
Wexford	−2.9	−13.5 to 9.1	0.62	2.3	−8.9 to 14.8	0.70
Wicklow	−9.1	−18.9 to 2.0	0.10	−1.0	−11.8 to 11.0	0.86
Combined	−3.5	−8.9 to 2.2	0.23	−2.5	−8.0 to 3.2	0.38
Cancer						
Limerick	−9.2	−20.0 to 3.2	0.14	−2.3	−14.4 to 11.5	0.73
Louth	−3.7	−14.7 to 8.8	0.55	−10.5	−21.5 to 1.9	0.09
Wexford	−6.4	−17.7 to 6.4	0.31	−4.6	−16.5 to 9.0	0.49
Wicklow	−15.4	−25.8 to −3.5	0.013	−3.1	−15.3 to 10.9	0.65
Combined	−8.6	−14.2 to −2.6	0.006	−5.3	−11.3 to 1.2	0.11
Lung cancer						
Limerick	−2.8	−26.0 to 27.6	0.84	−3.5	−27.1 to 27.7	0.80
Louth	−7.3	−27.6 to 18.5	0.54	−25.3	−42.8 to −2.3	0.033
Wexford	−1.4	−25.3 to 30.1	0.92	−3.0	−25.9 to 27.0	0.83
Wicklow	−20.4	−39.0 to 4.0	0.09	−20.8	−39.6 to 3.7	0.09
Combined	−8.2	−19.6 to 0.2	0.09	−13.6	−24.6 to −1.1	0.035
Digestive disease						
Limerick	0.4	−27.4 to 39.0	0.98	−21.1	−46.5 to 16.3	0.23
Louth	−20.0	−42.4 to 11.1	0.18	−26.7	−49.7 to 6.7	0.10
Wexford	−18.7	−44.0 to 18.1	0.28	21.8	−14.6 to 73.8	0.28
Wicklow	−9.7	−39.2 to 34.2	0.61	11.7	−23.5 to 63.1	0.57
Combined	−12.1	−26.2 to 4.8	0.15	−4.9	−21.1 to 14.7	0.60

[a] Adjusted for smoothed mortality rates by cause in Coastal counties, influenza weeks, and temperature.

[b] Causes in **boldface** are principal categories; the rest are subcategories.

APPENDIX J. Effects of the 1990 Coal Ban on Mortality Rates in Dublin

This appendix provides more detailed presentations of the analyses of mortality rates in Dublin and the estimated effects of the 1990 coal ban. Season-specific directly standardized mortality rates are presented for all cardiovascular causes and two major subcategories (Figure J.1), all respiratory causes and two major subcategories (Figure J.2), and all other causes and two major subcategories (Figure J.3). Table J.1 presents the estimated effects of the 1990 ban stratified by heating versus non-heating seasons; Table J.2 presents the estimated effects stratified by age class.

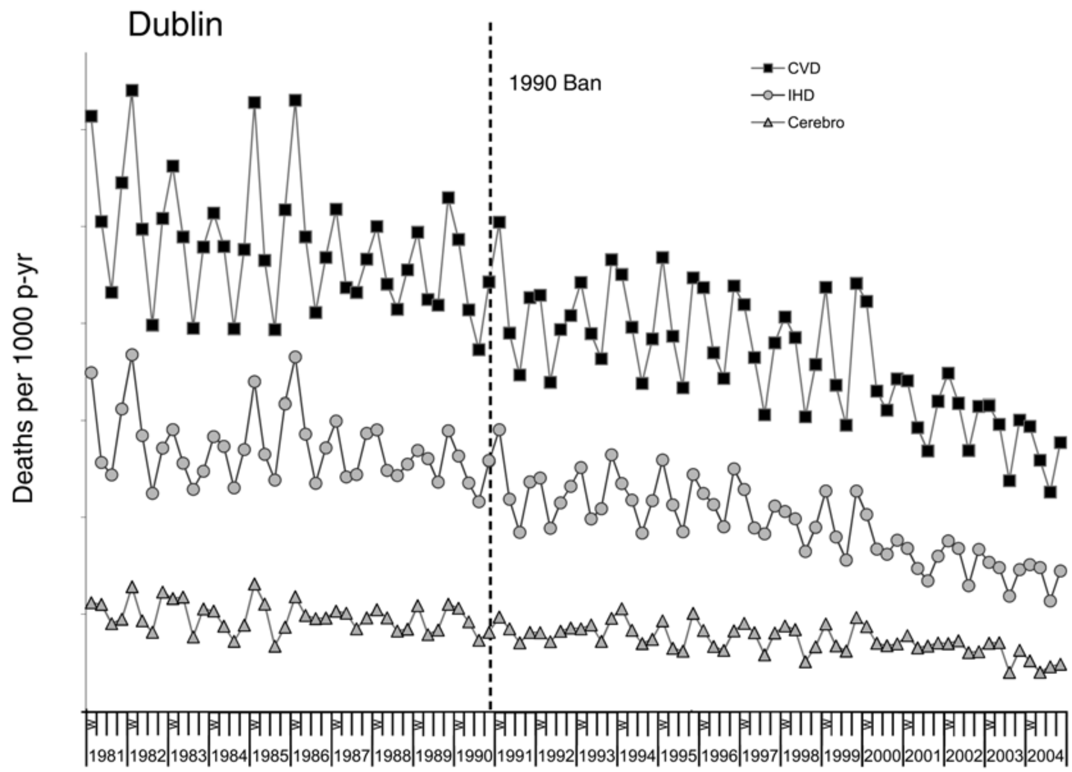


Figure J.1. Dublin County Borough mortality rates by cause and season, directly standardized for age and sex. Causes include all cardiovascular disease (CVD) and two subcategories, ischemic heart (IHD) and cerebrovascular (Cerebro) diseases. W indicates winter.

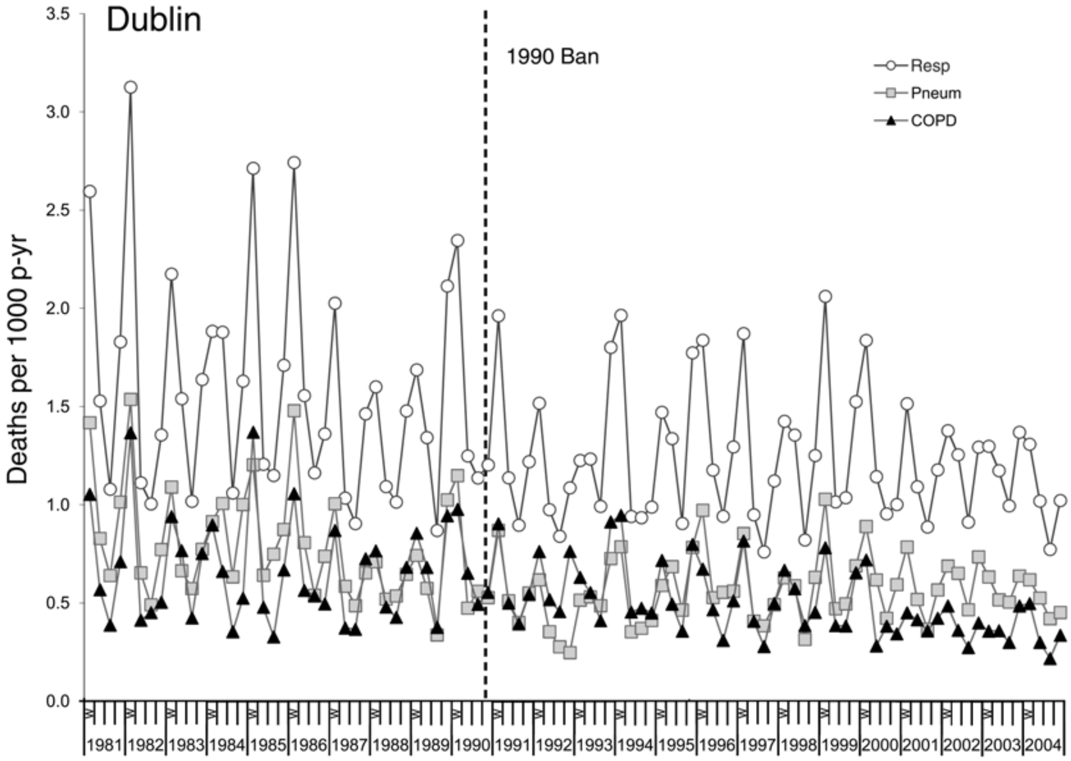


Figure J.2. Dublin County Borough mortality rates by cause and season, directly standardized for age and sex. Causes include all respiratory disease (Resp) and two subcategories, pneumonia (Pneum) and COPD. W indicates winter.

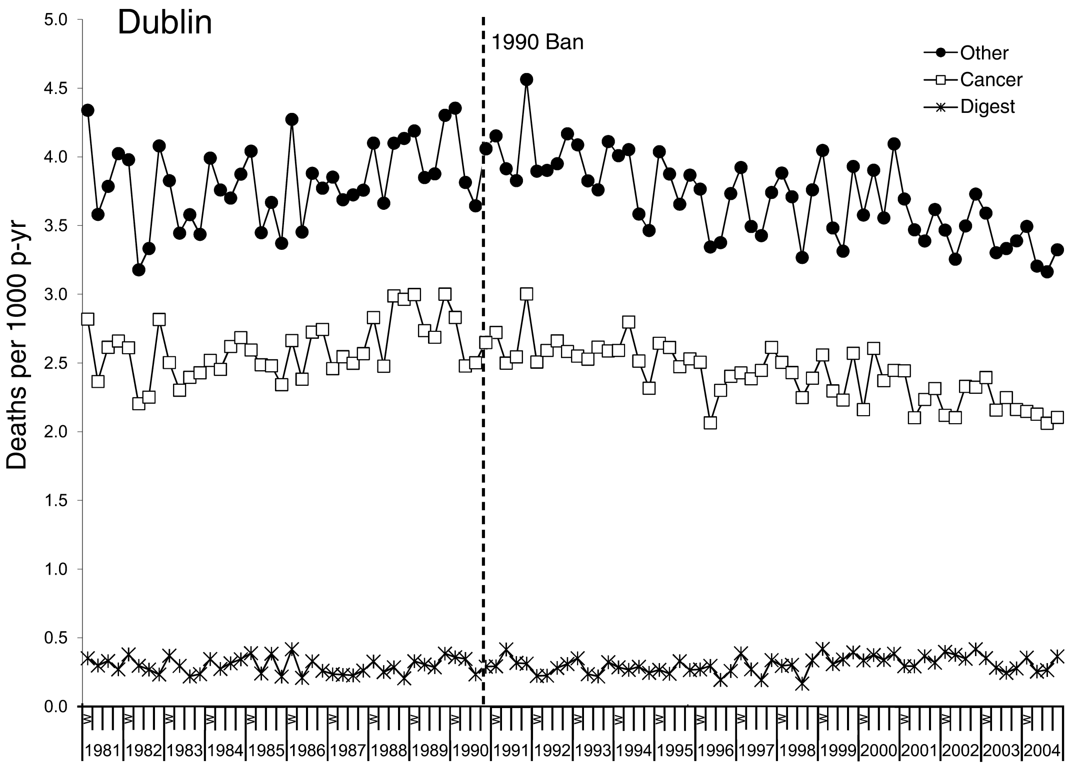


Figure J.3. Dublin County Borough mortality rates by cause and season, directly standardized for age and sex. Causes include all other (not cardiovascular or respiratory) disease and two subcategories, cancer and digestive (Digest) disease. W indicates winter.

Table J.1. Estimated Percentage Changes in Dublin County Borough Mortality Rates by Cause for the Heating and Non-Heating Seasons After the 1990 Coal Ban Compared with Pre-Ban Rates[a]

	Adjusted Effect of Ban		
Cause[b] / Season	Change (%)	95% CI	*P*
Total			
Heating	−1.6	−8.3 to 5.5	0.65
Non-heating	−1.7	−9.6 to 6.8	0.68
Cardiovascular Disease			
Heating	3.0	−8.9 to 16.5	0.64
Non-heating	−3.7	−15.9 to 10.2	0.58
Ischemic heart disease			
Heating	3.6	−12.4 to 22.4	0.68
Non-heating	−4.5	−20.6 to 14.7	0.62
Cerebrovascular disease			
Heating	−8.9	−30.7 to 19.7	0.50
Non-heating	−9.0	−32.8 to 23.2	0.54
Respiratory Disease			
Heating	−21.6	−30.6 to −11.4	0.000
Non-heating	−10.7	−23.7 to 4.5	0.16
Pneumonia			
Heating	−23.6	−36.5 to −8.1	0.00
Non-heating	−19.5	−36.2 to 1.5	0.07
COPD			
Heating	−27.9	−40.2 to −13.2	0.001
Non-heating	−11.2	−30.6 to 13.6	0.34
Other			
Heating	−2.2	−10.0 to 6.5	0.62
Non-heating	−0.8	−9.0 to 8.1	0.850
Cancer			
Heating	−7.8	−16.9 to 2.3	0.13
Non-heating	−5.0	−14.3 to 5.3	0.327
Lung cancer			
Heating	−14.1	−29.7 to 5.0	0.14
Non-heating	−12.8	−27.9 to 5.5	0.160
Digestive disease			
Heating	2.8	−22.5 to 38.2	0.82
Non-heating	5.0	−22.9 to 42.9	0.76

[a] Adjusted for smoothed mortality rates by cause in Coastal counties, influenza weeks, and temperature.

[b] Causes in **boldface** are principal categories; the rest are subcategories.

