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Does emissions trading lead to air pollution hot spots? Evidence from an urban ozone control programme

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Abstract: This study is an empirical investigation into the contentious issue of possible sub-area hot spots caused by emissions trading in a pioneering application of a cap-and-trade market approach to reducing aggregate stationary-source volatile organic compound emissions in the Chicago severe ozone non-attainment region. When sub-areas are defined as populated zip codes, 89 out of 95 affected codes revealed a decrease and six an increase in emissions over pre-trading levels. If these six sub-areas are increased slightly in size by adding adjacent zip codes, emissions will be reduced in all sub-areas. Those sub-areas with the largest initial emissions revealed the most significant reductions after trading. The study also finds that trading has significantly reduced both aggregate market-wide levels and the variation in sub-area emissions from pre-trading patterns. Spatially constraining the present region-wide market to pre-empt possible future hot spots could reduce savings in pollution control costs by over 40%.

Keywords: cap-and-trade market; emissions trading; pollution control cost savings; spatial pollution hot spots.

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1 Introduction

The spatial relationship of harmful environmental externalities to adjoining populations has received increased attention recently in the US with a focus on the location of incinerators, Toxic Release Inventory (TRI) emitters, landfills, and National Priority List Superfund areas [1]. This study addresses a new and quite different issue in the matter of spatial pollution impacts: does market-based incentive regulation, although reducing market-wide pollution, lead to sub-area increases (hot spots) in pollution over baseline affecting nearby resident populations? Specifically, we compare the before and after spatial distribution of pollution that results from the application of a new mandatory cap-and-trade market programme to reduce stationary-source emissions of volatile organic compounds (VOC) in the Chicago severe ozone non-attainment region. This market incentive programme replaced traditional regulation that determined the before-trading sub-area distribution.

The Chicago region contains almost 200 stationary-source VOC emitters widely scattered about a large urban region with varied socio-economic groups residing close by. Our objective is to analyse the after-trading pattern to see what changes were brought about by this novel programme in the existing distribution of emissions. In sharp contrast, the great majority of prior studies investigating spatial disamenities, or issues of environmental justice or equity, have been concerned with the siting or location of pollution sources and the definition of affected populations in terms of class and race. A review of the issues and literature on these concerns is provided in this journal by Haynes *et al*. [1]. Our focus being different, we can move quickly to an analysis of sub-area emission changes brought about by trading.

Compared with traditional regulation, the autonomy and anonymity of transactions in the cap-and-trade market make increases in emissions in sub-areas more difficult to predict and can thus raise some concerns about spatial impacts. Moreover, market incentive programmes are of recent origin with few studies of spatial pollution patterns available. It would appear that traditional regulation has a spatial or sub-area advantage in that pollution is reduced in all affected sub-areas by the same proportion because traditional regulation typically sets performance standards or fixed rates of emissions per unit time for certain processes (or pipes), often requiring the same pollution control technologies for all emitters [2]. However, appreciable variations in the hours of production of existing firms and movements of new firms into a sub-area can increase emissions over historical or baseline values. Thus, increases in sub-area emissions over the baseline can occur under both traditional and market-incentive regulation. A careful empirical before and after analysis is required in both cases.

To explain our analysis and findings in detail, this study is divided into the following sections. We first describe how a cap-and-trade market may rouse concerns about differential spatial impacts caused by emissions trading. We next discuss the choice of a sub-area for the before and after analysis of trading. We then explain our before and after methods of detecting actual hot spots including a detailed account of our databases. Our results are displayed in maps and histograms relating emissions to sub-areas and population characteristics. We then raise the question of the possible policy response to hot spot concerns, and examine subdividing the market as one response. We introduce a specially designed cost-minimisation model based on individual emitter marginal control functions to estimate the loss in pollution control cost savings that would result from such subdivisions. We conclude with a discussion of directions for further research.

2 The invisible hand of the market and concern about hot spots

The success in reducing market-wide aggregate pollution in the highly regarded US sulphur dioxide or acid rain emissions trading programme [3] has not alleviated all concerns that emissions trading in the cap-and trade market design can lead to sub-area or inter-temporal increases in air pollution over baseline or historic emissions, as expressed by Drury *et al*. [4]. Only detailed spatial studies and an understanding of emissions trading can deal adequately with these concerns.

Under the mandated cap-and-trade market incentive approach of the Chicago programme, the Illinois Environmental Protection Agency (Illinois EPA) decentralised pollution control decisions to the firm but retained the power to set the aggregate cap (in this case at a 12% reduction from historic or baseline levels) and to monitor and enforce market rules and VOC emissions reporting. Firms were allotted free of charge tradable permits as a fraction (0.88 with some adjustment for special circumstances) of their historic or baseline emissions. They could sell permits anywhere in the region, buy from anyone in the region, and bank permits for one year. The unified spatial market was adopted in the interest of maximising potential control-cost savings from trading. The basic rule of the market is that an emitter must turn over to the agency a tradable permit for each 200 pounds of VOC emissions [5].

Under the region's cap-and-trade policy, continuing traditional regulation sets a pre-trading ceiling on an individual firm's emissions that would appear to prohibit any sub-area increases over that level, but it is possible for these increases to occur if existing firms expand production or if new firms move into the sub-area. Neither the expanded nor the new firm would be allocated additional tradable credits but they could enter the market to buy what was required. There are no restrictions on the market that would prevent such increases from occurring. On the contrary, it is expected that firms that can reduce emissions cheaply will do so and sell permits to firms for whom reducing emissions is more expensive than purchasing permits, thus achieving cost savings in comparison with traditional regulation [6].

In a competitive cap-and-trade market in which firms have varying marginal pollution control costs, it is expected that firms will reduce emissions by various percentages, implying that it should be advantageous for some firms to increase emissions over their allotment [7]. As the micro-decisions about reducing emissions or trading are now in the hands of the emitters, independent of the regulating agency, the spatial pattern of emissions becomes evident only at the end of the ozone period, from May to September, when emitters must report their emissions and turn over to the Illinois EPA the correct number of tradable credits.

3 Delineating the appropriate sub-area and its relation to potential hot spots

How to specify an appropriate sub-area to investigate increased emissions or hot spots and the associated harm function are among the most difficult topics in the analysis of spatial environmental analysis. This is clearly true in the case of VOC emissions and ozone concentrations [8]. It is to be noted that these are fund pollutants that dissipate in the atmosphere over time. VOC emissions, in addition to being a precursor of ozone, can be harmful to health in their own right. They arise from a wide variety of processes in the region ranging from candy making, to plating, to painting cars, and on to the refining of crude oil. The hydrocarbon stream may be scrubbed, burned, absorbed in carbon, or reduced in production inputs such as less emitting paints, glues, and the like [9]. What remains will diffuse in space from vents, pipes, chimneys, or other openings. The spatial spread of hydrocarbons is difficult to model since the range of emissions and formation of concentrations depend on meteorology and chemical reactions, among other variables.

