The globalization of smoke:

Co-evolution in science and governance of a commons problem

Alex Farrell[1]
Department of Engineering and Public Policy
Carnegie Mellon University

Terry J. Keating
American Association for the Advancement of Science

Eighth Biennial Conference
International Association for the Study of Common Property
June, 2000
Bloomington, IN

Abstract:

Air pollution has been with humankind for at least as long as has fire, but it has evolved from a mostly domestic problem of cookstove smoke to a range of regional, international, and global commons phenomena such as ozone layer depletion, acidification, photochemical smog, and climate change. Over time, the character of these phenomena and the scientific understanding of them have co-evolved along with the ways in which societies have chosen to deal with them. This paper will trace the co-evolution of the science and governance of several important air pollution problems, smoke, transboundary industrial pollution, and photochemical smog, focusing mostly on the United States. It will emphasize the role science and technology have had in shaping societal responses, and in the conceptual frameworks upon which these responses are based.

---

[1] Corresponding author: Baker 129, 5000 Forbes Avenue, Pittsburgh PA 15213-3890, afarrell@andrew.cmu.edu.
The preparation of this paper was supported by the National Science Foundation through the Center for the Human Dimensions of Global Change (SBR-9521914). .

1 Introduction

Over the last 50 years a number of different forces have had the effect of globalizing air pollution, an environmental problem traditionally associated with short-range physical phenomena and controlled through local arrangements. Some of these forces are related to the increasing ability to communicate rapidly across long distances and the emergence of global trade (Friedman 1999). The others are associated with the immense increases anthropogenic contributions to geochemical cycles in which the atmosphere is an important part (Smil 1985). One result of these increases has been the creation of long-range air pollution problems, the sources and effects of which are not self-evident. As scientific research more clearly and convincingly demonstrated the existence of long-range air pollution problems, governance issues naturally arose. Not surprisingly, approaches to controlling long-range air pollution air pollution were at first quite similar to those used for traditional local air pollution problems, but have evolved since.

In this paper, we examine several examples of how the governance of air pollution has changed over time as technical knowledge has advanced and the scale of the problem has increased. We hope to illuminate more precisely how the resource has been governed in the past and what resource governance concepts can be usefully applied to it in the future. In particular, we will discuss the conceptual frameworks that have been applied to air pollution problems in the past and will critically evaluate the application of Common Property Resource theory in this case. We will show that there is a trend towards the globalization of phenomena originally considered local, and a tend of management strategies to lag behind in the transition from local to larger scales. In addition, as different atmospheric phenomena have come to the attention of decision-makers over time, there is a tendency for the scale of the problems to increase. Importantly, these twin trends towards globalization are often *driven* by scientific and engineering improvements. Thus technical change is seen as the ultimate source of stress for resource management systems.

The paper is laid out as follows. The remainder of this introductory section describes the various concepts that underlie the management strategies that have been applied to managing atmospheric resources in the past and which may be useful in the future. The next section on the atmosphere describes several specific illustrations of how this globalization occurred and how the management strategies adopted. Some concluding remarks follow that.

1.1 Concepts

Several distinct concepts have been applied to air pollution over time, these are shown in Table 1 (Black 1980; Patton-Hulce 1995; Pearce and Shaw 1992; Schlager and Ostrom 1992; Soroos 1997). Each of these concepts has been used in the past to describe air pollution and give scholars and practitioners from different disciplines a means of dealing with the issue. Indeed, air pollution is a canonical example for several of these concepts, called ‘smoke’ in discussions of nuisance law and externalities, and ‘clean air’ in discussions of public goods and commons. However, these concepts are largely independent and their arrangement in the table is not meant to suggest specific relationship or hierarchy among them.

The legal concepts, nuisance and negligence, are both very old, originating in English Civil Law. Nuisance is the stronger of the two, and is based on a notion of property rights – it is used to stop or require compensation for activities that prevent individuals from using their private property, or that harm or inconvenience the public. Negligence is a less stringent standard than nuisance, and entirely dependent on what a "reasonable man, guided by those ordinary considerations which ordinarily regulate human affairs, would do" (Black's Law Dictionary 1981 p. 1032). Both of these concepts, however, are based on some idea of "rights." Under a legal approach, the right of the aggrieved party to the use of their own property (or the right of the public to freedom from hazards or discomforts) trumps any interest of the nuisance-causing or negligent party to continue their activities. Disputes are resolved by judicial decisions.

Table 1: Concepts applied to air pollution

Concept	Discipline	Definition	Examples
Nuisance	Law	Unreasonable, unwarranted, or unlawful use by a person of his own property which endangers life or health, offends the senses, or obstructs reasonable and comfortable use of property	Noise, sparks from railroad
Negligence	Law	Failure to use such care as a reasonably prudent and careful person would use under similar circumstances.	Reckless driving, malpractice
Externality	Economics	A reduction (or an increase) in a person's production or utility that occurs due to the activities of another person	Water pollution, pollination (positive)
Public Good	Economics	Commodity which if supplied to one person is available to others at no cost (non-rival consumption and non-excludable access)	National defense, scenic views
Commons	Political Science	A domain of resources which is available to multiple actors, finite, and subtractable (rival consumption)	Grazing lands, Fisheries
Sovereignty	Political Science	The supreme rights that independent political jurisdictions possess, a self-sufficient source of political power.	European Kings, modern nations
Inefficiency	Engineering	Wasteful use of resources through the poor design, operation, or maintenance of equipment	Manually-stoked coal boilers