Table J.2. Estimated Percentage Changes in Dublin County Borough Mortality Rates by Cause for Two Age Groups (<75 and ≥75 years) After the 1990 Coal Ban Compared with Pre-Ban Rates[a]

	Deaths per 1000 p-yr		Adjusted Effect of Ban		
Cause[b] / Age (yr)	Pre-Ban	Post-Ban	Change (%)	95% CI	*P*
Total					
<75	5.07	4.03	−1.1	−9.0 to 7.6	0.80
≥75	111.74	97.97	−1.6	−3.0 to −0.2	0.021
Cardiovascular Disease					
<75	2.19	1.51	−5.9	−17.6 to 7.5	0.37
≥75	56.70	45.39	1.1	−1.5 to 3.7	0.42
Ischemic heart disease					
<75	1.47	0.94	−8.1	−21.8 to 7.9	0.30
≥75	27.38	21.69	−0.0	−3.6 to 3.7	0.99
Cerebrovascular disease					
<75	0.34	0.23	−10.7	−35.2 to 23.0	0.49
≥75	13.53	10.68	−9.3	−14.1 to −4.4	0.00032
Respiratory Disease					
<75	0.54	0.39	−13.1	−28.9 to 6.3	0.17
≥75	22.10	17.82	−20.5	−22.5 to −18.4	0.00000
Pneumonia					
<75	0.17	0.12	−17.9	−42.1 to 16.5	0.27
≥75	13.11	9.34	−25.0	−27.5 to −22.4	0.00000
COPD					
<75	0.32	0.21	−17.5	−36.0 to 6.5	0.14
≥75	7.47	6.15	−23.9	−27.3 to −20.3	0.00000
Other					
<75	2.34	2.13	−3.9	−12.6 to 5.8	0.42
≥75	32.94	34.76	4.0	1.8 to 6.2	0.00029
Cancer					
<75	1.70	1.49	−10.2	−18.2 to −1.3	0.026
≥75	20.35	20.79	1.7	−1.1 to 4.6	0.23
Lung cancer					
<75	0.55	0.44	−17.6	−30.4 to −2.5	0.024
≥75	5.30	5.14	−5.7	−10.9 to −0.1	0.047
Digestive disease					
<75	0.14	0.16	16.4	−14.8 to 59.1	0.34
≥75	3.34	3.17	−4.3	−10.4 to 2.2	0.19

[a] Adjusted for smoothed mortality rates by cause in Coastal counties, influenza weeks, and temperature.

[b] Causes in **boldface** are principal categories; the rest are subcategories.

Appendix K. Effects of the 1995 Coal Ban on Hospital Admissions in Cork County Borough

This appendix provides more detailed presentations of the analyses of hospital admissions in Cork County Borough and the estimated effects of the 1995 coal ban. Season-specific directly standardized and normalized hospital admissions rates are presented for all cardiovascular causes and two major subcategories (Figure K.1) and all respiratory causes and three major subcategories (Figure K.2).

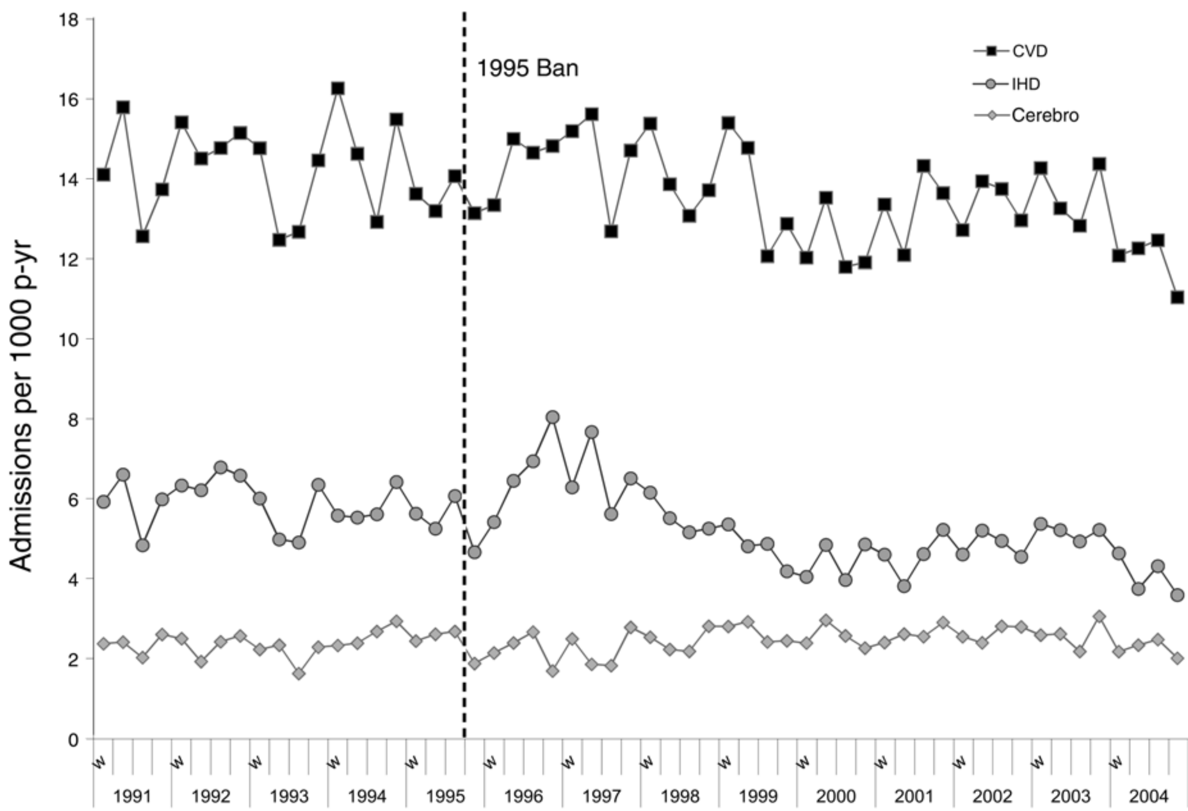


Figure K.1. Mean Cork County Borough hospital admissions rates by cause and season, directly standardized to the 1996 Irish population and normalized for underreporting to 1996 annual admissions for digestive disease. Causes include all cardiovascular disease (CVD) and two subcategories, ischemic heart (IHD) and cerebrovascular (Cerebro) disease. W indicates winter.

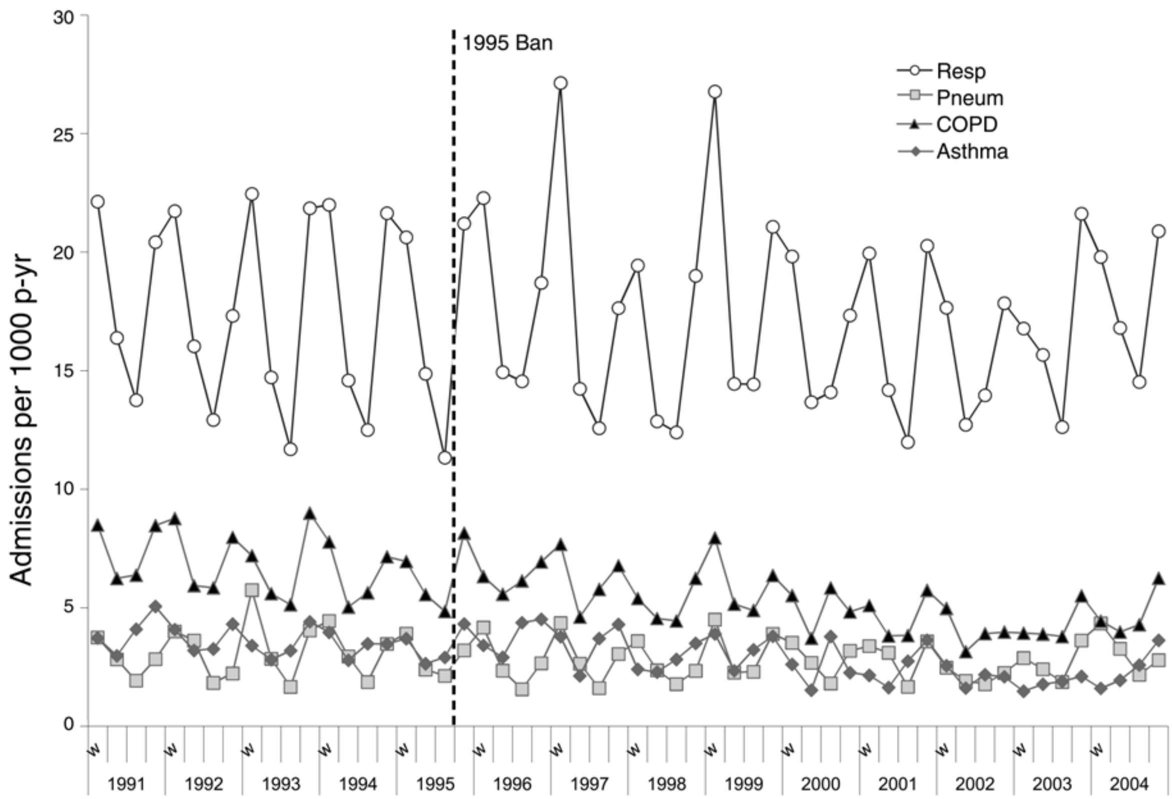


Figure K.2. Mean Cork County Borough hospital admissions rates by cause and season, directly standardized to the 1996 Irish population and normalized for underreporting to 1996 annual admissions for digestive disease. Causes include all respiratory (Resp) disease and three subcategories, pneumonia (Pneum), COPD, and asthma. W indicates winter.

APPENDIX L. Effects of the 1998 Coal Ban on Hospital Admissions in Affected Counties

This appendix provides more detailed presentations of the analyses of hospital admissions in the four counties affected by the 1998 coal ban. Season-specific directly standardized and normalized hospital admissions rates are presented for all cardiovascular causes and two major sub-categories (Figure L.1) and all respiratory causes and three major subcategories (Figure L.2). Table L.1 presents the county-specific and combined estimated effects of the 1998 ban stratified by heating versus non-heating seasons.

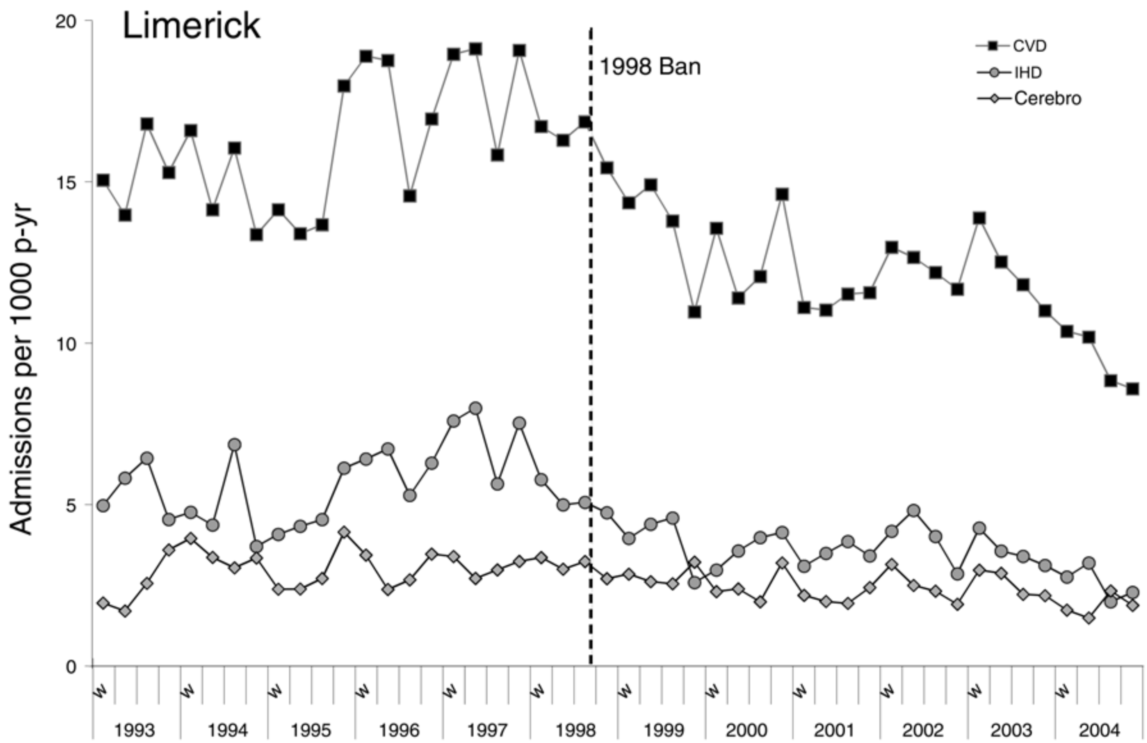


Figure L.1. Mean hospital admissions by cause and season for each of the four counties affected by the 1998 coal ban, directly standardized to the 1996 Irish population and normalized for underreporting to 1998 annual admissions for digestive disease. Causes include all cardiovascular disease (CVD) and two subcategories, ischemic heart (IHD) and cerebrovascular (Cerebro) disease. W indicates winter. (*Figure continues next page.*)