3.1 The sub-area harm function

The effect of emission exposure on the population depends on the number of sensitive people, inside and outside activities, and the concentration of hydrocarbons at the point of contact, and other variables. While there has been some research on the general harms of low-level ozone reported in Tolley [10], there has been less research on the harms of volatile organic compounds including those that are hazardous air pollutants, and much less research on local effects [11]. The US Toxic Substances Control Act requires testing rules for each chemical but only a few such rules have been promulgated by the US EPA. Monitoring of ambient air quality and emissions from individual or sub-area sources is proving to be more complex and costly than once believed. Setting zero risk or zero emissions for a source, or sub-area, is either prohibitively expensive, or simply impossible [12].

Low-level ozone concentrations formed as a result of combinations of precursors such as VOCs, nitrogen oxides, and weather conditions, follow complex spatial paths around the area. The several dozen scattered monitoring stations in the area indicate that the ozone plume is generally moved across and out of the region by the prevailing summer southwesterly winds frequently carrying the concentrations during hot summer months deep into the neighbouring State of Wisconsin and across Lake Michigan to localities in the State of Michigan such as Muskegon. Specific sub-area concentrations are difficult to measure and predict and yield little guidance on an appropriate sub-area for measuring harms [13,14].

Lacking detailed knowledge of how to measure sub-area harms accurately, we focus on VOC emissions and adopt a proximity ‘surrogate’ harm function that relates harms of this pollutant to the immediate area surrounding the sources of emissions. For our purposes, after balancing a number of factors, a hot spot is specified as a sub-area with a population where VOC emissions have increased due to trading over the pre-trading or baseline level.

3.2 The appropriate sub-area

The Chicago non-attainment region covers all of six counties and parts of two others. There are 118 townships averaging 32 square miles in area, 298 zip codes varying in area but averaging 13 square miles, and hundreds of census tracts varying widely in area. The counties appear too large in area to reveal hot spots in the detail we require, as Table 1 demonstrates. All counties exhibit a decrease in emissions ranging from 25.4 to 55.9%. The townships, a local government area, have been analysed by the Illinois EPA but leave scope for more detail. The census tract appears to provide too much detail for clear mapping analysis and portrayal.

Table 1 Population, emitters, before and after-trading emissions by county

County name	*Population (1999 number) of people)*	*Number of emitters*	*Baseline emissions (200 lbs)*	*After-trading emissions (200 lbs)*	*Percent change in emissions*
Cook	5,192,105	116	72,130	39,127	−45.90%
DuPage	890,164	11	4379	1932	−55.90%
Grundy	37,213	2	4944	3049	−38.40%
Kane	401,360	13	4328	2970	−31.50%
Kendall	53,914	1	614	459	−25.40%
Lake	616,422	10	4727	3210	−32.20%
McHenry	246,533	8	1887	995	−47.50%
Will	474,617	19	12,471	7303	−41.50%
Total	7,912,328	180	105,479	59,045	−44.00%

Note: Population data are 1999 estimates by CACI International Inc. All other data from Illinois EPA Annual Performance Review Report of 2000 and 2001 [5]. Only a few townships included in Grundy and Kendall counties are included in the severe ozone non-attainment region, but population estimates are for the entire county.

The zip code, a US Postal Service area for mail delivery, appears to be the best compromise in terms of area and neighbourhood delineation. The zip code has been chosen as the sub-area for other studies of hot spots as in the California Comparative Risk Project [15]. It also is a spatial unit for which population and socio-economic data are available. There are 298 zip codes in the non-attainment area 95 of which contain one or more VOC emitters in their boundaries. These 95 are the potential candidates to be tested by our hot spot definition.

3.3 The databases

The Illinois EPA has provided us with emitter addresses, tradable credit allotments, tradable credit retirements (actual emissions during the year 2000), and tradable credit purchases and sales, from which banks may be calculated. Given the allotments and policy cap, we were able to estimate the baseline emissions for each enterprise. The agency also made available breakdowns for those emitters for whom some or all of their VOC emissions were hazardous air pollutants such as benzene. However, specific data on HAP emissions are not yet available. Much of these data were presented in spreadsheet format, and can be provided to researchers. Valuable supplementary data are presented in the first annual evaluation reports of the Illinois EPA [5].

The agency has made a number of quality control checks to validate reported emissions data. This is an important function of the government, since systematic errors in emissions data would affect the creditability of the tradable emission permit and the reliability of our hot spot analysis. Over 50% of the market participants were visited during 2001 to check record keeping and VOC control equipment and processes. Violations were detected in seven cases with corrections made to the data. Further checks were made on 59 submitted reports with four minor record keeping errors detected and corrected [5].

4 Detection and analysis of actual hot spots in the year 2000 due to emissions trading

4.1 Mapping the before-trading zip code distributions of population and baseline emissions

The city of Chicago has a population of about three million out of almost eight million in all affected counties. The city centre is located along the lake about halfway up Cook County as revealed in the map of Figure 1. The areas of greatest population density, which are also areas of residence of low income and minority populations, are located on the near west and south sides of the city centre. The city north side area is also densely settled, but the residence of more middle and upper income households. Other concentrations of population, mainly middle income, may be seen in northwest Cook County and on the west in DuPage County.

Baseline emissions are before-trading emissions and the zip code distribution revealed in the Figure 2 map is the result of years of traditional regulation, frequently termed command-and-control. Baseline emissions also reveal the location of the almost 200 major emitters covered by the cap-and trade market. A concentration of emissions is revealed on the near south and southwest sides of the city, areas of residence of low income and minority populations, and a concentration on the northwest side of Cook County in a more middle income area.