There is a greater distinction between the two economic concepts, externalities and public goods. Externality is the term that economists most often use to describe air pollution, and it is very similar to nuisance, although economics offers very different solutions for the problem than does the law. Economists see the problem as an absence markets for whatever makes up the externality (i.e. there is no market for clean air) and the standard prescription for such market failures is to seek ways to define and enforce property rights, and thus enable market forces to solve the problem. Failing this, the economic solution (called Coasian bargaining) is for the parties to enter into negotiations in which the aggrieved parties *pay* the party causing the externality to reduce its severity, or eliminate it completely (Coase 1960). Instead of the rights of one party trumping those of another, a balance of interests is sought; the payment serves to equalize the benefits that the aggrieved party gains by the reduction of the externality with the costs of making the reduction. Crucial to this approach is that the positions of the parties are very different, one causes the externality, the other suffers from it. Contemporary proponents of this approach tend to be distrustful of political institutions being able to legitimately (i.e. fairly) resolve disputes, and attempt to move as much of the decision-making into markets as possible (Anderson and Leal 1991). Of course, in this approach the relative wealth of the two parties is very important – richer parties are more likely to be better off if disputes are resolved through markets than if they are resolved through political mechanisms.

Public goods are resources offer opportunities for "non-rival consumption," that is, more than one person can benefit from the commodity (or service). They are also non-excludeable, that is, there is no way to prevent others from using the commodity (or service). Classic examples include national security, which all citizens benefit from, and scenic views can be viewed repeatedly without being used up. Because consumers are generally aware of the non-rival consumption aspect of public goods, many of them may act as "free-riders" and refuse to pay for the commodity or service, thus market mechanisms often fail to provide them in sufficient quantity. Since markets fail in providing public goods, this is generally resolved by assigning that role to government. The primary dispute involves deciding how much of the public good to provide.

Commons are resources that are available to multiple actors (like public goods) but are finite and rival in consumption (a property sometimes called subtractable).[2] As an example, it was impossible to exclude anyone from using grazing lands in the American West for many years since there was no cost effective means of fencing off land. Yet grazing lands are not a public good in that the vegetation eaten by herds can be consumed only once (in a given time period). Technology can be used to make commons into private property (such as the invention of barb wire fencing). This concept is directly political and rather more complex than the preceding concepts in that can be used to describe *how* the political decisions that underlie nuisance, externalities, and public goods are actually arrived at (Schlager and Ostrom 1992).

In contrast to economics, the study of commons does not attempt to remove decision-making from the political sphere, rather it attempts to understand the politics of resource management. However, the commons approach essentially assumes that all parties have identical positions relative to the resource, making it difficult to use in cases where there is an inherent pattern in how the parties relate to the resource. For instance, Mitchell works through a detailed, but somewhat complicated and contorted discussion of how air pollution can be thought of as a commons problem (Mitchell 1999). Connolly extends this thinking usefully by developing the ideas of "differential rivalry" and "the power to destroy" the resource (p. 131), showing that an air pollution problem can look more or less like a commons problem to differently-situated actors (Connolly 1999). These are probably the best discussions of how air pollution can be thought about within a commons framing, but they end up so forced and so different from typical analyses of common property resources that they mostly demonstrate the limits of this approach.

There are two other concepts that have been occasionally applied to air pollution. The first is sovereignty, which is somewhat similar to nuisance, but applies only to independent political jurisdictions. It comes up in cases of trans-boundary air pollution. The second is engineering inefficiency, in which air pollution is seen as a form of waste stemming from poor design, maintenance, or operation of engineered systems. When this concept is successfully applied to air pollution, disputes can often disappear as the polluter finds it in their self-interest to curtail the activity that is disturbing the other party.

1.2 Characterizing the atmosphere

The atmosphere is a difficult resource to characterize, and it is often *not* treated as a resource at all, but as a means of transmitting externality-causing effects (Soroos 1997 pp. 213-223). If the atmosphere is to be thought of as a commons, then specific resource units and the

[2] A similar economic concept is the "club good".

consumptive or productive use of those units must be identified. One could imagine oxygen molecules as the resource unit, since oxygen is needed for respiration and combustion. However anthropogenic demands for oxygen are miniscule compared to the amount available everywhere. Moreover, atmospheric oxygen is constantly recycled in the Carbon, Sulfur, and Nitrogen cycles, so the quantity available will remain essentially unchanged for many centuries and anthropogenic demand can be ignored.

When thought of as a resource, the term "clean air" is most often used, which means that the atmosphere is free of offending substances. Most of these offending substances are anthropogenic, although some natural features produce them as well, such as sulfur springs. As we show below, air pollution problems are most often framed as nuisances, externalities, or sovereignty issues when offending substances are noticed in the air and their sources can be determined. The atmosphere can also serve as a disposal for unwanted or offending substances, such as cookstove smoke, and it tends to have a limited ability to absorb and then dispose of offending substances. In the case of smoke, for instance, these processes include dilution and deposition (the offending substances dissipate and essentially fall out as dust).[3] The limits to the disposal ability (sometime called 'assimilative capacity') are usually related to the idea of maintaining the air clean enough to avoid a nuisance problem. Thus the idea of the atmosphere as a resource for disposal proceeds from a prior notion of the rights of individuals downwind to breathe air free from offending substances.