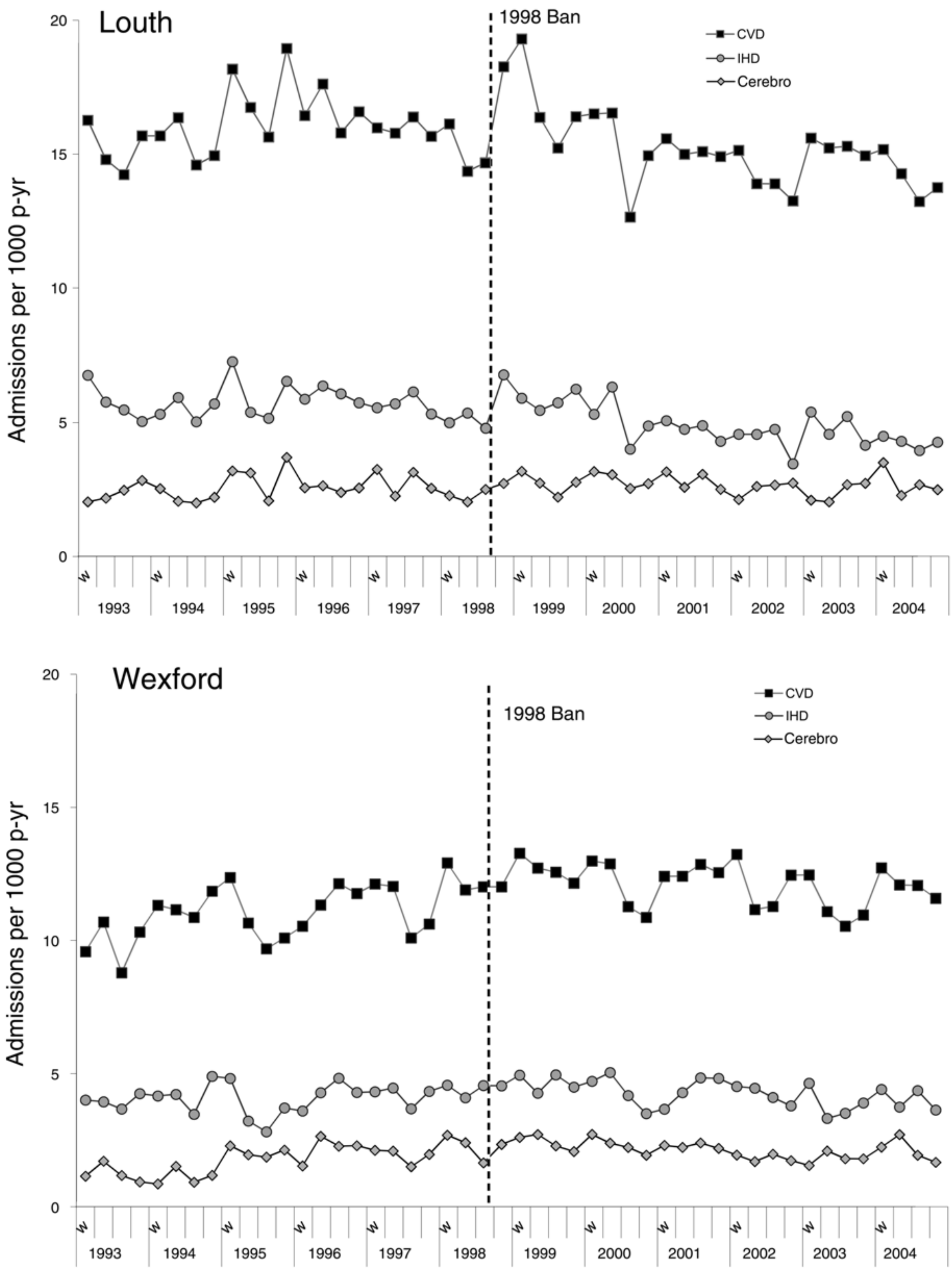
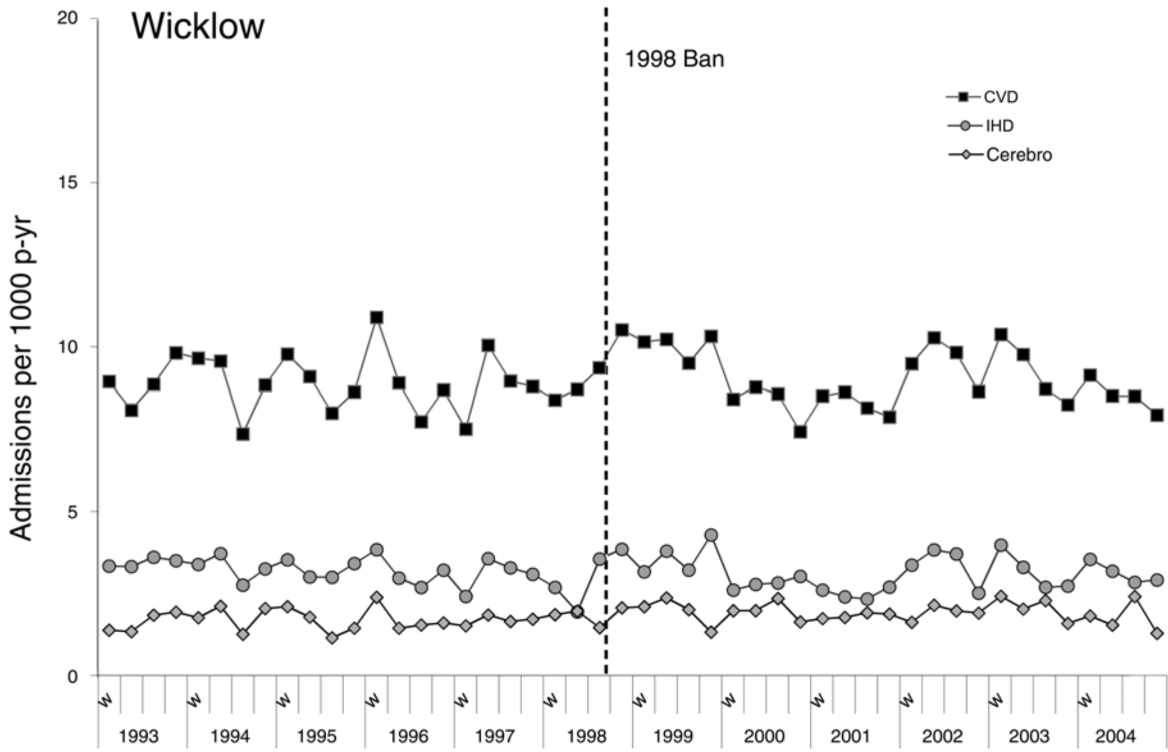


Figure L.1 (*Continued*).



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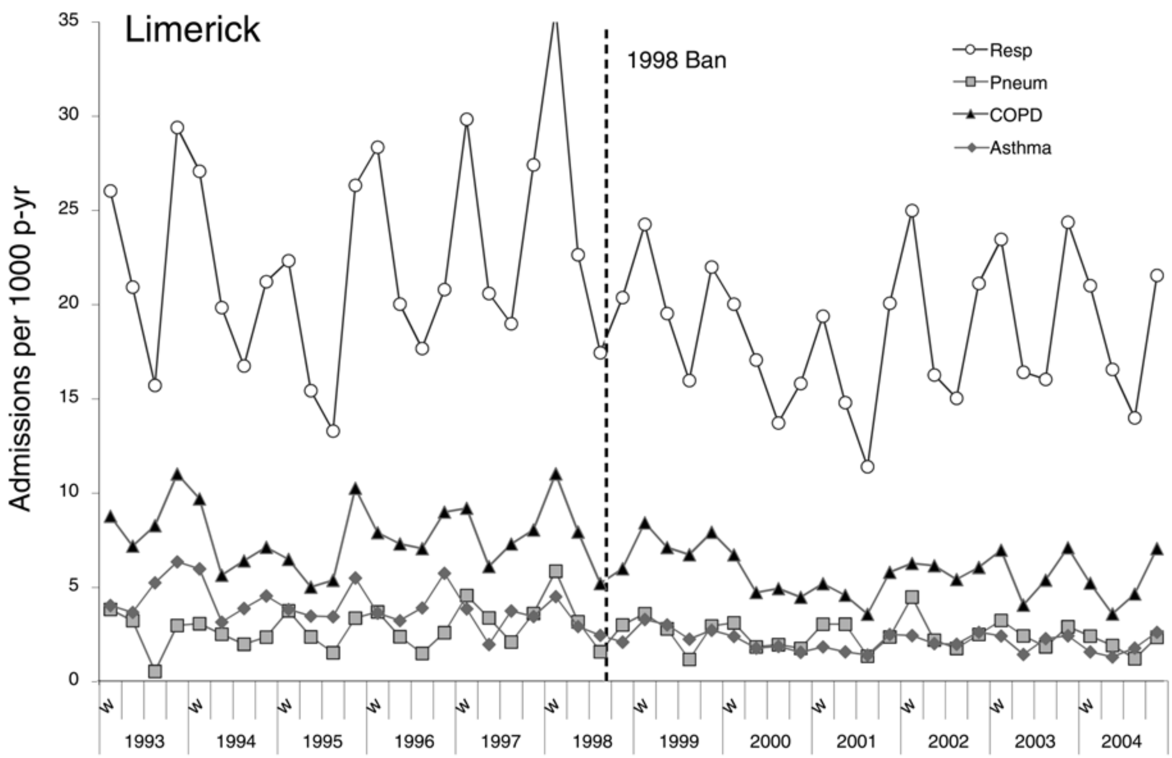
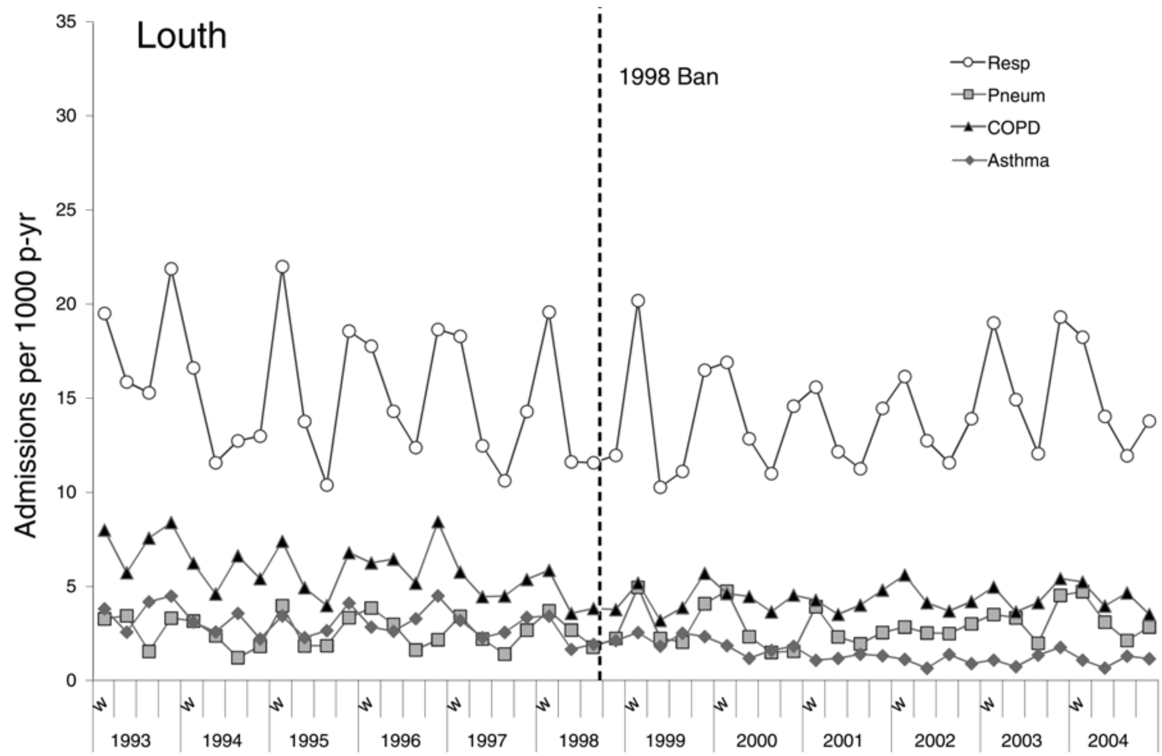
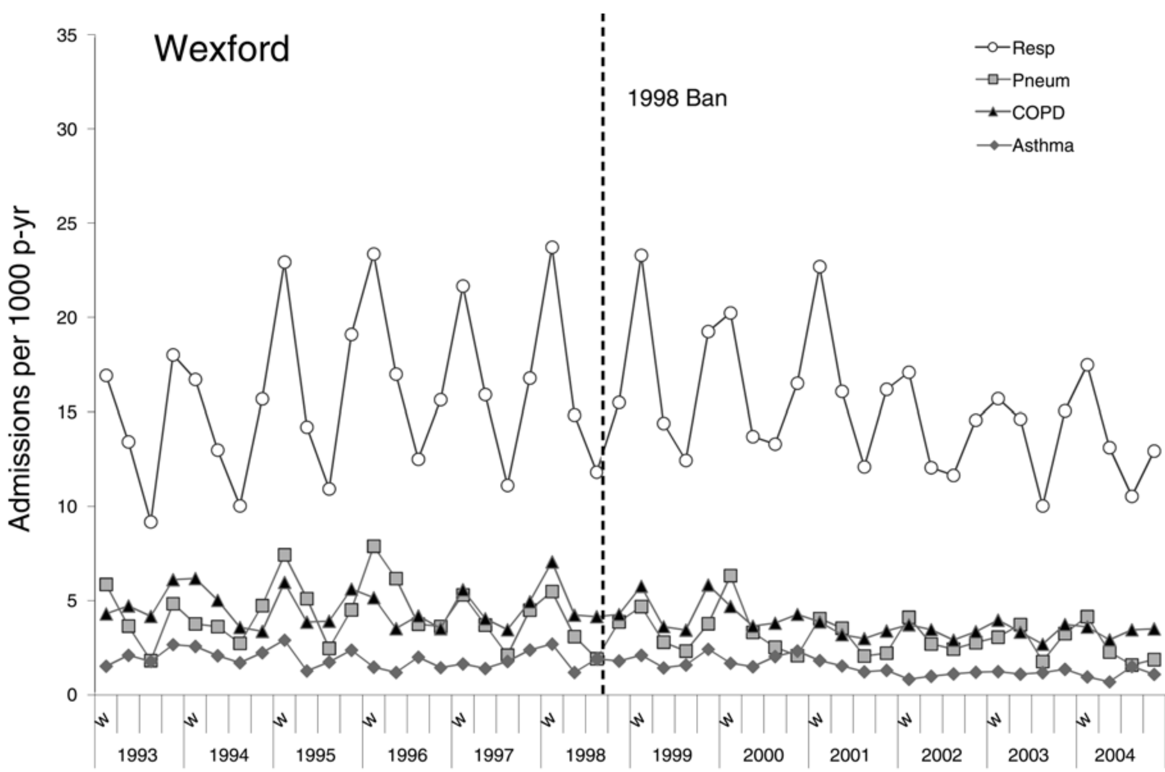