Figure 1 1999 estimated population by zip code. Total population is 7,912,328 people for the eight county area. Total population in zip codes with emitters is 3,215,295

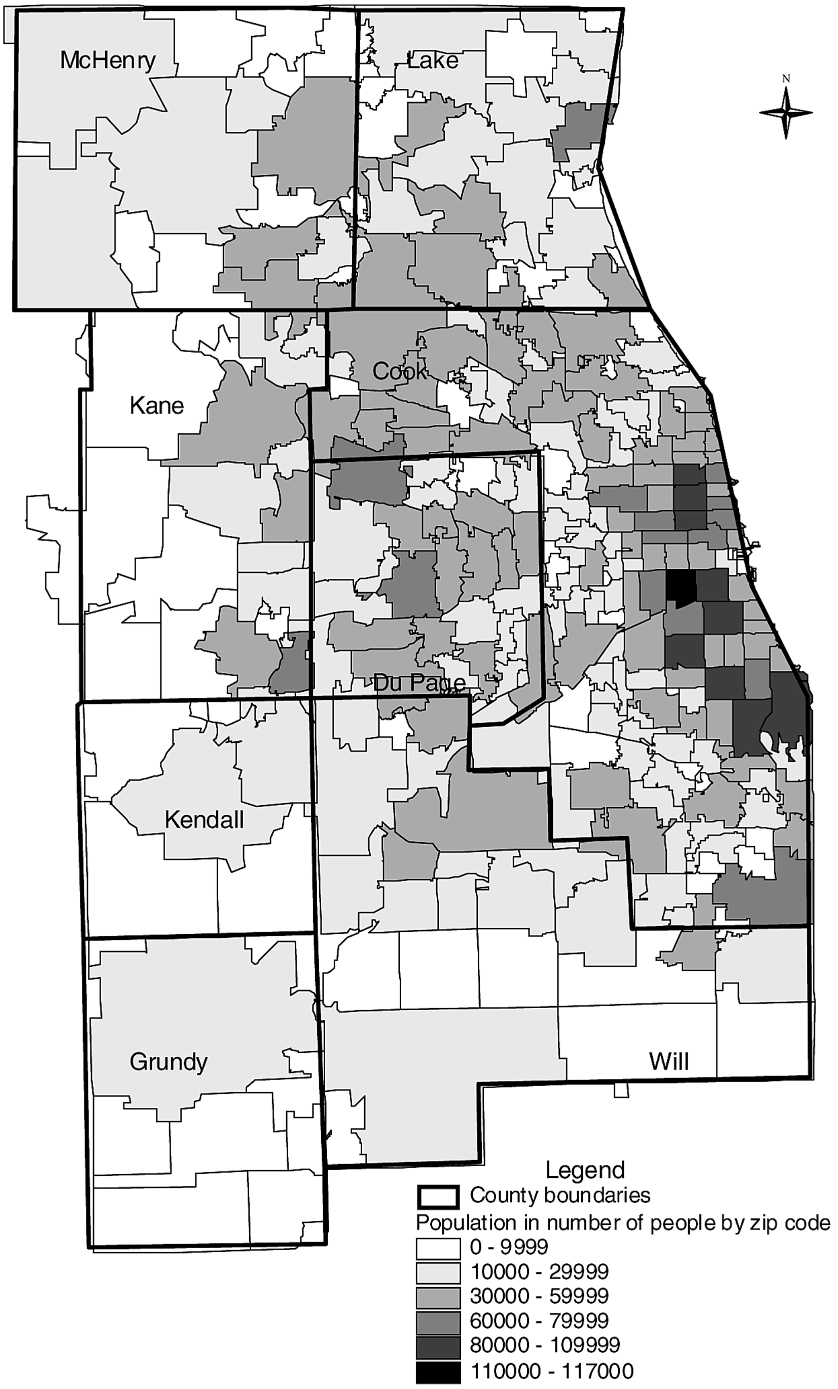
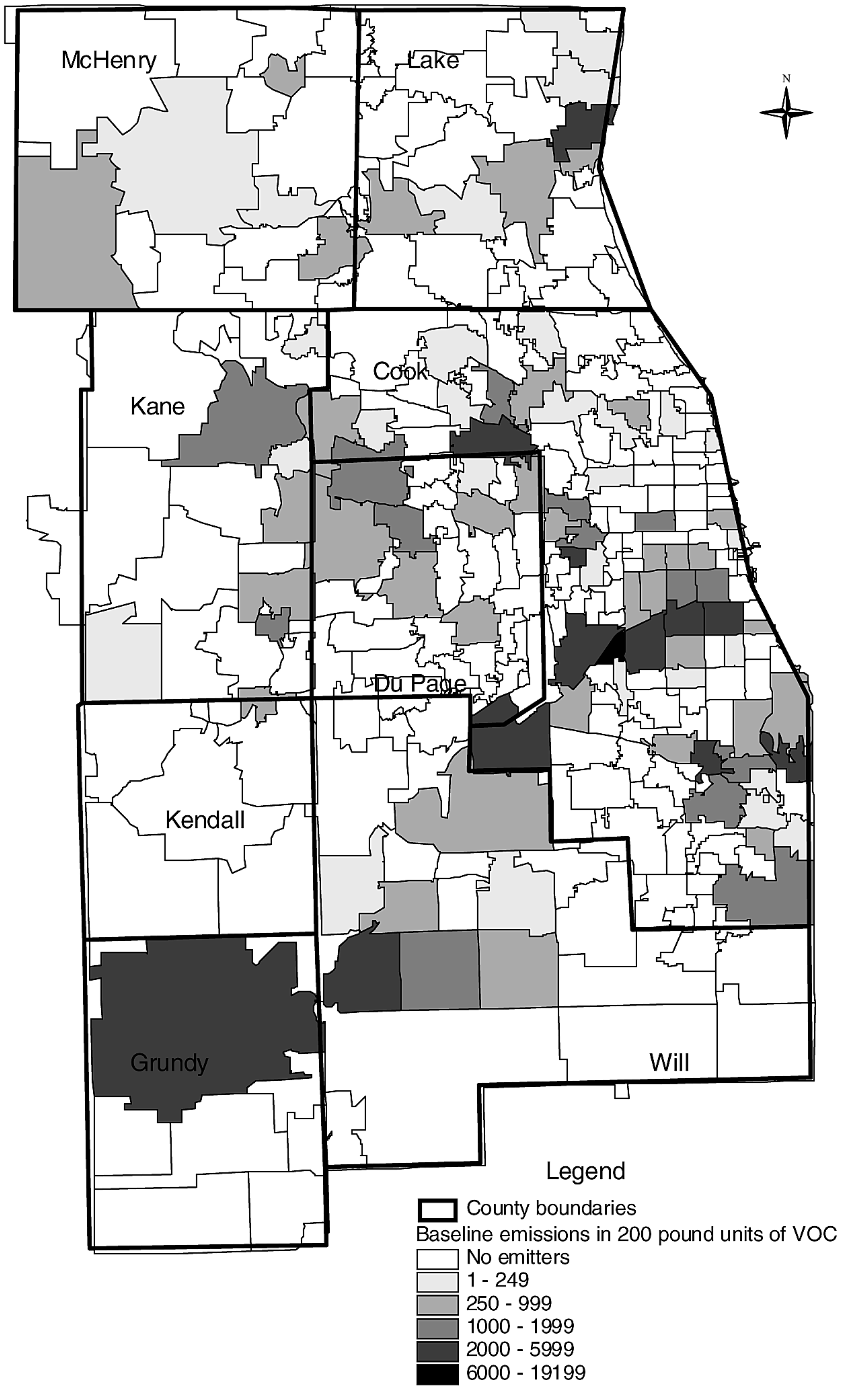