However, it has been discovered that there are other ways in which assimilative capacity can be limited. These limits often arise when the removal processes of the offending substances cause some sort of undesirable change themselves.[4] This phenomenon can be considered an example of congestion, as different sources crowd each other in trying to find a way for rendering their emissions harmless (Mitchell 1999). This can occur when the substance is already present in the environment and anthropogenic additions become significant relative these amounts, or when the substance is only found in anthropogenic waste streams and can interfere with natural processes. For instance, both sulfur and nitrogen exist in various compounds in nature, and they cycle through various chemical processes, but human additions to these cycles have become very large and have caused deleterious effects (Ayres, Schlesinger et al. 1997; Husar and Husar 1990; Regens 1993; Smil 1990). On the other hand, some pesticides are only created by industrial processes and can cause disease and death in both humans and wildlife (Jones and de Voogt 1999).

The atmosphere can be thought of as a resource in one other way, it provides various services, including climate and ultra-violet ray protection. These services are most easily described as public goods issues, since they do not suffer from rivalry. The remainder of this paper, however, will focus on several cases of air pollution, not on these public good services provided by the atmosphere.

---

[3] Of course, this process has its own problems. Smoke falling out of the air in industrial cities can create a real problem of soiling garments and buildings, leading to costs for extra cleaning. The final fate of air pollutants can be so important that it dominates the problems created while the pollutant is actually airborne (e.g. acidification).

[4] The "power to destroy" concept that Connolly develops is essentially about exceeding the limits of the assimilative capacity of the environment to remove offending substances and prevent damage to ecosystems (i.e. acidification).

2 Cases

This section will provide a description of the most important cases in which the scale of air pollution increased over time as the science and engineering associated with them improved. They include some of the most long-standing air pollution problems and the first examples of air pollution problems that crossed political boundaries.

2.1 Smoke

Smoke pollution is generally an annoyance or a health threat, and it typically results as a side effect of some consumption or production process. Most smoke-producing processes involve fuel combustion, such as home cooking and heating, or steelmaking. Indeed cookstove smoke is one of the most important air pollutants in developing nations, partly due to the constituents of the smoke itself and partly due to the very high exposure levels that result from short, direct exposure pathways (Smith 1993; Smith 1994). For the majority of human history, these sources have been among the most important forms of air pollution and have been major public policy problems in cities such London and Pittsburgh (Brimblecombe 1987; Davidson 1979; Grinder 1980; Markham 1994; Tarr 1996; Tarr and Zimring 1997).

Most smoke pollution results from the combustion of bituminous or lower-quality coal, which is very common (some smoke also comes from industrial processes (Jones 1974)). Smoke consists of heated air and combustion gases, fly ash, unburned coal particles, unburned volatile gases, and impurities, particularly sulfur oxides. Smoke can be controlled by controlled, complete combustion, using cleaner coal (such as non-volatile anthracite), or switching to a different fuel. The discomforts and health hazards carried by smoke plumes in the air are prototypical nuisance problems. The effects of smoke are aesthetic deterioration (i.e. dirty and dismal surroundings), respiratory irritation and disease, and increased cleaning costs. Smoke is also easily observable, no special instruments are needed to know if a location is smokey.

Smoke first emerged as a public problem in London, when coal began to substitute as an energy source for wood (Brimblecombe 1987). Although the problem was noted almost immediately, for many decades, few effective means of managing these problems existed and for the most part they went essentially unsolved. The most egregious instances were sometimes resolved through the courts, when the aggrieved parties could afford counsel. In these instances, the conceptual framework employed was nuisance.

However, over time this approach became difficult to apply meaningfully in practice as larger and larger numbers of people came to live in cities, and industrial processes grew in number and size. Early U.S. cities were small and generally used wood until the 19th century. Once they started to burn coal, however, inhabitants of these cities could suffer from intense periods of acidic (due to the sulfur oxides) mixtures of smoke and fog (London thus had the original ‘smog’) without there being an obvious polluter causing the problem (Clapp 1994). The problem, often called the “smoke evil” after the Civil War, became more and more severe in midwestern cities that relied on bituminous coal for fuel, whereas cities on the Eastern Seaboard that mostly used anthracite coal (e.g. Philadelphia) were largely exempt (Grinder 1980; Raufer 1998 pp. 77-78). This tendency for air pollution problems to increase in physical scale is an important and repeated trend through history, and one that will cause continual problems in resource management as institutions are repeatedly grown out of.

Thus the concept of a nuisance became unusable for thinking about air pollution problems in larger cities and a weaker concept was adopted – negligence (Hurst 1956). Moreover, the

Industrial Revolution weakened the interpretation of nuisance law generally in the Anglo-American countries, adding to the tendency to shift air pollution into a framework of negligence (Brenner 1974). Grinder puts it starkly, “In and out of the courts, it was almost a commonplace notion that a young, burgeoning economy could expand only if those who were injured could not sue and collect damages in full measure” (1980 p. 91). Courts were not shy about making this plain, effectively arguing that although their homes were “being invaded by this smoke . . . we hold that ‘public policy’ is more important than private property” (Rothbard 1924). Thus sparks from a railroad locomotive could cause the complete destruction of several homes yet the company escape liability.[5]

Numerous symbolic actions were taken under the negligence concept, the first air pollution statute was passed in 1868 in Pittsburgh, when the city council banned the use of bituminous coal or wood by railroads within the city limits, and the next year banned beehive coke ovens (Tarr 1996 p. 230). Other cities followed with similar prohibitions, but none were enforced, since doing so would have essentially meant shutting down virtually all industry. Indeed, during downturns in the business cycle, the smoke problem was ‘abated’ but many observers noted that the cure (i.e unemployment) was worse than the disease. In a sense, then, the dilemma of smoke pollution was ignored as less important than the link between smoke and prosperity.