Figure L.2. Mean hospital admissions by cause and season for each of the four counties affected by the 1998 coal ban, directly standardized to the 1996 Irish population and normalized for underreporting to 1998 annual admissions for digestive disease. Causes include all respiratory (Resp) disease and the three subcategories pneumonia (Pneum), COPD, and asthma. W indicates winter. (*Figure continues next page.*)





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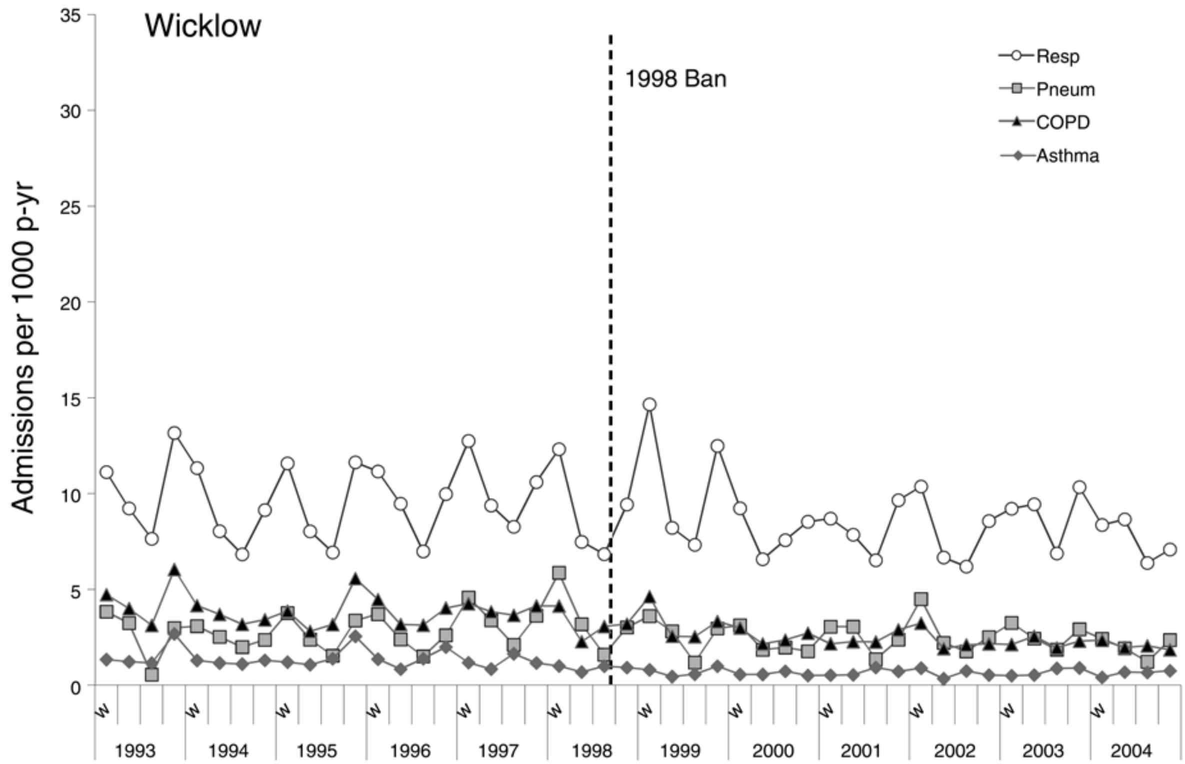

Figure L.2 (*Continued*).

Table L.1. Estimated Percentage Changes in County and Combined Standardized, Normalized Hospital Admissions Rates by Cause for the Heating and Non-Heating Seasons (1993 to 2004) After the 1998 Coal Ban Compared with Pre-Ban Rates[a]

	Heating Season			Non-Heating Season		
Cause / County	Change (%)	95% CI	*P*	Change (%)	95% CI	*P*
Cardiovascular Disease						
Limerick	−5.0	−11.3 to 1.8	0.14	0.2	−6.4 to 7.2	0.96
Louth	−2.3	−11.7 to 8.1	0.66	−1.9	−11.4 to 8.5	0.70
Wexford	11.4	2.2 to 21.4	0.014	13.0	3.8 to 22.9	0.005
Wicklow	−6.3	−13.3 to 1.2	0.10	7.0	−1.2 to 16.0	0.10
Combined	−1.5	−5.4 to 2.5	0.45	4.4	0.2 to 8.7	0.04
Ischemic heart disease						
Limerick	−5.7	−16.6 to 6.5	0.34	−5.5	−15.8 to 6.1	0.34
Louth	−15.4	−29.0 to 0.8	0.06	−14.7	−28.1 to 1.4	0.07
Wexford	2.3	−11.1 to 17.7	0.75	20.5	4.5 to 39.0	0.011
Wicklow	−12.6	−23.1 to −0.5	0.04	−0.6	−13.0 to 13.6	0.93
Combined	−7.5	−13.6 to −0.9	0.03	−0.4	−6.9 to 6.7	0.92
Cerebrovascular disease						
Limerick	−1.6	−16.1 to 15.4	0.84	−1.5	−15.7 to 15.1	0.85
Louth	13.8	−10.6 to 44.9	0.29	7.0	−16.7 to 37.5	0.60
Wexford	37.6	10.5 to 71.4	0.004	6.5	−13.0 to 30.3	0.54
Wicklow	1.2	−15.1 to 20.5	0.90	17.2	−2.1 to 40.4	0.08
Combined	8.1	−1.7 to 18.9	0.11	6.3	−3.3 to 16.8	0.20
Respiratory Disease						
Limerick	−2.1	−7.2 to 3.4	0.45	1.9	−4.3 to 8.5	0.56
Louth	8.3	−1.7 to 19.2	0.11	−1.1	−11.4 to 10.4	0.84
Wexford	−5.8	−11.9 to 0.7	0.08	2.7	−5.1 to 11.1	0.51
Wicklow	−9.6	−15.9 to −2.9	0.006	−2.8	−10.7 to 5.7	0.50
Combined	−3.6	−6.8 to −0.2	0.04	0.6	−3.3 to 4.7	0.75
Pneumonia						
Limerick	13.7	−1.6 to 31.4	0.082	3.2	−1.6 to 31.4	0.74
Louth	21.8	−2.0 to 51.3	0.076	36.3	−2.0 to 51.3	0.022
Wexford	−36.1	−43.8 to −27.5	< 0.0001	−35.4	−43.8 to −27.5	< 0.0001
Wicklow	3.7	−10.8 to 20.4	0.64	17.9	−10.8 to 20.4	0.09
Combined	−8.6	−15.2 to −1.4	0.02	−7.2	−15.2 to −1.4	0.12
COPD						
Limerick	−4.6	−13.2 to 5.0	0.34	−6.2	−13.2 to 5.0	0.23
Louth	−8.1	−22.3 to 8.7	0.33	−23.5	−22.3 to 8.7	0.0038
Wexford	−11.6	−22.5 to 0.8	0.067	−11.5	−22.5 to 0.8	0.094
Wicklow	−31.7	−39.4 to −22.9	< 0.0001	−23.4	−39.4 to −22.9	0.0001
Combined	−14.1	−19.2 to −8.8	< 0.0001	−14.2	−19.2 to −8.8	< 0.0001
Asthma						
Limerick	−32.3	−41.3 to −22.0	< 0.0001	−29.2	−41.3 to −22.0	< 0.0001
Louth	−14.6	−34.3 to 10.8	0.23	−36.7	−34.3 to 10.8	0.0008
Wexford	−15.3	−31.7 to 5.0	0.13	−9.5	−31.7 to 5.0	0.38
Wicklow	−50.3	−60.1 to −38.1	< 0.0001	−34.2	−60.1 to −38.1	0.0003
Combined	−31.1	−37.5 to −24.1	< 0.0001	−27.7	−37.5 to −24.1	< 0.0001

[a] Estimated by Poisson regression adjusted for weekly temperature, influenza epidemics, and hospital admissions for digestive disease. County estimates were combined by inverse-variance weighting.

[b] Causes in **boldface** are principal categories; the rest are subcategories.

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OTHER PUBLICATIONS RESULTING FROM THIS RESEARCH

Goodman PG, Rich DQ, Zeka A, Clancy L, Dockery DW. 2009. Effect of air pollution controls on black smoke and sulfur dioxide concentrations across Ireland. J Air Waste Manag Assoc 59:207–213.

ABBREVIATIONS AND OTHER TERMS

BS	black smoke
COPD	chronic obstructive pulmonary disease
ESRI	Economic and Social Research Institute
HIPE	hospital in-patient enquiry
ICD-9	International Classification of Disease, Ninth Revision
ICD-9-CM	International Classification of Disease, Ninth Revision, Clinical Modification
Irish EPA	Irish Environmental Protection Agency
NO_2	nitrogen dioxide
p-yr	person-year
$PM_{2.5}$	particulate matter ≤ 2.5 µm in aerodynamic diameter
PM_{10}	particulate matter ≤ 10 µm in aerodynamic diameter
RFA	Request for Applications
SO_2	sulfur dioxide
TGA	total gaseous acidity

COMMENTARY
Health Review Committee

HEI

Research Report 176, *Effect of Air Pollution Control on Mortality and Hospital Admissions in Ireland,* D.W. Dockery et al.

INTRODUCTION

Over the past two decades, numerous studies have documented associations of air pollution with adverse effects on human health (Pope and Dockery 2006; Rückerl et al. 2011). Such evidence has led to the implementation of air quality standards to protect public health. The standard for particulate matter (specifically, particulate matter ≤ 2.5 µm in aerodynamic diameter [$PM_{2.5}$]*) is one of the most stringent, and recently has been tightened in the United States (U.S. Environmental Protection Agency [EPA] 2012). Air quality has improved substantially over the years in the United States and Western Europe, with downward trends in concentrations of several major pollutants. In large part, these air quality improvements have been achieved through effective control of emissions from both stationary and mobile air pollution sources. Such interventions to improve air quality have taken place on different scales (local, regional, or national) in many locations around the world.

To date, however, few interventions have been systematically evaluated to assess their actual impacts on air quality and health. The need to ensure that those policies are effective at achieving their intended public health benefits has been an important driving force for HEI's outcomes research (previously referred to as accountability research).

HEI launched an initiative to improve the evidentiary basis for assessing the health impact of interventions to improve air quality with its 2000–2005 Strategic Plan (Health Effects Institute 2000). In 2003, HEI published a monograph setting out a conceptual framework to address research needs; it identified the types of evidence required as well as the methods by which that evidence could be obtained (HEI Accountability Working Group 2003). Four Requests for Applications (RFAs), issued between 2002 and 2004, solicited studies to measure the health impacts of actions taken to improve air quality (see Preface). The study led by Dr. Douglas W. Dockery of Harvard School of Public Health was funded under an RFA that sought proposals for studies of the health effects of real-world experiments, that is, planned actions taken with the intent of improving air quality or other actions that might have resulted in changes in air quality.

Dockery, with principal collaborators Dr. Luke Clancy, of the TobaccoFree Research Institute, Dublin, and Dr. Patrick Goodman, of the Dublin Institute of Technology, proposed to extend a widely cited analysis conducted by Clancy and colleagues (2002) on the impact on air quality and mortality of a 1990 ban by the Irish government on the marketing, sale, and distribution of coal in Dublin, Ireland. That study reported that the ban had led to a 71% decrease in the mean concentration of ambient black smoke (BS), from 50.2 µg/m³ (pre-ban) to 14.6 µg/m³ (post-ban), and a 34% decrease in the mean concentration of sulfur dioxide (SO_2, measured as total gaseous acidity), from 33.4 to 22.1 µg/m³. Concomitantly, the investigators observed decreases of 6%, 16%, and 10% in total, respiratory, and cardiovascular mortality, respectively, which they attributed primarily to the decrease in particulate air pollution brought about by the coal ban (Clancy et al. 2002). The Irish government extended the ban to 11 smaller Irish cities: first to Cork, Ireland's second largest city, in 1995; then to Arklow, Drogheda, Dundalk, Limerick, and Wexford in 1998; and finally to Celbridge, Galway, Leixlip, Naas, and Waterford in 2000.

In the current study, Dockery and colleagues extended their earlier work on the effects of the ban in Dublin to the effects of the bans in these 11 cities. In addition to including more cities, their study (1) doubled the study period from 12 to 24 years; (2) included hospital admissions data in the health evaluation; (3) analyzed changes in mortality in a "comparison" population (a population living in cities where bans had not been implemented and assumed to be unaffected by the bans under investigation); and (4) corrected changes in mortality for background

Dr. Douglas W. Dockery's 3-year study, "Effects of Air Pollution on Mortality and Hospital Admissions in Ireland," began in March 2003. Total expenditures were $590,023. The draft Investigators' Report from Dockery and colleagues was received for review in January 2010. A revised report, received in March 2011, was later revised again in December 2011 and was accepted for publication in February 2012. During the review process, the HEI Health Review Committee and the investigators had the opportunity to exchange comments and to clarify issues in both the Investigators' Report and the Review Committee's Commentary.