Figure 2 Year 2000 baseline emissions in 200-pound units of VOC by zip code



Another interesting aspect of these zip code distributions is that the correlation coefficient between population and baseline emissions is not significantly different from zero. It is apparent that some zip codes have a large population and large volumes of emissions, but this link is offset by the distribution of emitters in outlying areas where land is cheaper, transportation more rapid, and population densities less. Some large emitters such as the 3M Corp., BP Amoco refinery, Corn Products Co. and the Abbott Labs Co. are found in these outlying areas surrounded by small populations.

4.2 Mapping the after-trading zip code distribution of emissions

The striking impression of the map of Figure 3 is that emissions have been reduced by trading in almost all zip codes, and the variation and range of emissions have been significantly reduced. Of special interest is the reduction in emissions in the densely settled city centre areas with their concentrations of low-income and minority populations.

On another spatial dimension, a significant finding is the changes in the means and variances of the before and after-trading zip code distributions, and the reductions in those codes with the greatest volumes of emissions. These changes are brought out in the histograms of Figure 4a and b.

Figure 4a provides a histogram view of the range of pre-trading emissions by zip code by arraying codes from highest to lowest baseline emissions along the abscissa, and plotting baseline emissions along the ordinate. It may be seen from the diagram that the top 20 zip codes account for well over 50% of all emissions. These codes are of special interest to the extent that local emissions inflict harms on the local population.

The reduction in emissions in almost all zip codes after trading is brought out in the histogram of Figure 4b where zip codes are once again arrayed from high to low in terms of baseline emissions along the abscissa, but the ordinate now portrays after-trading emissions. The mean emission value for zip codes with emitters prior to trading was 1132 of VOC 200 pound units with a standard deviation of 2176; the mean declines to 643 units after trading with a standard deviation of 1396.

Trading has brought about a significant reduction in the top 20 codes with highest before-trading pollution volumes. If zip codes are arrayed on the abscissa from highest to lowest after-trading emissions (not shown) with after trading-emission volumes on the ordinate, the top 20 codes revealed a marked reduction in the mean and standard deviation. The mean is reduced from 3611 to 2033, measured in 200-pound units, and the standard deviation is reduced from 3848 to 2617. This is in sharp contrast with the much smaller changes revealed among the lowest 20 zip codes in volume where the mean is reduced from 166 to 105 and the standard deviation from 43.3 to 42.9. We interpret these changes to be indications that local harm has been reduced in those sub-areas where it was most significant.