During this time, civic organizations and women’s leagues across the United States took up repeated campaigns against smoke. These were driven largely by aesthetic reasons, since many of the leaders of anti-smoke crusades were wealthy enough not to live in the dirtiest, furthest downwind parts of town, and wealthy enough to afford the significant amounts of time they devoted to the work. These groups took several actions, petitioning government and industry to solve the problem and serving as smoke inspectors to monitor industrial smokestacks. They appeared to use a conception of smoke somewhat like nuisance behind their actions.

Eventually a less severe form of enforcement through the negligence approach was developed, the idea of a “standard of care” which meant no emissions of dense black smoke. This standard was enforced more or less against industry from about 1880 to the beginning of the First World War, when war production needs swept concerns about smoke away.

By the 1920s some advances in coal combustion technologies were made for industrial boilers, and the conceptual framework for smoke was transformed yet again from an issue of negligence to a problem of inefficiency. Under this framework, smoke was a sign of wasted resources, a problem that could be solved with better equipment design and operation (especially better stoking). Instead of sanctions and fines, cities deployed ‘educational’ efforts to improve encourage mechanical stokers and down-draft boilers. Boiler owners were generally receptive to these programs because they saved costs while making them look good. These improvements air quality thus occurred by transforming the problem into an engineering problem, the solution of which offered benefits to industry.

These efforts were so effective that by the 1930s many smoke experts felt that the problem was largely one of household coal consumption (although the Depression’s impact on manufacturing may have had something to do with it as well). The solutions to the problem were well understood by then, consumers needed either a “smokeless fuel” or modern coal-burning equipment that would minimize emissions. Unfortunately, both were expensive and a political solution to the difficult problem of regulating domestic coal consumers eluded all until, after an

---

[5] *Ryan v. The New York Central Railroad*. (Friedman 1973 P. 411).

especially severe smoke episode, the city of St. Louis passed the nation's first law requiring in the home either mechanical stoking or smokeless fuels on April 8, 1940 (Tarr and Zimring 1997). This was a daring step, and city officials knew their careers were on the line, so through the fall and winter they strove to enforce the law and to ensure sufficient quantities of low-smoke fuel were available at reasonable prices.

The effort worked; the winter heating season of 1940-41 in St. Louis was a landmark for its improved air quality. Soon many other cities were sending emissaries to learn how it was done. However, the Second World War slowed (or reversed) efforts at smoke control, producing some of the worst smoke conditions yet experienced, and fomenting crisis conditions in some cities, such as Pittsburgh (Lubove 1995 pp.106-117).

After 1945, an amazing thing happened, the long-intractable smoke problem suddenly and permanently retreated.[6] The many St. Louis-style ordinances passed across the country undoubtedly helped, but the real reason was more subtle – the sudden (and unexpected) availability of a completely smokeless fuel, natural gas (Tarr 1996 pp. 227-230, 251-253). The fuel was supplied from the Texas and the Southwest through large pipelines constructed with new welding techniques, the first of them built during the war as a defense against the German submarine threat (Yergin 1991 pp. 375-6, 430). The spread of natural gas rapid, interstate gas transmission more than doubled between 1946 and 1950. A crucial factor in this success was that natural gas was vastly more *convenient* a fuel than coal, the latter required constant attention and needed to be shoveled at inconvenient times (e.g. 5am). It was largely consumer preference, not regulation that drove this rapid change, although Other energy technology substitutions came into play, such as the electrification of industry and the switch to diesel-electric locomotives (again driven by consumer choice, not regulations, Tarr 1996 pp. 262-283), and by the late 1950s smoke was a relatively minor problem in all U.S. cities.[7]

2.2 Transboundary Disputes

During this same period, the concept of transboundary air pollution between two jurisdictions emerged, generally in conjunction with smelter operations. At the time the problem was labeled one of "sulphurous acid gas," but heavy metal poisoning (particularly arsenic) is likely to have been a major part of the problem as well. Disputes essentially involved an upwind party which operated and emitted the pollution in one jurisdiction, and one or more parties in a downwind jurisdiction that suffered the damages. In these cases, the atmosphere is not a resource, but a carrier of pollution which damaged farms, grazing land, and forests. In each case the solution was judicial.

The first case is the *Georgia vs. Tennessee Copper Co.* (1909) decision by the U.S. Supreme Court (206 U.S. 230 and 237 U.S. 474, 477) in which the Court upheld the State of Georgia's request for an end to the pollution. The Court's decision rests greatly on notions of sovereignty:

> "This is a suit by a State for an injury to it in its capacity as a quasi-sovereign. In that capacity, the State has an interest independent of and behind the titles of its citizens in all the earth and air within its domain."

---

[6] In some places, industrial pollution of various sorts got worse after 1945.

[7] A similar pattern occurred in Europe, although it was delayed by several decades in various nations due to the greater difficulty in backing coal out of the energy system (Farrell 1998; Markham 1994). Governments in Europe seemed much reluctant to reduce coal mine employment or to allow unprofitable heavy manufacturing to close than in the U.S.