* A list of abbreviations and other terms appears at the end of the Investigators' Report.

trends in mortality that may have been occurring because of other changes over time by using a different Irish "reference" population than they had used in the earlier study.

This Commentary is intended to aid the sponsors of HEI and the public by highlighting both the strengths and limitations of the study and by placing the Investigators' Report (IR) into scientific and regulatory perspective.

STUDY SUMMARY

STUDY OBJECTIVES

Dockery and his colleagues assessed the effect of the bans on coal sales implemented in 12 Irish cities from 1990 to 2000 on air pollution and health. The specific objectives of the study were to

- Quantify the effects of the coal sale ban on particulate (BS) and SO_2 pollution.
- Quantify the effect of the coal sale ban on total (non-accidental or non-trauma), cardiovascular, and respiratory mortality adjusted for age and sex distribution of the population, weather, season (climate), influenza epidemics, and background trends in mortality.
- Quantify the effect of the coal ban on hospital admissions for cardiovascular and respiratory disease, adjusted for age and sex distribution of the population, weather, season (climate), and influenza epidemics.

The effects on mortality were assessed after the 1990, 1995, and 1998 bans. Effects on hospital admissions were studied after the 1995 and 1998 bans. Effects on mortality and hospital admissions were estimated separately for the ban in each city; in addition, a combined effect was calculated for the smaller cities affected by the 1998 ban.

METHODS

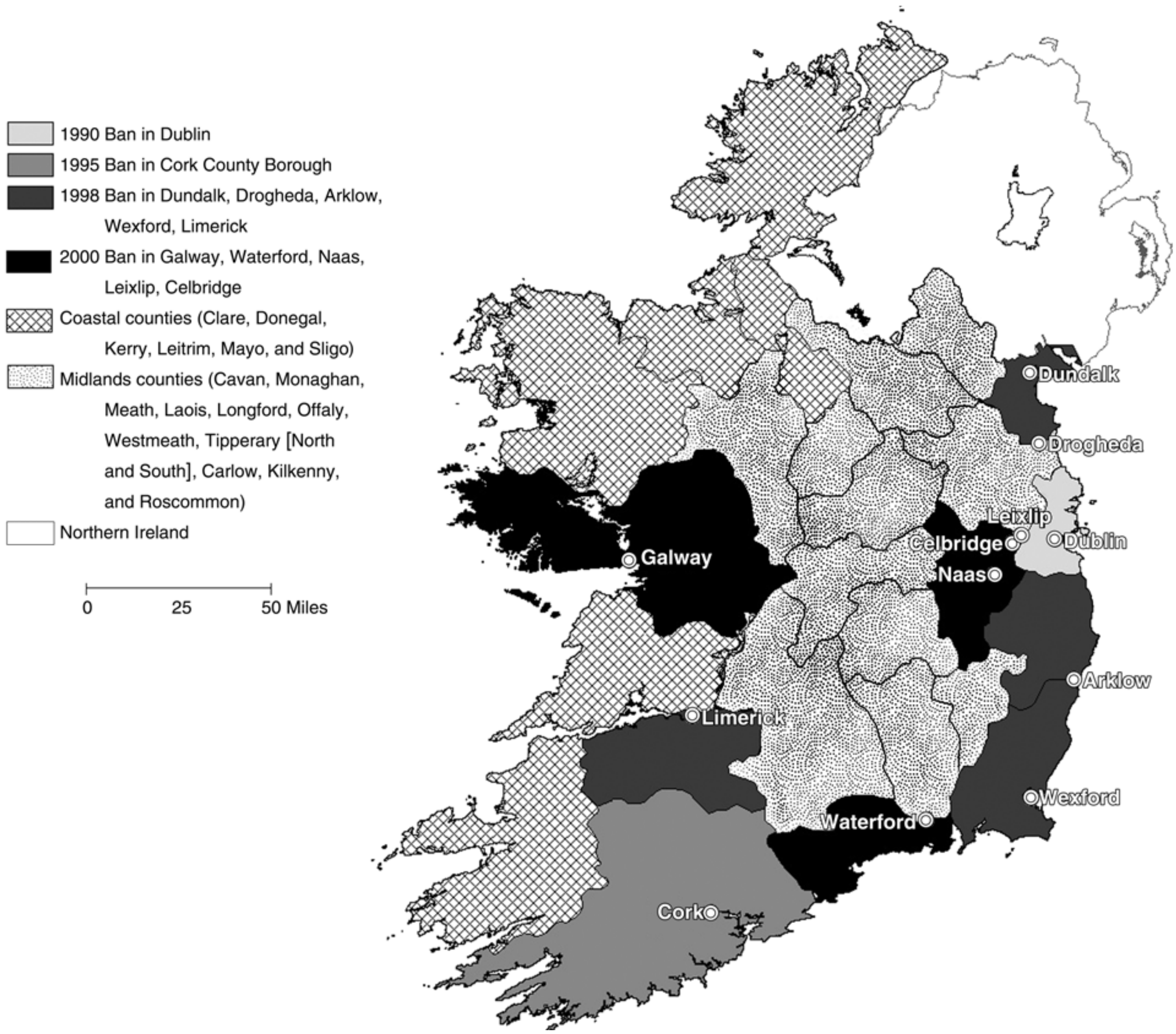
Study Populations

The Republic of Ireland is a relatively small country (approximately 69,300 km^2), with a 1996 census population of about 3.6 million and a population density of approximately 52 persons per km^2. The study focused on the Republic of Ireland, which consists of 26 counties, not including the 6 counties that comprise Northern Ireland (part of the United Kingdom). Commentary Figure 1 provides a map of Ireland showing three populations that the investigators defined for different purposes: the study population, the primary focus of the study, was drawn from the cities and related counties in which bans were implemented; a "comparison" population, residing in counties where no bans were implemented; and a "reference" population, used to adjust for long-term secular trends in health in both the study and comparison populations. Each is described briefly below.

Study Population in Areas with Coal Bans The study population was drawn from 12 cities in which coal bans were instituted, located in nine different counties. The 12 cities affected by the various bans are located in three geographic regions — seven in the east, three in the south, and two in the midwest; most are on the east coast (see Commentary Figure 1). Dublin, located in the east, is the largest city in the Republic of Ireland with a 1996 census population of 481,854. Cork, located in the south, the second largest Irish city, is a major port and industrial area with a population of 127,187. The other cities affected by the later bans (in 1998 and 2000) were much smaller (1996 census population ranged between 8,557 and 57,241). Commentary Table 1 presents an overview of the study characteristics of each of the ban-affected cities and associated counties (population, number of air pollution monitors, health evaluations conducted, and study periods).

Comparison Population in Areas without Coal Bans A new feature of this study of the coal bans relative to the earlier study in Dublin was that the investigators planned to compare changes in health outcomes in the study population (ban areas) with those in an appropriate "comparison" population in which coal bans were not instituted and that were assumed to be unaffected by the bans in the neighboring counties. The purpose of this comparison was to provide an additional assessment of whether any effects observed in ban areas could be attributed to the coal bans or to other factors that might also have led to changes in air pollution and health over the same time periods. The comparison population (711,993 people in 1996) was drawn from the 12 Midlands counties shown in Commentary Figure 1. These 12 counties were more agricultural than the ban-affected counties but the population was generally similar (in terms of age, sex ratios, population density, percentage of land used for farming, and total income level) to the populations affected by the bans (with the exception of Dublin).

Reference Population As in other intervention studies, a "reference" population was used to adjust for potential background trends in health in Ireland over the study period resulting from economic, societal, or other trends unrelated to the coal bans under investigation. The study was conducted at a time when Ireland's economic fortunes were rising, the so-called Celtic Tiger period that started in the mid 1990s and ended in about 2008.



Commentary Figure 1. Map of Ireland showing the locations of the study population (cities and counties affected by the 1990, 1995, 1998, and 2000 coal bans), the "comparison" population (the Midlands counties), and the reference population (the Coastal counties). Northern Ireland was not included in the study.

The reference population available for this study (542,532 people in 1996) lived in six western coastal counties in Ireland (referred to as the Coastal counties or reference counties) that were more distant from the ban-affected counties. Although the reference counties were more rural and less developed compared with the counties directly affected by the bans, the limited data available on county characteristics suggested that the two populations were more or less similar. The one exception was Dublin, which had a higher population density and higher incomes, a higher proportion of women, and younger average age than the reference population. The previous study of the coal ban in Dublin had used the entire remaining population of the Republic of Ireland as the reference population.

The reference (Coastal) population was used to adjust mortality, but not hospitalization, rates in both the study (ban area) population and the comparison (Midlands) population. Hospital admissions data were not available for the reference and comparison populations. Therefore, a different approach was used to account for background trends in hospital admissions in the study population (see Hospital Admissions in the Statistical Analyses section below).

Air Pollution Data

In the 12 cities affected by the ban, daily BS and SO_2 measurements were compiled from 1981 to 2004 from fixed-site monitors. These were the only pollutants for

Commentary Table 1. Overview of the Population, Health, and Monitoring Data Available for the Cities and Counties Affected by the Coal Bans

Ban Year / City	County	City Population[a]	County Population[a]	Number of Monitors	Health Evaluation	Study Period[b]
1990						
Dublin	Not used	481,854	481,854	6	Mortality	1981–2004
1995						
Cork	Cork	127,187	420,510	6	Mortality Hospital admissions	1981–2004 1991–2004
1998						
Arklow	Wicklow	8,557	102,683	1	Mortality Hospital admissions	1981–2004 1993–2004
Wexford	Wexford	15,862	104,371	— [c]	Mortality Hospital admissions	1981–2004 1993–2004
Limerick	Limerick	52,039	165,042	4	Mortality Hospital admissions	1981–2004 1993–2004
Dundalk	Louth	25,762	92,166	2	Mortality Hospital admissions	1981–2004 1993–2004
Drogheda	Louth	24,460	92,166	1	Mortality Hospital admissions	1981–2004 1993–2004
2000						
Naas	Kildare	14,074	134,992	1	Not included	
Leixlip	Kildare	12,451	134,992	1	Not included	
Celbridge	Kildare	12,289	134,992	1	Not included	
Waterford	Waterford	42,540	94,680	2	Not included	
Galway	Galway	57,241	188,854	3	Not included	

[a] Based on the 1996 Census population.

[b] The first study period listed is for the air pollution and the mortality analyses; the second is for the hospital admissions analyses. Although air pollution data were compiled for the period 1981–2004, analyses focused mainly on the 5 years before and 5 years after the bans (see Statistical Analyses section).

[c] Monitoring data were available only before the ban.

which regular monitoring data were available for the study period and were obtained from the Irish Environmental Protection Agency (Irish EPA). As indicated in Commentary Table 1, the number of monitors available for analysis differed per city and ranged from one (e.g., Arklow and Drogheda) to six (Dublin and Cork). No air pollution data were available from Wexford after the ban. BS was measured by reflectometry and SO_2 was measured as total gaseous acidity (TGA) (British Standards Institute 1969, 1983). Although the authors assumed all the gaseous acidity was from SO_2, other acidic and alkaline gases including nitrogen dioxide (NO_2) were also likely to have affected the measurements. As discussed more fully in the Health Review Committee Evaluation section, the Committee therefore preferred that this metric be referred to as TGA rather than SO_2.

Health Data

The effects on mortality were assessed after the 1990, 1995, and 1998 bans (see Commentary Table 1). Effects on hospital admissions were studied after the 1995 and 1998 bans, but not after the 1990 ban because of limited availability of comparison data before 1990. The investigators did not evaluate the effects of the 2000 ban because little follow-up time had accrued when this study began in 2003.

Mortality Daily total non-accidental and cause-specific mortality data on all deaths in Ireland were obtained from death certificates for the 24-year period from January 1, 1981, to December 31, 2004. The periods from January 1, 1981, to the date of each county-specific ban (September 1, 1990, for Dublin; October 1, 1995, for county Cork; or October 1, 1998, for the counties Limerick, Louth, Wexford, and Wicklow) were defined as pre-ban, and the periods after these dates until December 31, 2004, were defined as post-ban.

To adjust for changes in age and sex distribution in the Irish population throughout the study period, daily mortality rates were directly standardized by age (using 5-year age categories) and sex, first using the linearly interpolated county-specific census population (which was updated every 5 years), and then finally using the 1996 total Irish population as the standard population.

Rather than use daily standardized mortality rates as in the original Dublin study, the investigators summed the daily standardized mortality rates to produce a weekly standardized rate, which could be matched with weekly indicators of influenza epidemics.

For all bans except the Dublin 1990 ban, mortality data were aggregated at the county instead of city level. The main reason for this was that the investigators found that the exact coding of residence in the death records for areas smaller than a county was not reliable for the later bans.

Hospital Admissions Given the more limited availability of data on hospitalization admissions, the study periods for the analyses of these data were about half the length of those for the mortality data. Daily counts of hospital admissions for cardiovascular and respiratory diagnoses were compiled for 1991 through 2004 for residents of county Cork affected by the 1995 ban and for 1993 through 2004 for residents of the counties affected by the 1998 ban. Pre- and post-ban periods were defined as in the mortality analysis.

Using the same methods as for mortality, the investigators compiled weekly hospital admissions rates, standardized by age and sex. In the course of their analysis, the investigators found that hospital admissions were seriously underreported, especially before 1995, after which point greater than 90% of actual admissions were estimated to be reported. Therefore, they developed an approach for correcting hospital admissions for underreporting in each city by using annual admissions for digestive-disease diagnoses obtained from hospitals in the same ban-affected counties.