Figure 3 Year 2000 after-trading emissions in 200-pound units of VOC by zip code

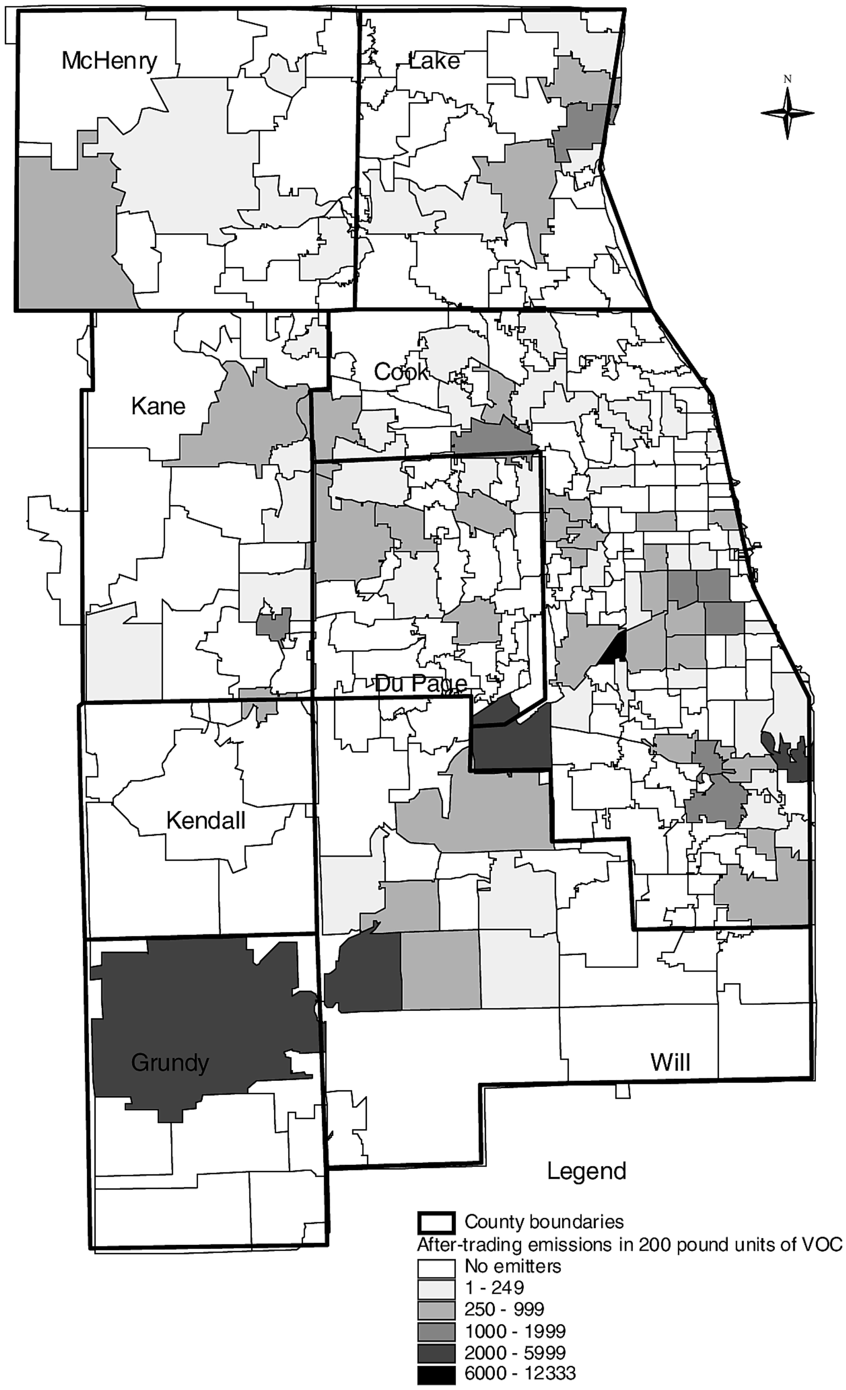
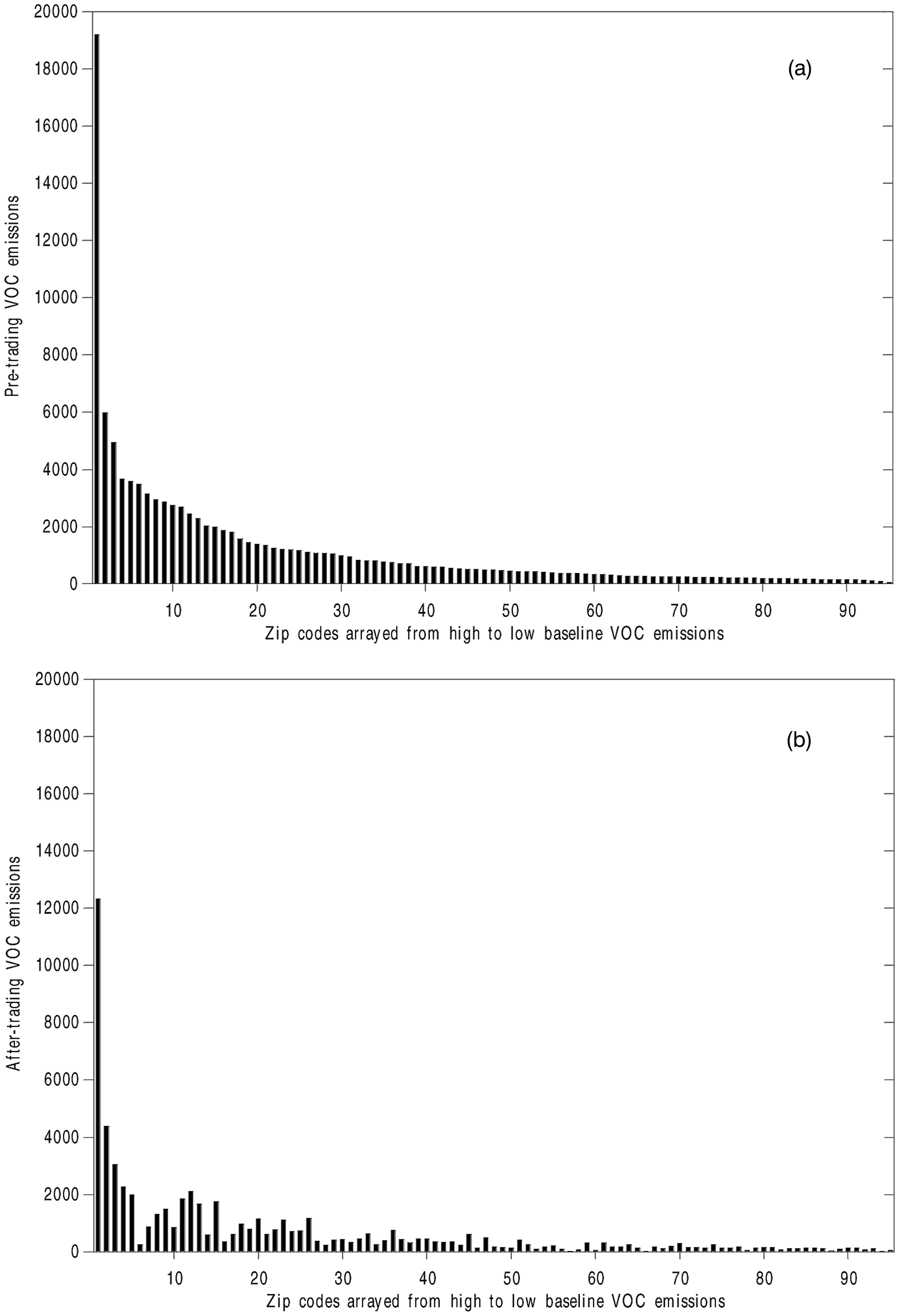


Figure 4 (A) Baseline or pre-trading emissions by zip code in 200-pound units of VOC. (B) After-trading emissions by zip code in 200-pound units of VOC



4.3 Mapping the sub-area zip code distribution of reductions or increases in emissions after trading

The Figure 5 map brings together the maps of Figures 2 and 3 and reveals more clearly the decreases or increases in 200-pound units of emissions by zip code due to trading. Zip codes with no emitters and no emissions are left blank. The six zip codes revealing increases are isolated and scattered about the region. The significant reduction in all but one of the zip codes (60644) with resident low-income and minority populations is noteworthy.

To further evaluate those six zip codes, we have prepared in Table 2 a list of these codes together with their population, their baseline and their after-trading emissions. The population of the six codes is about 5% of the region's population living in zip codes with emission sources. These six codes emitted slightly less than 5% of the region's VOC emissions in the year 2000. Among the six were two codes where we could estimate an increase in hazardous air pollutant discharges by assuming a fixed proportion of these discharges to other VOC emissions. These two codes had about 3% of the region's population in affected areas and less than 1% of the stationary-source VOC emissions. Adding new processes and extending hours, both of which required emitters to purchase additional tradable credits, were mainly responsible for the emissions increase over baseline in the six codes.

The question of the sensitivity of our spatial measure to incremental changes in the area arises in the case of these six codes. One plausible change would be to enlarge each of the codes by adding the abutting zip codes that contained emissions. As may be seen in Figure 5, that meant adding one abutting code to two of the original six, adding two codes to two of the six, and adding three codes to the remaining two of the six. When this is done, we obtain the important result that in all of the newly defined sub-areas, the increases in emissions due to trading were changed to decreases as can be seen in Table 2.

5 Should trades in sub-areas of the market be constrained to pre-empt future actual hot spots?

While trading has, in fact, reduced almost all sub-area emissions, it may be asked what policy changes could pre-empt possible increases in sub-area emissions induced by trading in the future? Constraining the market to prevent hot spots requires, in principle, either restricting flows of transactions in certain sub-areas or a system of weighted tradable credits reflecting the different populations in sub-areas as developed by Teitenberg [2]. Either type of constraint negatively impacts the workings of the market, increases transactions costs, and involves costs as shown by Stavins [16] and Montero [17]. The benefits of constraining the market would be the reduction in local harm to the extent this can be reasonably estimated.