This case also established the standing of States to sue for pollution in the case where the harm is clear,

> " . . . it is a fair and reasonable demand on the part of that sovereign that . . . the forests on its mountains . . . should not be further destroyed or threatened by the act of persons beyond its controls, that the crops and orchards on its hills should not be endangered from the same source."

This reasoning seems very much like the concept of nuisance, which, by the time this decision was handed down, had largely faded from private American air pollution jurisprudence. The remedy that the Court required was an annual payment and an agreement to reduce the probability of damage to the downwind parties, again more than was available to citizens at the time.

The first (and so far the only) international dispute that dealt directly with transboundary pollution, is the 1938 *Trail Smelter* arbitration agreement between the Canada and the U.S. (35 Am J. Intl. L. 684, 1941; (Brown-Weiss 1993 pp. 245-256). The subject of 17 years of litigation, this decision, by the International Joint Commission (created by the 1909 Boundary Waters Agreement between the two nations), followed very similar logic, holding,

> "The Tribunal, therefore, finds that . . . no State has the right to use or permit the use of its territory in such a manner as to cause injury by fumes in or to the territory of another or the properties or persons therein, when the case is of serious consequence and the injury is established by clear and convincing evidence."

These decisions codified the general idea that it was impermissible for one jurisdiction to pollute another in both U.S. national and international law. The standard was perhaps a bit higher in that a "serious consequence" proved with "clear and convincing evidence" is needed. However, in these cases, the effects of pollution were directly sensible—the polluting facilities emitted a visible plume of smoke which was irritating and affected plant growth for several miles. Thus there was little need for any sort of scientific assessment of these problems, they were directly sensible; a person could generally observe the sources of pollution, patterns of transport, and its effects. Subsequent air pollution problems would prove much more difficult to understand, and not much easier to solve.

2.3 Tropospheric ozone (photochemical smog)

As the "smoke evil" was finally being overcome in U.S. cities in the middle of the 20th Century, a new, more subtle air pollution problem emerged, photochemical smog. Although completely different from the mixtures of smoke and fog that originally earned the name, when it was first observed in Los Angeles, the contemporary name for urban air pollution stuck to the new problem. Photochemical smog is a mixture of many pollutants, but the principal (and easiest to measure) component is ozone.[8] This chemical, which is a particularly active form of oxygen found at very low (background) concentrations in all parts of the lower atmosphere, was first discovered and measured in the 19th century but it remained mostly a scientific curiosity for about a century (Colbeck and Mackenzie 1994). The reactions that form ozone are highly complex and non-linear, and intermediary chemicals, such as peroxy-actyl nitrate (PAN), can be

[8] In this paper we will ignore the stratospheric ozone layer, which is essentially a different phenomenon.

just as harmful to human health as ozone. (We will follow standard practice and use the terms "ozone" and "smog" interchangeably to refer to this phenomenon.)[9]

Smog is mostly a human health problem, a good metaphor is that ozone creates a "sunburn" on lung tissue. In very high concentrations it can cause severe chest pain, breathing difficulties, eye irritation, and impair the normal development of children's lungs. Asthmatics and the elderly can have particular difficulties and discomfort breathing air that has even moderate concentrations of ozone. Ozone can also brown, stunt, and even kill vegetation. Because these effects are not much like resource management issues, they have caused ozone to traditionally been dealt with as externality or public good issue. However, the very recent advent of regional disputes about long-range transport and some emissions trading concepts, ozone has been framed more along the lines of Connolly's "power to destroy" CPR concept.

In the troposphere, ozone is basically formed by the sunlight-driven reactions of oxides of nitrogen (NOx) in the atmosphere. These reactions can be greatly accelerated by the presence of volatile organic compounds (VOCs). These two classes of chemical are called ozone precursors. Ozone formation is very sensitive to local meteorology and topography, so the character of the problem varies substantially from place to place and from one day to another. Generally, the warmer, calmer, and sunnier it is, the worse the ozone problem will tend to be.

One of the most challenging aspects of tropospheric ozone is that, unlike smoke, dilution is *not* an effective means of dealing with the problem. Smoke is made up of small solid particles that are not normally found in nature in substantial quantities (volcanoes and fires being two obvious exceptions). These particles are removed by literally falling out of the atmosphere, usually relatively close to the source. They also disburse and become so dilute in the atmosphere that they cannot be detected any longer. On the other hand NO_X, VOCs, ozone, and many of the rest of the compounds in photochemical smog are gases that occur naturally and can persist for days. In this sense, smog is an adverse change in atmospheric chemistry brought about by excessively large human additions of certain compounds (e.g. the ozone precursors). The reactions that finally clear these anthropogenic additions proceed relatively slowly, and over the several days it takes, winds can blow them hundreds of kilometers. Of course, none of this was obvious when the problem was first detected.[10]

2.3.1 Discovering Ozone

Tropospheric ozone was first noticed as a problem in the early 1940s in Los Angeles when mysterious, noxious clouds began to appear and farmers near highways in the area started to notice mysterious crop damage (Haagen-Smit 1950; Haagen-Smit, Darley et al. 1951; Middleton, Kendrick et al. 1950).[11] Los Angeles presents almost a unique case in that it's physical conditions (topography, meteorology, and emissions profile) are very conducive to the formation of ozone (K&U pp. 41-46). There are very few natural sources of VOCs in the region (it being largely a desert) and incoming winds originate in a marine environment largely devoid of VOC sources. In addition, the LA basin is ringed by mountains, effectively blocking significant long-

[9] For a textbook description of tropospheric ozone, see (Seinfeld and Pandis 1998).