Other Variables

In time-series analyses, investigators typically adjust for the presence of influenza episodes because they can also affect patterns of mortality and morbidity, especially in winter. Because there was no routine influenza surveillance system in Ireland during the study period, the investigators relied on an alternative approach to adjust for influenza. For each week of the year, they calculated the percentages of total deaths in Ireland for which pneumonia and influenza was listed as the cause of death and compared these with the percentages that would normally be expected given seasonal patterns. Influenza episodes were defined as at least two consecutive weeks in which the percentage of deaths from influenza and pneumonia was higher than the 95th percentile of expected deaths.

Temperature can also substantially affect both air pollution and mortality and morbidity patterns. In this study, the mean temperature for each week was calculated from hourly observations at one nearby weather station (for the 1990 and 1995 ban). In the 1998 ban, the investigators used data from three nearby weather stations located in three counties.

STATISTICAL ANALYSES

Air Pollution

For each of the cities with multiple monitors, the investigators calculated the mean BS and TGA concentrations across the reporting monitors in each city. Season-specific averages are shown in graphs in the IR for the entire study period (1981–2004) and for the 5 years before and after the respective bans. Descriptive statistics were used to characterize BS and TGA concentrations for 5 years before and after each coal ban was implemented. They used t statistics to test for differences in the mean and the maximum concentrations between the pre- and post-ban periods. P values less than 0.05 were considered to indicate statistical significance.

Mortality

The investigators used an "interrupted" time-series analysis to estimate the change in mortality rates after each coal ban. Typically time-series analyses of air pollution and health estimate the effects of day-to-day variations in air pollution on day-to-day variations in mortality or morbidity counts after seasonal and long-term trends, weather, and influenza epidemics have been taken into account. In situations such as in this study, in which the intervention implemented leads to substantial and immediate changes in air pollution levels, an interrupted-time-series analysis may be used in which a binary indicator variable is used to separate the data for the periods before and after the ban. Using this method, the actual changes in concentrations of air pollutants are not used in the analyses.

With the use of Poisson regression models, the investigators regressed the mortality rates on this indicator variable (i.e., before or after the ban), adjusting for the seasonal and long-term background trends, weather, and influenza epidemics. Specifically, the logarithm of the weekly (cause-specific) standardized mortality rate was the dependent variable. An indicator variable for influenza, a linear term for mean weekly temperature, and smoothing function for background mortality rates were added to the model as covariates. The investigators modeled background mortality rates, derived from the reference population (Coastal counties) described earlier, using a Loess smooth function to adjust for long-term mortality trends and seasonal variation. They explored several approaches to adjusting statistically for background trends in extensive simulation analyses (see IR Appendix G). Ultimately, they decided to use a smoothing window of 25 weeks (about 6 months).

They used Proc GenMod procedures in a SAS statistical software package to estimate the regression parameters via maximum likelihood estimation. In their models, the weekly mortality rates were assumed to be statistically independent, which is generally not the case. The investigators justified this assumption by their extensive correction for background trends, which removed most of the correlation between mortality rates for sequential weeks within the ban areas. Tests for significance of the ban effect were conducted via Wald tests. Results were expressed as the percentage change in mortality with 95% confidence intervals per city.

Because of the relatively small populations in the four 1998 ban counties, the investigators decided to combine the estimates to increase the power of the study. They combined individual county estimates for the 1998 ban into a single estimate, using weights equal to the inverse of the variance of the county-specific estimates (the larger the county, the smaller the variance of the estimate and the larger the weight).

Finally, the investigators repeated the mortality analysis using the data from the comparison population (the Midlands counties) and compared the two sets of results.

Hospital Admissions

For cardiovascular and respiratory hospital admissions, the investigators used the same statistical approach as for the mortality analyses. An exception was that, in the absence of a reference population to account for background trends in hospital admissions, they developed a different approach. Specifically, they included a smooth function (with a similar smoothing window as in the mortality analysis) in their models for the county-specific weekly hospital admissions rate of digestive-disease diagnoses. Moreover, their method to correct for underreporting, as described above, was intended to correct for long-term background trends in health throughout the study years as well. In addition, no comparison counties were available for analysis.

Additional Sensitivity and Simulation Analyses

Given that the goal of the coal ban was to reduce air pollution levels mainly in the heating season (November–April), the health analysis was repeated with an extra indicator variable for season (heating versus nonheating season) and an interaction term ("season*ban") was added to the main model. In addition, whereas the main analyses were conducted for all ages, sensitivity analyses were done separately using two age groups (0–74 years and ≥75 years) for the mortality analyses.

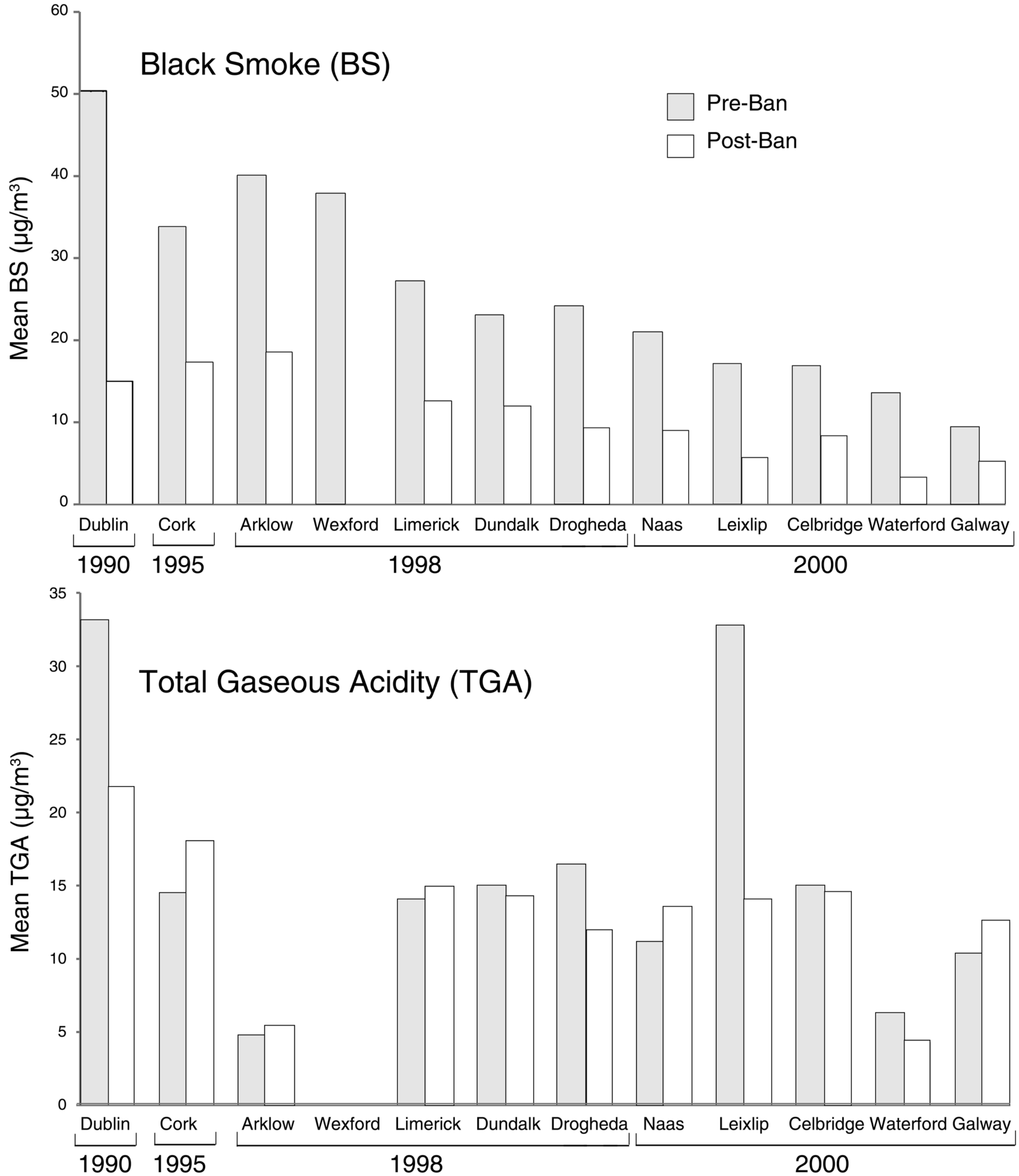
Comparison of Current and Previous Approaches to Investigating the Dublin Ban

Although the basic approach of this study was similar to that taken in the previous study of the effects of the Dublin coal ban on mortality (Clancy et al. 2002), there were some methodologic differences. Specifically, the current study used a longer study period than the previous one (24 versus 12 years) and used weekly rather than daily mortality rates. Rather than analyze changes in health outcomes only in the counties affected by the ban, it analyzed changes in a presumably unaffected comparison population from the Midland counties of Ireland. It used a different reference population (i.e., from the Coastal counties) than the original study (rather than from all of Ireland outside of Dublin) to adjust for analyses for background changes in mortality. The current study also used a different statistical method (time-matched smoothed reference rather than time-matched mortality rates) to correct for background trends and used a different Poisson regression model (GenMod rather than robust M-Estimator regression) to estimate health effects. To understand the effects of these differences on their results, the investigators evaluated them one by one in additional simulation and sensitivity analyses described in detail in the IR.

MAIN RESULTS

Air Pollution

Mean BS concentrations were lower after the ban in all cities as compared with the pre-ban period, with decreases ranging from 4 to 35 μg/m^3 (−45% to −70%) (Commentary Figure 2). The largest absolute reduction in the mean BS concentration was in Dublin (35.4 μg/m^3, 70%), which was also the city with the highest pre-ban mean BS concentrations (50.4 μg/m^3). Mean BS concentrations were lower in each successive pre-ban period. Overall variability



Commentary Figure 2. Mean of daily BS and TGA concentrations for the 5 years before (Pre) and after (Post) each of the Irish coal bans in 1990, 1995, 1998, and 2000. BS concentration decreases (Post minus Pre) were highly significant ($P < 0.0001$) for all cities. TGA concentration decreases were highly significant ($P < 0.0001$) for Dublin, Drogheda, Leixlip, and Waterford. TGA concentration increases were highly significant ($P < 0.0001$) for Cork, Limerick, Naas, and Galway.

in BS concentrations, including the number of extreme values, decreased substantially after each of the sequential coal bans. The largest decreases were in winter — when coal had been used for residential space heating — with little pre- to post-ban change in BS concentrations in summer. The effects on BS concentrations were seen immediately in the first winter after each ban and persisted more or less throughout the study period in each city (see IR Figure 11).

In contrast, TGA concentrations followed no general pattern after the bans (Commentary Figure 2). In some cities there were substantial and significant decreases in the post-ban periods (e.g., Dublin, Drogheda, Leixlip, and Waterford), whereas in other cities there were substantial increases (e.g., Cork, Naas, and Galway).

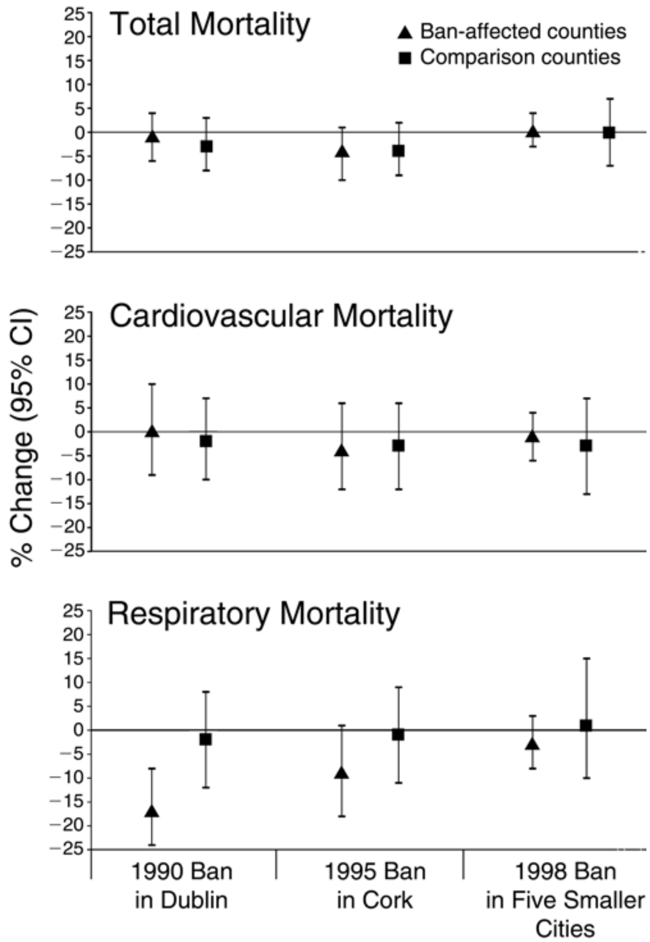
Mortality

The investigators found no decrease in total and cardiovascular mortality after the 1990, 1995, and 1998 bans in the ban-affected counties, compared with the decreases in the comparison counties (Midland counties) presumed to be unaffected by the bans (Commentary Figure 3).

They did observe a substantial decrease (−17%) in respiratory mortality in Dublin after the 1990 coal ban, a decrease that was not observed in the comparison counties (Commentary Figure 3). This decrease was larger in the heating season, compared with the nonheating season (−22% versus −11%, respectively) (see IR Figure 31 and Appendix Table J.1) and especially evident (−21%) in the oldest age group (≥75 years) (see IR Figure 32 and Appendix Table J.2). Among analyses of the subcategories of respiratory mortality, pneumonia mortality in particular decreased in Dublin (−21%), a decrease not observed in the comparison counties. Mortality from chronic obstructive pulmonary disease (COPD) also decreased in Dublin (−22%), but a similar decrease occurred in the comparison counties (see IR Table 18).