Figure 5 Year 2000 after-trading changes in emissions from baseline in 200-pound units of VOC

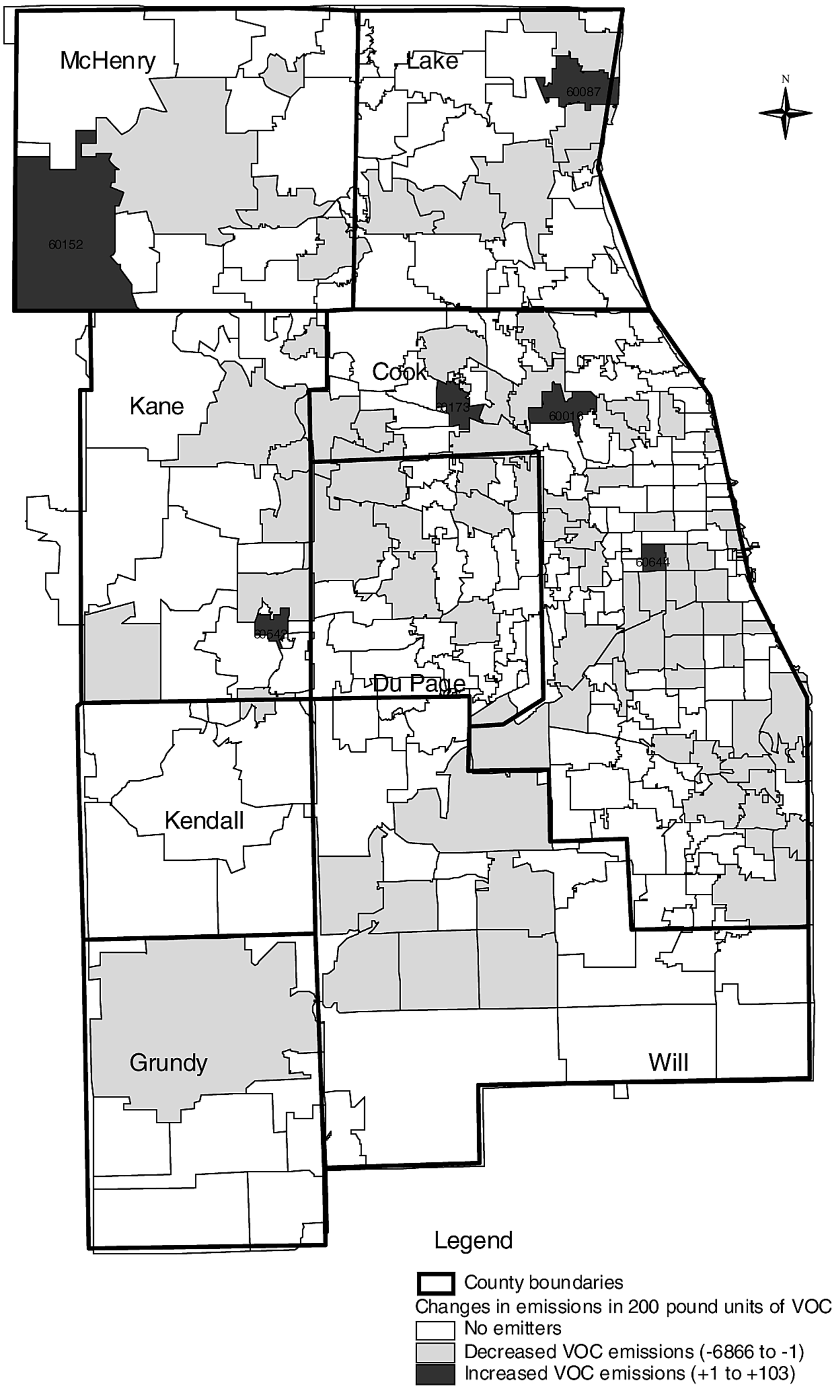


Table 2 Data for six zip codes that experienced increases in emissions after-trading during the year 2000

Zip code	*Population (estimated for 1999)*	*Baseline emissions (200 lbs)*	*After-trading emissions (200 lbs)*	*Change in emissions (200 lbs)*	*After-enlargement change in emissions (200 lbs)*
Zip codes with VOC increases					
60644	57,298	512	615	+103	−544
60542	9411	1114	1176	+62	−67
60087	29,119	243	295	+52	−874
60173	8713	226	245	+19	−2131
60152	10,484	488	495	+7	−87
60016	50,391	49	56	+7	−283
Subtotal	165,416	2632	2882	+250	−3986
Zip codes with HAP increases*					
60644	57,298	244	310	+66	−581
60016	50,391	49	56	+7	0
Subtotal	107,689	293	366	+73	−581

*These two codes experienced increased HAP emissions based on our estimates of a fixed proportion of HAP to VOC emissions for all emitters in zip codes experiencing increased VOC emissions.

Sources: All baseline, allotment, and emissions data provided to the researchers by Illinois EPA.

The issue of constraining the market was dealt with in the Los Angles region by dividing the local cap-and-trade market for sulphur dioxide and nitrogen oxide tradable credits into two zones, an inland and a coastal zone, and preventing trades from the former to the latter because of prevailing winds [18]. No estimates are available as to the benefits and costs of this constraint. The issue arose in the national cap-and-trade sulphur dioxide market established in the 1990 US Clean Air Act Amendments when complaints were heard from New York State and other downwind states that the pollutant was blown their way by the prevailing winds from the Midwest [19]. The New York legislature passed a law signed by the governor prohibiting electric utilities in that state from selling sulphur dioxide tradable credits to states in the Midwest. No estimates are available as to the benefits or costs of this constraint.

We can take a step forward in this study on this issue by estimating the costs of constraining purchases in certain sub-areas of the Chicago market. For this purpose we have available a cost minimisation model built on estimated marginal control costs for the almost 200 individual emitters participating in the market as discussed in Kosobud, Stokes and Tallarico [20]. Given marginal control costs, tradable credit allotments, and the assumption of cost minimising behaviour, our model can be solved for credit prices, trades, and aggregate control costs under the region-wide cap-and-trade market. The same procedure can be used for a spatially constrained market. The model can next simulate aggregate control costs under traditional regulation where each emitter must reduce emissions by a given percentage. The costs may then be compared. An explanation of the model specification is available in the appendix.