[10] One way to understand the phenomenon of tropospheric ozone to consider elevated concentrations a result of a relatively limited capacity of the atmosphere to assimilate (dispose of) ozone and its precursors.

[11] An extremely thorough analysis of the Californian air pollution experience through 1975 is provided by James Krier and Edmund Ursin, which, to save space will be referred to as K&U from here forward (Krier and Ursin 1977).

range transport. For these reasons tropospheric ozone developed as a problem in the Los Angeles area about two decades before it did anywhere else in the world.

These initial observations conformed well to the traditional ideas of air pollution as a local, urban problem, as well as the idea that the problem would respond to the control of local VOC emissions. By far the largest source on anthropogenic VOCs were cars and trucks (LA County had 4% of the nation's motor vehicle registrations in 1940, K&U p. 44). At the time, NO_X control was technologically infeasible. On the other hand, engineers knew how to control VOC emissions from cars, at least in theory, and VOC controls the added benefit of decreasing emissions of carbon monoxide and specific hydrocarbons that were believed to be responsible for eye irritation and other acute health effects (Roth, Zieman et al. 1993). Thus, early ozone control efforts in California focused completely on VOC control.

The researchers who initially discovered the ozone problem were quick to suggest a policy remedy: the control tailpipe emissions (Haagen-Smit and Fox 1954), but their suggestion did not make their way into policy very fast. From the mid 1940s through the end of the 1950's there were vociferous arguments about what this new pollution problem *was* and where it came from (not everyone was willing to accept the scientists arguments right away, see K&U pp. 52-89). While these questions were eventually settled, the issue of *what* to do about controlling smog continues to today. As early as 1945, a "standard of care" ordinance was passed by Los Angeles City. This approach was recognized as inadequate in spatial extent almost immediately, and similar legislation at the County level was soon enacted, but the County could not enforce its will on the municipalities. For the next several years the city of Los Angeles urged its neighboring municipalities to join the effort, but eventually had to turn to nuisance suits filed in State courts. This proved to be useless, too, and the problem was not solved until a 1947, when a State bill creating a unified county air pollution control district for the entire area was created. The spatial extent of the problem seemed to increase, as did the institutions designed to deal with it, just as in the case of smoke pollution.

The findings of Haagen-Smit and his colleagues prompted automobile manufacturers to invest in atmospheric chemistry research and later led to the regulation of automobile emissions in California and at the national level. An important part of the response of the automobile industry to the growing potential for emissions control regulation was to create a "cross-licensing" agreement in 1954 which was claimed to support efforts to cooperatively develop emissions control technologies, but which actually stopped most research on pollution control technologies (Bailey 1998, Esposito 1970 pp. 41-47, Bedingfield 1970).[12]

Since then, California has generally found itself leading the nation in the science and governance of smog. In general the approach to the problem has been to impose increasingly stringent regulations on the sources of ozone precursors. As with the case of smoke regulation, this pattern of regulatory solutions (rather than property rights regimes) shows that the framework being used is one of public good. In addition, the smog case illustrates how scientific and engineering progress can affect the governance of a pollution problem, and visa versa.

2.3.2 Political and Economic Forces

While these events were taking place in California, most cities in the eastern United States were struggling with acute problems associated with CO, sulfur dioxide, smoke, and soot. Meanwhile, ozone remained a problem that was thought to be restricted to Los Angeles, where

[12] A phenomenon the Nader group called, "Twenty Years in Low Gear."

the meteorology and topology create ideal conditions for the formation and accumulation of ozone.[13] Furthermore, air pollution was still perceived as a wholly local problem. The U.S. Department of Health, Education, and Welfare, which was responsible for air pollution issues before the formation of the EPA, stated that "instances of troublesome interstate air pollution are few in number ... unlike water pollution, air pollution is essentially a local problem."[14]

Over time, support for a more active role for the federal government in controlling air pollution grew from several sources. One source of support was from mayors and other urban leaders who felt powerless against large firms who were outside their borders and beyond their control, yet still a cause of pollution in their municipalities (Davies and Davies 1975 p. 83). Another source of support was industry, which began to face stringent regulations in states and cities and hoped that by taking the issue to the federal level, they would gain a uniform and more moderate regulatory structure (Andrews 1999 pp. 209-213). In addition, the new environmental advocacy groups that emerged in the 1960s preferred national-level policy (Andrews pp. 218-221, Hays pp. 461-464). Presidential politics played a crucial role – air pollution regulation was a major area of contention between candidates Nixon and Muskie, both of whom were goaded on by Ralph Nader's organization. Finally, note that this new emphasis for a federal policy grew out of changes in popular perceptions (in large part due to obvious air pollution disasters) and politics, not out of scientific research.

In the 1970 Clean Air Act Amendments, Congress established a national air quality management framework based on conjoint federalism that remains largely in place today (Portney 1990). Under this framework, Congress assigned responsibility for establishing National Ambient Air Quality Standards (NAAQS) to the newly-created Environmental Protection Agency (EPA). Responsibility for determining how to achieve those goals was left to the States, each of which was required to prepare a State Implementation Plan (SIP) that defined the emissions control regulations that would enable the state to attain the NAAQS. In addition to these state-specific SIPs, the EPA was assigned the authority to set minimum standards for new stationary sources and for mobile sources, so as to establish a "level playing field" for economic competition among cities and to protect interstate commerce.