Respiratory mortality decreased by smaller percentages in the later bans — 9% after the 1995 ban in Cork and by 3% after the 1998 ban (combined for counties Limerick, Louth, Wexford, and Wicklow). No decreases were observed in the comparison counties for those time periods (Commentary Figure 3). Note that decreases in respiratory mortality were not observed consistently across the individual counties affected by the 1998 ban. In comparisons between heating and non-heating seasons, there was some evidence of a greater decrease in respiratory mortality for the heating season after the 1995 ban but not after the 1998 ban.

For the combined category of "other" causes of mortality (i.e., cancer, lung cancer, and digestive diseases), the investigators reported borderline significant decreases (−7%) only after the 1995 ban in Cork. Among these other causes of mortality, lung cancer deaths in particular decreased after all bans; however, similar decreases were observed in the comparison population (see IR Table 18).



Commentary Figure 3. Percent changes in cause-specific mortality for the ban-affected and comparison counties after the 1990, 1995, and 1998 coal bans. CI denotes confidence interval.

Hospital Admissions

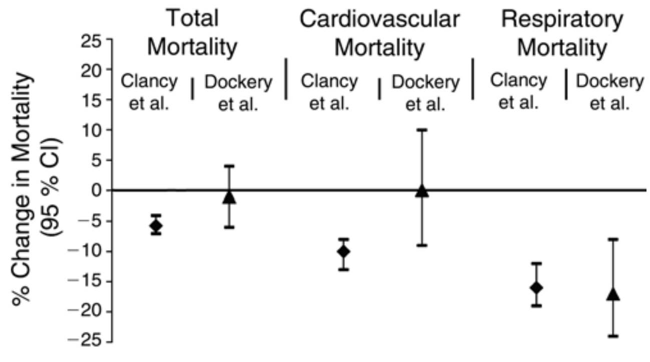
The investigators found decreases in cardiovascular hospital admissions after the 1995 and 1998 bans (−4% and −3% [combined results], respectively), although the decrease after the 1995 ban was not statistically significant (Commentary Table 2). In addition, effects on cardiovascular hospital admissions after the 1998 bans were not consistent across the individual counties (see IR Table 16).

Respiratory hospital admissions decreased substantially after the 1998 ban (−9%, combined estimate) but not after the 1995 ban (Commentary Table 2). Decreases were observed in three of the four individual counties affected

Commentary Table 2. Percentage Changes in Hospital Admissions for Cardiovascular Disease and Respiratory Disease After the Institution of Coal Bans in 1995 and 1998[a]

Disease Category / Ban Year	Percent Change in Hospital Admissions (95% CI)
Cardiovascular	
1995	−4 (−10 to 3)
1998	**−3 (−6 to −1)**
Respiratory	
1995	4 (−3 to 10)
1998	**−9 (−11 to −6)**

[a] Significant results are indicated in **bold**. The 1995 data reflect the ban in Cork. The 1998 data reflect the bans in Arklow, Wexford, Limerick, Dundalk, and Drogheda (the pooled estimate is given). Note: there were no comparison counties available for this analysis. Hospitalization data were not available for the 1990 and 2000 bans.



Commentary Figure 4. Comparison between estimated percent changes in mortality after the 1990 coal ban in Dublin from the previous study (Clancy et al. 2002) and the current study (Dockery et al. 2013). CI denotes confidence interval.

by the 1998 bans. The investigators reported substantial decreases in hospital admissions for certain subcategories of respiratory disease — namely, a combined 21% decrease in admissions for COPD and a 38% decrease in admissions for asthma after the 1998 ban. Decreases were also evident in each of the individual county estimates (IR Table 16). Decreases in admissions for COPD and asthma were also observed after the 1995 ban (−7% and −3%, respectively), although they were not statistically significant (see IR Table 14). The investigators found little consistent evidence of a difference in the effects of the 1995 and 1998 bans by heating season.

Comparison of Current and Previous Results for the 1990 Dublin Ban

Commentary Figure 4 illustrates the major differences in findings between the 2002 study by Clancy and colleagues and the current study with respect to the 1990 Dublin ban. The figure shows that the reported decrease in respiratory mortality in the current study (−17%) is similar to that reported in the previous study (−16%), although with wider confidence intervals. However, in the current study, the investigators showed effectively no decrease in total or cardiovascular mortality (−1% and 0%, respectively) after the ban, whereas the previous study reported substantial decreases (−6% and −10%, respectively). Based on extensive simulation analyses, the investigators reported that these differences were largely caused by differences in the approaches taken to correct for long-term background trends in mortality that were unrelated to the intervention being studied. The investigators stated in the current report that their previous analyses had likely "overestimated the effects of the Dublin ban on mortality rates for those causes with substantial long-term trends, that is, total and cardiovascular deaths." The adjustment for background trends is crucial to interpretation of these studies and is extensively discussed in the Health Review Committee's evaluation below.

HEALTH REVIEW COMMITTEE EVALUATION

The HEI Health Review Committee independently reviewed the study by Dockery and colleagues and found it to be an important, thoughtful, and rigorous effort. The study adds substantially to the limited number of studies of air pollution interventions and their effects on human health, providing important insights. The Committee specifically complimented the investigators on their thorough and groundbreaking effort to disentangle health effects that were related to the intervention from those that were not. In particular, the insights gained from the analysis of health outcomes in comparison counties (i.e., those presumably unaffected by the coal ban) and their application to the analysis of the intervention were considered extremely useful. The methods deployed will be likely used in other intervention studies covering long time periods.

The Committee's evaluation focused on a few important issues that might have influenced the results of the current study and that provide important lessons for future intervention studies. Their evaluation is divided into a relatively brief assessment of air pollution analyses and findings and a more extensive discussion of the health outcome analyses. The latter section focuses on the complexity of correcting properly for trends in air pollution and health that are unrelated to the intervention being investigated and on the difficulty of ensuring that there is no bias in the results. Although the primary objective of the current study was to extend the earlier work to the effects of the bans in other Irish cities, it also provided a unique opportunity to compare the approach and results of the current study with those of the original study of the effects of the 1990 ban in Dublin.

AIR POLLUTION EVALUATION

The Committee thought that the investigators provided ample evidence that the coal ban significantly reduced the concentrations of BS, particularly during the heating season, and that the results in Dublin confirmed the earlier observations by Clancy and colleagues (2002). However, the Committee thought that the investigators' comments that the BS reductions were "dramatic and immediate in all cities" should be somewhat tempered by the observation that BS concentrations were already decreasing in the years before the later bans were implemented (5, 8, and 10 years after the ban in Dublin). The reasons for this trend in decreasing BS are not fully known. One likely explanation is that, because Dublin was the main center for the importation of coal, the local ban in Dublin might have affected the availability of coal in the other cities, as well as in the rest of the country, from 1990 onward. Other changes, such as a general switch to natural gas for space heating, might also have contributed to the trend in decreasing BS concentrations.

Pollutant Measurements

The Committee considered BS to be a suitable air pollution indicator for evaluation of the coal ban because combustion is the most important source of BS. BS is highly correlated to other combustion indicators including elemental carbon (HEI Panel on the Health Effects of Traffic-Related Air Pollution 2010).

Because the exact composition of BS is difficult to characterize and depends on location, season, and combustion source, a direct comparison to more general indicators of particulate matter is not possible. In addition, BS is no longer widely measured. BS has been measured in Europe since the 1920s, but its use as a metric has been phased out since the introduction of particulate matter ≤ 10 μm in aerodynamic diameter (PM_{10}) and $PM_{2.5}$ as the new regulatory particulate metrics in most countries (although some countries, including the Netherlands, England, and Ireland, continue to measure BS in specific locations) (Janssen et al. 2011).

Although the Committee agreed with the investigators' decision to analyze TGA measurements in relation to the bans, it was not as convinced as the investigators that TGA should be interpreted primarily as a measure of SO_2. TGA is a non-specific measurement, reflecting the effects of other acidic and alkaline gases that occur in ambient air (such as nitric oxide, NO_2, nitric acid, ozone, and ammonia). Although the interpretation of TGA primarily as an indicator of SO_2 might have been valid in the past, when SO_2 concentrations were much higher, SO_2 concentrations have decreased substantially in recent decades in much of Western Europe and North America (World Health Organization [WHO] 2000). Concentrations of NO_2 and other gases might have increased during the study period as a result of an increase in traffic or other changes related to a fast-growing economy (the Celtic Tiger effect). As the investigators noted in their report, it is possible that any decrease in SO_2 that might have occurred after the coal bans might have been masked by an increase in NO_2 or other acidic or alkaline gases. The Committee thought that, ultimately, the nonspecificity of the TGA measurement was likely to have been a main reason for the inconsistent decreases found in "SO_2" concentrations after the bans. The Committee also emphasized that the overall levels of TGA were relatively low and close to the limit of detection, except in the cities of Dublin and Leixlip, where clear decreases in TGA were found.

Air Quality Monitoring

A number of factors beyond the control of the investigators limited the air pollution assessment in this study. BS and TGA were the only two pollutants that were systematically monitored in the study period, and for these pollutants only one or a few monitors per city were available. In addition, monitoring data were only available in the cities affected by the coal ban; no comparable data were available for the unaffected areas (i.e., the comparison and reference counties). The use of 5-year averages before and after the bans provided some confidence that longer-term (meteorologic) trends did not significantly affect the results. However, analysis of air pollution data from the unaffected areas, had it been available, could have shed more light on whether the BS decreases were caused just by the coal bans or also by regionwide background changes in air quality associated with other changes in policies or weather.

Pollutant Analyses and Implications for Health Outcomes Analyses

The Committee thought that Dockery et al. could have taken steps to provide a more complete characterization and interpretation of the monitoring data. The investigators did not examine whether the concentrations measured at monitors in the same cities (where available) were correlated. In addition, it was not clear where the monitors were sited or whether they represented urban background, traffic, or industrial sites. The investigators did not describe how they dealt with missing data.

In terms of the air quality analysis, the investigators did not explain their decision to focus mainly on the 5 years before and after the respective bans, given that their analysis of the health outcomes covered a much longer time period. Also, the investigators relied on simple *t* tests to evaluate differences in mean pre- and post-ban concentrations, which ignored the potential dependence structure of the data.

Despite the shortcomings noted above, the investigators' decision to evaluate observations from a variety of Irish cities where bans were implemented at different times, their relatively uniform findings of significant decreases in BS concentrations, particularly during heating seasons after the bans, and a lack of evidence for alternative explanations (e.g., other policies that might have affected air quality) provided a reasonable foundation for the health effects analyses. Further, the Committee noted that any limitations in the available air quality data did not directly hamper the health analysis in the study because the investigators relied on an indicator variable (i.e., for before and after the bans) to estimate changes in health outcomes after each ban rather than estimating the percentage change per unit decrease of a certain pollutant.

HEALTH OUTCOMES EVALUATION

The Committee thought that the authors had taken a thoughtful and defensible approach to the selection of health data and to their analysis with respect to the coal bans. The mortality analysis was thorough, and the estimates were corrected extensively for seasonal and long-term background trends, weather, and influenza epidemics. The inclusion in the health evaluation of a comparison population presumably unaffected by the bans was a valuable improvement over the earlier study. The hospital admissions evaluation was also a useful addition to the study design. However, serious underreporting issues and the lack of data from a reference population — to account for long-term hospital admissions trends — reduced the Committee's confidence in the hospital admissions results. An important challenge faced by the investigators in this study was how to account properly for long-term background trends in health associated with societal changes that occurred with Ireland's rising economic fortunes from the mid-1990s to about 2008, the so-called Celtic Tiger period, or other changes occurring at the same time that were unrelated to the policy under investigation.

The Committee agreed with the investigators that the previous study likely overestimated the effects of the Dublin ban on mortality rates for those causes with substantial long-term (decreasing) trends that might have been related to other factors (such as improved health care or healthier lifestyles). This was especially the case for the cardiovascular mortality estimates, because by 2000, cardiovascular mortality rates in Ireland were almost half their levels in the 1980s (Department of Health and Children 2003) and by 2010 had decreased by 67% from their 1980 levels (Department of Health and Children 2010). In addition, cardiovascular mortality affects total mortality because it constitutes such a large part of total mortality. Respiratory mortality was probably not overestimated in the previous study, because background changes in mortality appeared to be much smaller for respiratory causes. The lack of effect of the coal bans on cardiovascular and total mortality in the current study points to the difficulty of disentangling effects of an intervention from those of other factors that affect public health over a long time period.

Quality of Mortality Data and Standardization

The mortality data that the investigators obtained from the Irish Central Statistics Office for the study period were of high quality and offered almost complete coverage. However in the death records, the coding of residence was not reliable for areas smaller than a county for the later bans. This lead to a difference in aggregation of data for the 1990 ban in Dublin (city level) and for the later bans (county level). The investigators' approach to standardizing age and sex was valid and necessary, given the tremendous shift in population distribution over time — that is, the number of children decreased, while the number of elderly adults increased and the number of middle-aged adults (30–59 years) increased substantially over the study period. This shift was caused in part by the tremendous improvements in the Irish economy, which brought an influx of immigrants and returning Irish nationals.

Choice of Populations Affected by the Bans

The choice of study populations affected by the bans was reasonable. The decision (except for the 1990 ban in Dublin) to include all the residents in a county, not just those in the cities, increased the sample size considerably: almost half of the Irish population was eventually included in the study populations potentially affected by the bans. The analysis also covered more than two decades, adding to the power of the study. Although the power was in theory increased by including residents outside the cities, the Committee thought that this decision might have led to the underestimation of the effects of the later bans (1995 and 1998). Reductions in air pollution concentrations due to the citywide coal ban were likely to have been more pronounced inside than outside the city. Any health effects related to those reductions would, therefore, be likely to have been greater for city residents than for residents living at increasing distances away.