The model can be used to estimate the loss in control cost savings compared to traditional regulation as each constraint is introduced. Table 3 shows the base case control cost savings of $319,000 compared to traditional regulation given the 2000 market price of $76.00. Simulating the restriction of purchases in the six zip codes with increased emissions reduces savings by a modest 3.45% to $308,000 and lowers the price to $74.96 as demand for credits is reduced by this constraint. The simulated north-south constraint that restricts purchases in the 25 southernmost codes, introduced because of the prevailing winds from the southwest during the summer, reduces savings by 18.8% to $259,000 and price falls to $70.01. Another simulation that restricts purchases within the City of Chicago reduces savings by 29.2% to $226,000, and reduces price to $68.29. Combining all constraints reduces savings by about 44.8% to $176,000 and lowers price to $63.56. What is interesting is that even in this most draconian case, emission trading still saves control costs compared with command and control regulation.

Table 3 Effects of sub-area restrictions on emission trading cost savings, tradable credit equilibrium prices, and number of credits traded: year 2000 trading season

[1] Restrictions on credit purchases in selected zip codes	*[2] Credit equilibrium price ($ per 200 lbs of VOC)*	*[3] Control costs under traditional regulation (× $1000)*	*[4] Control costs under emissions trading (× $1000)*	*[5] Control cost savings (3–4) (× $1000)*	*[6] Number of credits traded*
No restrictions (12 % reduction)	76.00	822	503	319	3809
Restrictions on purchases in six hot spot zip codes	74.96	822	514	308	3661
Restrictions on purchases in 25 most southern zip codes	70.01	822	563	259	2962
Restrictions on purchases in the 19 Chicago zip codes with emitters	68.29	822	596	226	2720
Restrictions on purchases in all of the above cases	63.56	822	646	176	2052

There are 95 zip codes in the non-attainment area in which emitters are located. Zip codes were chosen for restrictions on purchasing credits to investigate the effect of spatial restrictions on the gains from emissions trading. All dollar values are in current (2000) prices.

Sources of estimates: Simulations with the optimisation model [21].

Against these costs should be balanced the changes in harm from constraining the market. Here we have to be very careful because the constraints reduce emissions in designated areas but can increase them in other areas. When constraints are introduced there is a redistribution of emissions over the region due to the change in equilibrium price that results. As price falls, emitters in certain zip codes may choose to buy more permits and emit more rather than reduce emissions, as they would have under the unconstrained market. A detailed harm function, beyond the scope of this study, would be required to appraise these net effects although they are likely to be small in relation to the loss in control cost savings.

6 The problem of inter-temporal hot spots

Emitters reduced their emissions by 44% from baseline during 2000 rather than 12%, and banked about 37,400 tradable credits that could be used in 2001 to cover emissions or allowed to expire [5]. There is evidence that suggests that this large bank of credits was not built up primarily for later use. Marginal control costs appear to have decreased more than expected leading many emitters to over-control rather than trade credits, which may explain a large part of this bank. A similar mistake characterised the early years of the sulphur dioxide cap-and-trade market as explained by Ellerman *et al*. [3]. In addition, emitter concern about the workings of this new market seems to have led to over-control and over-banking.

One implication of these large banks is that the public obtained cleaner air than policy required during 2000. Another implication is that emitters utilised more resources in controlling emissions than the market cap required. Our expectation that a substantial part of the bank would be allowed to expire was confirmed by early reports for the year 2001. Emitters did not increase emissions in 2001, but reduced their emissions by 52% from baseline rather than the unchanged 12% cap. Part of this reduction was likely due to the economic recession of that year. They allowed 13,920 tradable credits of their year 2000 bank to expire using the rest to cover part of their 2001 emissions. This left them with a bank of 66,900 credits for use in 2002 with implications for additional expirations and tradable credit price declines.

7 Conclusions and directions for further research

Concerns about hot spots were greatly eased by the spatial patterns of the first year of the new cap-and-trade market. Reductions were achieved by trading in 89 out of 95 codes. When the six codes with VOC increases after trading, two of which contained increased hazardous air pollutants, were enlarged by abutting codes with emitters, all revealed decreases. Market-wide VOC emissions were reduced by three times more than the policy goal of a 12% cap reduction. Emission trading has substantially reduced the range and variation of emissions among sub-areas and contributed to a significant reduction of emissions in those sub-areas with large pre-trading volumes.

Early evidence indicates that the pattern of tradable permit sales and purchases is being repeated in the year following the start-up period. This implies that the spatial patterns will be similar. Preliminary data indicate that the aggregate emissions did not increase in the second year of the programme signifying that no inter-temporal spike caused by first year banks was observable. Due to the one-year banking provision of the Chicago market design any credits issued in 2000 and not used before 2001 expired.

The unconstrained market was estimated to have saved about $319,000 during the first year. To evaluate proposals to spatially constrain the unified market to pre-empt possible future hot spots, we employed a specially designed optimisation model to estimate the loss in control cost savings compared with traditional regulation that would result. Dividing up the market into special areas implies creating tradable permits that are constrained either by price weights so that they trade at less than a one-to-one ratio depending on their place of issuance, or denying emitters in certain sub-areas the right to buy from other sub-areas.

Adopting the latter constraint, we found that the loss in savings would be small if the six zip codes with increased emissions due to trading were constrained from purchasing permits. The loss increases to about 45% of unconstrained savings if other potential hot spot areas were also restricted with respect to trades. The benefits of reducing harm to the population by this constraint must be balanced against the redistribution of emissions that may increase harm outside the constrained sub-areas. It is impossible to estimate on the basis of present knowledge whether net harm would increase or decrease due to restricting trades. The net effect is likely to be small given the magnitude of the changes against which must be balanced the significant efficiency costs of spatially constraining the market.

The early results indicate that the Chicago ozone control cap-and-trade market can take its place along side of the US sulphur dioxide market as a pioneering example of the welfare-enhancing implementation of emissions trading to achieve environmental goals. The interest in the programme expressed by other urban areas is an indicator of this success. That both cap-and-trade programmes require continued monitoring and evaluation with respect to hot spots is also clear.

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References

1 Haynes, K.E., Lall, S.B. and Trice, M.P. (2001) 'Spatial issues in environmental quality', *International Journal of Environmental Technology and Management*, Vol. 1, Nos. 1/2, pp.17–31.

2 Tietenberg, T.H. (1995) *Emissions Trading: An Exercise in Reforming Pollution Policy,* Resources for the Future, Washington, DC.

3 Ellerman, A.D. et al. (2000) *Markets for Clean Air: the US Acid Rain Programme*, Cambridge University Press, Cambridge, UK.

4 Drury, R.T. *et al*. (1999) 'Pollution trading and environmental injustice: Los Angeles' failed experiment in air quality policy.' *Duke Environmental Law and Policy F.* Vol. 9, pp.231–277.