The manner in which tailpipe emissions controls became ubiquitous in the U.S. illuminates some of the important economic forces that have led to the globalization of air pollution. Automobiles are manufactured in enormous quantities on highly automated production lines that are expensive to change, and the costs and time it takes to design a new car are significant. Automakers tend to design models for a single market as much as possible to minimize these costs, so the same car is sold in Connecticut, Texas, and Hawaii. To create the large, homogenous market that fits large-scale auto manufacturing, U.S. automakers tend to support uniform standards (e.g. safety) at the national level.

A good example of how this worked are the actions of the General Motors, which in 1970 testified before Congress that requiring the use of catalytic converters in 1973 could cause massive economic disruption and job losses. As a result, Congress did not include such a requirement in the Clean Air Act, but given the more serious nature of the problem in California

[13] For a good history of early air pollution legislation and regulation in the United States, see (Stern 1982; Tarr 1996; Tarr and Zimring 1997). For a good history of the pioneering work in the 1940s, 50s, and 60s in California, particularly with respect to motor vehicle controls, see (Krier and Ursin 1977). For a discussion of the last 40 years of so, focusing at the national level, see (Bailey 1998; Hayes 1998; Portney 1990).

[14] Un-named HEW sources cited in (Davies and Davies 1975 p. 51).

catalysts *were* required there. GM's response to this requirement was to *voluntarily* install catalytic converters on all of its vehicles, oddly enough without any economic dislocation. When questioned later by Congress, GM's representative noted they had originally said the catalyst requirement *could* cause disruptions, not that they *would*. Since then, U.S. automakers have consistently advocated uniform standards nationwide, successfully lobbying to have this provision included in statute in 1990 and taking the EPA and various states to court to enforce the provision.

These same forces have played out in Europe with even greater effect. A wide variety of analysts note that European Union regulations for "air quality" were essentially about harmonization of standards to promote more free trade, not about achieving environmental objectives (Bennett 1991; Boehmer-Christiansen 1989; Boehmer-Christiansen 1990; Dietrich 1996; Farrell and Keating 1998). Harmonization of standards is particularly important to the automotive and vehicle fuel sectors due to their economic structure, and less for the electricity (and electricity generating equipment) markets. Indeed, both Boehmer-Chritiansen and Dietrich strongly argue that the environmental regulations were very important factors (although not dominating) in the evolution of the structure of the European automobile industry. A key part of this argument (particulary Dietrich's version) is the importance of the US market, in which very stringent emissions standards were introduced. Thus, firms which exported to the US (such as Mercedes and Saab) had to meet these standards and had incentives to promote their adoption everywhere in their sales territory, including at home in Europe. Indeed, Sweden had adopted US standards in 1976, as did several other nations by 1985 (Boehmer-Christiansen 1989).

2.3.3 Scientific advances

In addition to these economic forces that have tended to globalize air pollution, scientific advances also contributed. Most importantly, improved monitoring and modeling capabilities shifted scientific thinking about the problem as a local urban issue to one of regional scale. Second, the number and types of sources being regulated to control tropospheric ozone increased from an early focus on motor vehicles to a broader set that includes diverse sources of VOCs and large power plants. These changes, which were largely scientific, forced political responses.

In the 1970s, the development of a reliable instrument for measuring ozone in the ambient air led to two significant changes in the understanding and management of the ozone problem (Research Triangle Institute 1974; Research Triangle Institute 1975). First, a number of field studies were conducted in the eastern United States that suggested the possibility that ozone and its precursors could be transported downwind of urban areas leading to the formation of high concentrations of ozone in rural areas (Cleveland, Kleiner et al. 1976; Decker, Ripperton et al. 1976; Martinez and Singh 1979; Stasiuk and Coffey 1974; Vukovich, Bach et al. 1977; White, Anderson et al. 1976; Wolff, Lioy et al. 1977).[15] The mounting empirical evidence led Wolff and Lioy to conclude that there was a "river of ozone" that flowed along the eastern seaboard carrying ozone and its precursors from the District of Columbia, up through New York City, and on past Boston to Maine (Wolff, Lioy et al. 1977).

As empirical knowledge of ozone formation and accumulation improved over the 1970's and 1980's, so did computational capability. These two trends influenced the evolution of the models and analytic techniques used in the attainment planning process into larger-scale and more

[15] Simultaneous studies in Western Europe provided further evidence of the regionality of ozone (Cox, Eggelton et al. 1975; Hov, Hesstvedt et al. 1978; Isaksen, Hov et al. 1978).

complex formulations. Demonstrating a greater recognition of the regionality of ozone, air quality models have evolved from simplistic representations of photochemical relationships that focus on the urban core to increasingly sophisticated and expansive urban scale and regional models (Keating and Farrell 1998; Russell 1997).

Several research projects pushed the science forward at this time, and three field studies were particularly influential: the San Joaquin Valley Air Quality Study/Atmospheric Utility Signatures Predictions and Experiments (SJVAQS/AUSPEX), the Southern Oxidant Study (SOS), and the Lake Michigan Ozone Study (LMOS). In addition, EPA conducted a multi-State modeling study known as the Regional Ozone Modeling for Northeast Transport (ROMNET) effort. (Keating and Farrell 1998)[16] Among other things these were much more coordinated research endeavors than previous efforts had been. A number of other ozone assessments soon followed, including the 1989 Office of Technology Assessment (OTA) report *Catching Our Breath: Next Steps for Reducing Urban Ozone* (Office of Technology Assessment 1989), the conclusions of which helped shape the 1990 Amendments to the Act. At the same time, air quality regulators began to realize that NO_X controls might be more beneficial than VOC controls in many cases. After many areas in the country failed to attain the ozone NAAQS by the 1987 deadline set in 1977, EPA began to rethink their policy of focusing on VOC control. At this time many states were in violation of the Clean Air Act, but no federal sanctions were imposed. Instead the EPA issued guidance that allowed ozone nonattainment areas for the first time to consider NO_X control in lieu of VOC control (Roth, Zieman et al. 1993).