Choice of Populations Not Affected by the Bans

The evaluation of data from the comparison and reference populations in the analysis of mortality effects associated with the bans was an important addition to the study. Unlike the previous study, the current study included mortality analyses of a comparison population living in the middle of Ireland (the Midlands counties) that was presumably unaffected by the bans. This inclusion provided an additional assessment of whether the effects could be attributed to the coal bans or to other factors causing long-term air pollution and health changes. The reference population (which lived in several western counties [the Coastal counties] and was also presumably unaffected by the bans) was used to account for background trends in both the ban-affected populations and the comparison population. Initial analysis of data from the comparison population showed that there were residual background trends in cardiovascular and, consequently, in total mortality that had not been properly accounted for in the previous study; this was an important finding.

The importance of using comparison populations or areas in intervention studies has been highlighted in recent reviews of the literature on health outcome studies (Health Effects Institute 2010; van Erp et al. 2012). At this point in time, only a few intervention studies have made use of comparison areas in their evaluations, including the HEI-funded evaluation of traffic measures during the Atlanta Olympic Games (Peel et al. 2010) and of the congestion charging zone in London (Kelly et al. 2011). Peel and colleagues observed that the substantial reductions in ozone during the Olympic Games that had been attributed to traffic policies in an earlier study by Friedman and colleagues (2001) were also occurring in other cities in the Southeast that were unaffected by these policies, indicating that regional-scale (favorable) weather conditions might have played a large role in the ozone reductions (Peel et al. 2010). Kelly and colleagues (2011) were unable to demonstrate a clear effect of London's congestion charging zone on air quality, partly because unusual meteorologic conditions led to elevated regionwide air pollution levels at the same time and also because of the relatively small area of the zone compared with that of Greater London.

Whenever changes in air pollution and health over a long period of time are analyzed, whether using interrupted time series or other methods, it is crucial to account appropriately for possible background trends that might be related to factors other than the ones that are the focus of the analysis. This proved particularly true for the current study, which was launched to investigate the effects of the later coal bans (i.e., 1995 and 1998) during a time of great economic change in Ireland. The choice of a population to account for background mortality rates is far from trivial.

Principal Assumptions in the Choice of Reference Population The investigators chose to account for background mortality rates by using the reference population from the Coastal counties. A key assumption underlying the health analysis was that the reference population was unaffected by the bans. The Committee thought that choosing the population of the Coastal counties for use as the reference population was reasonable, especially given the prevailing westerly winds (which bring relatively clean air from the Atlantic Ocean) and the fact that the majority of the cities with coal bans were located on the eastern coast. However, the Committee noted that in a small country like Ireland it might be difficult to identify a genuine reference population unaffected by coal bans. The bans were implemented in the two largest Irish cities as well as in 10 smaller cities, and it is conceivable that these bans — along with possible related changes in fuel use over time — might also lead to considerable air quality improvements beyond those cities. If so, finding a truly unaffected reference population would be even more difficult for the later bans (1995 and 1998). If the reference population had in fact been somewhat affected by the bans, using this population to adjust for background trends could partially adjust for the effects of the bans, and hence to underestimate the bans' effects on mortality.

The second important assumption is that the reference population was comparable to the populations affected by the bans. Although the reference population chosen was the most reasonable under the circumstances, there were underlying subtle differences between it and the ban-affected populations that could have influenced the estimation of ban-related effects. The reference counties selected by the investigators were more rural than the counties directly affected by the bans. Rural populations are generally different from urban populations in age, socioeconomic status, and individual factors such as smoking; they might also have less access to health care. All are factors that can affect health. Age is by far the strongest predictor of mortality, and although all analyses were directly standardized for age, subtle differences in age distribution across populations may have influenced the results. Although there were no data on individual factors such as smoking and access to health care, small observed differences in baseline mortality rates between the reference and ban-affected counties might suggest some differences in underlying health. Specifically, the standardized total and cardiovascular mortality rates were somewhat lower in the reference counties (8.3 and 3.7 per 1000 person-years, respectively) than in the ban-affected counties (8.5–8.9 and 4.0–4.1 per 1000 person-years, respectively). On the other hand, the standardized baseline respiratory mortality rates were quite similar for the various study populations (see IR Table 4).

Given these types of questions about comparability, the investigators explored whether the choice of the reference population to correct for background trends affected the results. They compared the effect of the 1990 Dublin ban on mortality using (1) the reference Coastal counties and (2) the rest of the Republic of Ireland as they had done in the 2002 study. The results were not sensitive to this difference, which gave the Committee confidence that the reference population was thoughtfully chosen. Other intervention studies (e.g., Pope et al. 2007) have also looked at the sensitivity of the results with respect to the choice of reference populations. Pope and his colleagues estimated the mortality effects of a copper-smelter strike in four states in the American Southwest over a prolonged period of 15 years; the study also corrected for background trends in mortality using various reference populations, including the rest of the United States, the Eastern United States, or states bordering the four in which the strike took place. The reported mortality effects were quite stable, apart from the finding of a consistently smaller effect when the background mortality trends from the bordering states were used. The smaller effect might have been attributable to the possibility that the air quality of the bordering states was also affected by the strike, meaning that Pope and colleagues could have underestimated the mortality effects of the strike in that specific analysis.

The Committee emphasized that the two assumptions about the current study's reference population (that it was unaffected by the bans and that it was comparable to the ban-affected populations) apply to the comparison population as well. However, in this study, the Committee was particularly concerned about any violation of these assumptions in the reference population, because the reference population was used to account for background trends in both the ban-affected areas and the comparison areas.

Sensitivity of Results to the Statistical Approach to the Background Trends

The investigators discovered that, although the results of the study were not sensitive to the choice of reference population, they were sensitive to the statistical approach used to correct for background trends. When they explored this further in extensive simulation analyses, they found that a smooth function (with a smooth window of about 6 months) of the background rates was the most accurate reflection of the background trends.

Other intervention studies using an interrupted-time-series design have also reported similar sensitivity of results to the statistical approach used to correct for background trends. Johnston and colleagues (2013) investigated the mortality effects of a program to reduce wood smoke in a small Australian town and used population data from the rest of the state (Tasmania) and a smoothing window similar to that of the current study to adjust for background trends. Barr and colleagues (2012) evaluated the effects of a smoking ban in public places on acute myocardial infarction among the elderly in 387 counties across nine U.S. states. In the absence of a reference population, they used two approaches to account for background trends — by including either a linear function of time or different levels of a smoothing function of time. The investigators did not use other U.S. states to account for background trends; they argued that background trends differed from state to state and that many other states were already affected by smoking bans because they had partial smoking bans or a smoking ban prior to the study period. Wong and colleagues (2012) also used an interrupted-time-series design to investigate changes in mortality and life expectancy after a 1990 reduction of sulfur in fuel in Hong Kong. In the absence of a reference population, the investigators relied on other techniques, including the use of a smooth function term for time and the use of a moving average death rate. This led to considerable uncertainties in the investigators' estimates, especially in their (unconventional) analyses of the effects of life expectancy with an interrupted-time-series approach, in which a rather long time period (21 years) was evaluated. Collectively with the current Dockery report, these studies using a similar interrupted-time-series designs suggest that there is no common strategy for adjusting for background trends and that the adjustment can greatly affect the results, especially in the presence of long-term background trends.

Overall, the Committee felt that the investigators' additional sensitivity analyses demonstrated that the reference and comparison populations and the statistical model used to account for long-term background trends were thoughtfully chosen. However, there are limits to the amount of information that can be gleaned from sensitivity analyses, because they are restricted to the data at hand and still rely on assumptions that may be difficult to verify. The Committee could not rule out the possibility that bias may remain in the results obtained from this kind of interrupted-time-series study, in which the effects of the intervention on health may be confounded by long-term background trends yet it is not entirely clear how to adjust for them.

Adjustment for Influenza Epidemics

The Committee thought that the approach used to correct for influenza epidemics might have led to some overadjustment in the analysis of pneumonia mortality and, to a lesser extent, respiratory mortality. In the absence of a surveillance system for influenza in Ireland during the study period, the investigators constructed an indicator variable based on deviations in the numbers of deaths caused by influenza and pneumonia. At the same time, however, pneumonia was also one of the subcategories of respiratory mortality and was thus one of the outcome variables under study. The investigators did not provide information about the extent to which the deaths from pneumonia rather than from influenza contributed to this indicator. Although the Committee would have liked to see some sensitivity analysis, it ultimately thought that the degree of overadjustment was likely to be small.

Major Mortality Findings

The primary finding of this study was that respiratory mortality decreased by 17% after the 1990 ban in Dublin (much as the previous study found), by 9% after the 1995 ban in Cork, and by 3% after the 1998 ban in the five smaller cities. This pattern of declining decreases in effects was largely consistent with patterns of decreases in BS across the three successive bans. Although the decreases in respiratory mortality were not statistically significant in the latter bans (1995 and 1998), it is important to note that no decreases in respiratory mortality were observed in the comparison population presumably unaffected by the bans.

There were effectively no additional decreases in total and cardiovascular mortality after any of the bans when compared with the decreases in the comparison counties. These findings were clearly different from those reported in the previous study. The Committee thought that the investigators had conducted a very detailed analysis and provided a thorough discussion explaining that the differences between the two studies were largely caused by differences in the approach to correcting for background mortality trends. The Committee agreed with the investigators that the previous study had likely overestimated the effects of the Dublin ban on mortality rates for those causes with substantial background long-term (decreasing) trends, that is, cardiovascular deaths and total deaths. The Committee also agreed with the investigators that validation of the impact of air quality interventions on public health must come not only from secondary analyses or reanalyses but from replication in independent settings.

Evaluation of Hospital Admissions

The evaluation of hospital admissions was a useful addition to the study design that had not been a part of the previous study. However, the Committee thought that serious underreporting issues had hampered this evaluation. The investigators developed an ad hoc approach to adjust for underreporting by using hospital admissions for digestive-disease diagnoses. The Committee was not convinced that this approach solved the underreporting issue, and there were concerns that it might have violated the basic assumption of the investigators' statistical model (i.e., the independence of weekly hospital admissions rates). In addition, the investigators were unable to evaluate data from a reference population in order to account for trends in long-term hospital admissions or from a comparison population unaffected by the bans. These issues reduced the Committee's confidence in the hospital admissions results and led to a more cautious interpretation of the hospital admissions findings.

Confounding by Other Factors

In any study of interventions in the "real world" over a long time period, there is always a possibility that results can be confounded by other factors. In the current study, other societal changes — apart from the coal bans — that might have affected the counties with bans differently from the reference and comparison counties could have influenced the study results.

The Committee thought that the investigators had done everything in their power to investigate the coal bans thoroughly in terms of air pollution and health. Mortality estimates were corrected extensively for seasonal and long-term background trends, weather, and influenza epidemics. Detailed sensitivity and simulation analyses were performed at every step of the study. However, the Committee thought it would have been valuable if the investigators had documented other possible changes or interventions happening at the same time and had provided some insight into how these changes might have had a different impact on the affected and unaffected counties. Specifically, the coal bans were instituted during the Celtic Tiger period, a time of rising economic fortunes in Ireland, when it was the fastest-growing economy in Europe (Organisation for Economic Co-operation and Development [OECD] 2005). One could hypothesize a differential Celtic Tiger effect — that is, a set of swift changes in economic development whose impacts on health in the ban-affected counties (which were largely urban) could have differed from those of the unaffected counties (which were predominantly rural). Other differential changes over time might have included a nationwide switch to natural gas for space heating and changes in traffic, automobile emission controls, and fuel content over the same periods.

CONCLUSIONS

The Committee thought that the study by Dockery and colleagues was an important addition to the small number of studies that have investigated the effect of interventions on both air pollution and health. The investigators confirmed the existence of clear decreases in BS concentrations, particularly during the heating season, after the coal bans were implemented in the 12 cities between 1990 and 2000, beginning with the 1990 ban in Dublin. No general decrease was seen in TGA, an indicator of SO_2 concentrations, after the bans, likely because of the nonspecificity of the measurement method particularly at the lower concentrations that were present during the study period.

The study confirmed that respiratory mortality decreased after the Dublin ban and, to a somewhat lesser extent, after the later bans (1995 and 1998), a finding that was largely consistent with the decreases in BS across the three successive bans. However, the study did not find a reduction in total or cardiovascular mortality after either the 1990 ban in Dublin or the later bans. The notable difference between the previous and current study results was caused largely by differences in the approach to correcting for background mortality trends — trends unrelated to the intervention but related to other factors that affect public health over the long term.

The study holds important lessons for future intervention studies that plan to use an interrupted-time-series design in the presence of long-term background trends. The current study was conducted during a time when the Irish economy was the fastest growing in Europe and experiencing a number of social and economic changes, unrelated to the intervention under investigation, that could also have influenced trends in air pollution exposures and health. The study demonstrates the importance of using multiple approaches to evaluating and controlling for the effects of such confounding factors, including the use of comparison populations unaffected by the intervention and the use of simulation and sensitivity analyses to evaluate choices of reference populations and statistical models for adjusting for background trends. At the same time, the study illustrates the considerable challenges in this type of analysis, as it remains very difficult to disentangle the effects of the intervention from those of other factors that affect public health over the long term and to eliminate biases that lead either to overestimation or underestimation of the effects of the intervention on public health. Despite these challenges, the study provides evidence that the coal bans were effective at improving air quality and reducing mortality from respiratory disease.

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