5 Illinois Environmental Protection Agency (2001 & 2002) *Annual Performance Review Reports: Emissions Reduction Market System,* Springfield, IL.

6 Kruger, J.A., McLean, B.J. and Chen, R. (2000) 'A tale of two revolutions', in R.F. Kosobud (Ed.) *Emissions Trading: Environmental Policy's New Approach*, New York: John Wiley & Sons.

7 Montgomery, W.D. (1975) 'Markets for licenses and efficient pollution control programs', *Journal of Economic Theory,* Vol. 5, pp.395–418.

8 Mendelsohn, R. (1986) 'Regulating heterogeneous emissions', *Journal of Environmental Economics and Management,* Vol. 13, pp.301–312.

9 DePriest, W. (2000) 'Development and maturing of environmental control technologies in the power industry', in R.F. Kosobud (Ed.) *Emissions Trading: Environmental Policy's New Approach*, New York: John Wiley & Sons, pp.168–185.

10 Tolley, G. *et al*. (1993) 'The urban ozone abatement problem', in *Cost-Effective Control of Urban Smog,* Chicago, IL: Federal Reserve Bank of Chicago.

11 Freeman, M. (1972) 'The distribution of environmental quality', in A. Kneese and B. Bower (Eds.) *Environmental Quality Analysis,* Baltimore, MD: Johns Hopkins University Press, pp.243–278.

12 Portney, P.R. (2000) 'EPA and the evolution of federal regulation', in P.R. Portney and R.N. Stavins (Eds.) *Public Policies for Environmental Protection*, Washington, DC: Resources for the Future.

13 LADCO (Lake Michigan Air Directors Consortium) (2000) *Application of the REMSAD Modeling System to the Midwest*, Des Plaines, IL, January18. 35 pages.

14 Lui, F. (1996) 'Urban ozone plumes and population distribution by income and race: a case study of New York and Philadelphia', *Journal of the Air and Waste Management Association.*

15 California Comparative Risk Project (1994) *Toward the 21st Century: Planning for the Protection of California's Environment,* Sacramento, CA. May.

16 Stavins, R.N. (1995) 'Transactions costs and tradable permits', *Journal of Environmental Economics and Management,* Vol. 29, pp.137–148.

17 Montero, J.-P. (1997) 'Marketable pollution permits with uncertainty and transactions costs', *Resource and Energy Economics,* Vol. 20, pp.27–50.

18 Lents, J.M. (2000) 'The RECLAIM program after three years', in R.F. Kosobud (Ed.) *Emissions Trading: Environmental Policy's New Approach*, New York: John Wiley & Sons, pp.219–240.

19 Burtraw, D. (1996) 'The SO_2 emissions trading program: cost savings without allowances trades', *Contemporary Economic Policy*, April 14.

20 Kosobud, R.F., Stokes, H.H. and Tallarico, C.D. (2002) 'Tradable environmental pollution credits: a new financial asset', *The Review of Accounting and Finance*, Vol. 1, No. 4, pp.69–88.

21 Stokes, H.H. (2001) *Specifying and Diagnostically Testing Econometric Models,* Westport, CT: Quorum Books.

22 Illinois Environmental Protection Agency (1996) *Technical Support Document for VOM Emissions Reduction Market System*, Springfield, IL, October.

Appendix: The optimisation model used to simulate our spatial constraints

We define h_i as the historical or baseline emissions of the i^th^ firm, q_i is the allocation of currently dated credits for the i^th^ firm, r_i is the reduction in emissions during the season for the i^th^ firm, and t_i is the number of credits bought (if positive) or sold (if negative) during the season for the i^th^ firm. The firm accounting identity $r_i=h_i-q_i-t_i$ holds for all 180 emitters, whether trading is permitted or not. We shall consider credits that are banked for one year as a self-sale and include them in t_i. Credits may not be bought or borrowed from the future for current use. All variables are measured in 200-pound units of VOC. The emitter's objective function under trading is to minimise emissions reduction costs, r_i, and trading costs, t_i, knowing the control cost function, $c_{ri}(r_i)$, which is increasing in r and differentiable, and the trading cost function, $c_{ti}(t_i)$, or

$$Min\ c_{ri}\ (r_i)+c_{ti}\ (t_i),\ Subject\ to\ r_i \geq 0.0 \tag{1}$$

Knowing that $c_{ti}(t_i)=pt_i$, because p is the exogenous credit price, and also knowing that $\delta t_i/\delta r_i=-1$ because of the firm accounting identity, we can write the equilibrium conditions as

$$\partial c_{ri}(r_i)/\ \partial r_i - p \geq 0, \tag{2}$$

$$r_i[\partial c_{ri}(r_i)/\ \partial r_i - p] = 0, \tag{3}$$

$$r_i \geq 0 \tag{4}$$

The solution to (2), (3), and (4) yields the firm's optimal reduction, r_i^*, and therefore the optimal trades, t_i^*. Note that r_i^* could be zero or equal to h_i, and t_i^* could be positive or negative or zero. Marginal costs are equated to p for every firm deciding to reduce emissions, a requirement for minimum aggregate control costs. The optimal values for the firm's reductions and trades may be used to obtain a measure, S, of the aggregate cost savings of trading compared with command-and-control (CAC). We may estimate S as the difference in aggregate control costs between regulatory regimes, or

$$S=\sum_{i=1}^{m} c_i(h_i-q_i)-\sum_{i=1}^{m} c_{ri}(r_i^*)-\sum_{i=1}^{m} c_{ti}(t_i^*)$$

The first term is aggregate control costs under CAC, the middle term is aggregate control costs under trading, and the last term is the sum of equilibrium purchases and sales of credits. Except in the unusual case of equal marginal control costs functions and equal historical emissions for all firms, S is expected to be positive; that is, emissions trading leads to cost savings.

Demand and supply curves for credits may be derived from the marginal control cost schedules of firms. Since we can estimate the marginal cost functions of the 180 emitter firms in the year 2001 from Illinois EPA data [22], we may simulate where demand

and supply equilibrate in the market under the cap by trying out varying prices until sales equal purchases, or, equivalently, until the last term in (7) is zero. This approach may also be used to determine equilibrium credit prices when model constraints, parameters, and emissions targets are changed as described in Kosobud-Stokes-Tallarico [20].

For the purposes of this paper we assumed:

- perfect competition among technologies within Standard Industrial Classification (SIC) codes and all emitters with the same SIC code assigned the same marginal control costs
- full employment in the sense that demand curves were not changed, only movement along the curves was allowed
- cost functions for each emitter that could be adjusted by a common scalar to calibrate the model to reflect a market price of $76.00 for tradable credits, a price revealed in 2000.