By the time the importance of NO_X was beginning to emerge in the understanding of air quality planners, the engineering of NO_X emissions control technology and pollution prevention had advanced enough to make NO_X control a feasible option. About the same time, California began aggressively pursuing the control of NO_X emissions from stationary sources.

2.3.4 Recent Changes in Policy and Politics

These advances in the science of tropospheric ozone occurred simultaneously with changes in policy and politics. In 1988, almost 20 years after the passage of the 1970 Act, 112 million people (45% of the U.S. population) lived in areas that still were not in attainment of the ozone NAAQS (National Research Council 1991). In response, Congress attacked the ozone nonattainment problem in the 1990 Amendments to the Clean Air Act by prescribing a litany of specific control measures, mostly aimed at VOC emissions, that constitute the most specific set of control measures imposed by the federal government on States in the history of air pollution legislation. In addition they introduced three important innovations that have had an important impact on the governance of ozone precursors: requirements for Reasonably Available Control Technology for stationary source NO_X sources (NO_X RACT), the Ozone Transport Region, and the Title IV Acid Rain Program.

The NO_X RACT requirements marked the first time that stationary sources outside California had faced NO_X emissions controls, and the first time that national legislation led to NO_X controls on power plants. Although these emissions reductions were not stringent compared to what would come later, they did send a strong signal to the electric power industry (and to some large industrial facilities) that they could be the targets of further regulations.

---

[16] A field study involves the collection and analysis of air quality data, while a modeling study involves the application of (and often the development of) a computer model to study different scenarios. Generally, the results of field studies are used to evaluate modeling efforts.

The formation of the Ozone Transport Region and an accompanying Commission of State leaders (the OTC) is the most significant step that Congress has so far made to address the regional character of ozone (101st Congress 1990) §184).[17] Made up of 12 Mid-Atlantic and Northeast States stretching from Virginia to Maine and the District of Columbia, the OTC functions as a coordinating and negotiating group for regional ozone policy. The crucial accomplishment of the OTC relative to OTAG was the signing of a Memorandum of Understanding (MOU) in which the States committed themselves to aggressive NO_X emissions reductions [Ozone Transport Commission, 1994 #385. They subsequently developed an emissions trading program (the OTC NO_X Budget) focused on the electric power sector (Farrell 2000; Farrell, Carter et al. 1999).

The Title IV program is important because it is the "grand policy experiment" on emissions trading, specifically cap-and-trade programs (Stavins 1997). This approach to controlling pollution is much more like a CPR approach than the technology and product specifications used previously. In a cap-and-trade program, regulated firms are allocated a fixed number of allowances and are required to redeem one allowance for every ton of pollution emitted. The total allocations (the cap) are smaller than previous emissions, so regulated firms have four basic options: 1) control emissions to exactly match their allocation, 2) buy allowances to meet this redemption requirement, 3) "overcontrol," and bank allowances for use in future years (when fewer allowances will be allocated), or, 4) overcontrol and then sell their excess. The importance of the Title IV program is that it's introduction and early success has greatly eased the politics of introducing emissions trading (Joskow and Schmalensee 1998; Schmalensee, Joskow et al. 1998), which has helped enable applications in the control of photochemical smog.

2.3.5 The emergence of CPR approaches

Although the traditional approaches to controlling photochemical smog have not used a CPR framework, some recent developments are more compatible with this view. These include the use of cap-and-trade systems (discussed above) and the way in which the debate about long-range transport of ozone has been framed in the United States. Since the passage of the 1990 Amendments several NO_X emissions trading programs have come into being, most notably the OTC NO_X Budget, and California's RECLAIM program (Farrell 2000: Klier, 1997 #1743; Johnson and Pekelney 1996; Lents and Leyden 1996). These programs treat the atmosphere like a resource in that the allowances represent permission to emit a specific quantity of a certain pollutant. This permission, in turn, can be thought of granting to the polluter the use of a specific portion of the assimilative capacity of the environment. It is interesting to note, however, that the authors of these provisions have been careful to define allowances (and more specifically, the allocation of allowances to existing firms) as "limited authorization" to emit pollution, and that "[s]uch allowance does not constitute a property right" (§ 403(f) of the Clean Air Act). Nonetheless, allowances have many of the features of a property right, and operational rules about how they are to be used must be devised, using a system of collective-choice rules and constitutional procedures, much like in a CPR regime (Schlager and Ostrom 1992). Further, scholars have shown how these decisions influence the efficiency characteristics of emissions trading programs, reinforcing the need to deal with them (Foster and Hahn 1995).

[17] The OTC's activities are best documented in the series of briefing binders it has produced for its thrice-a-year meetings. See also http://www.sso.org/otc/ and http://www.epa.gov/acidrain/otc/otcmain.html.

The interstate debate about tropospheric ozone control has also seem the emergence of CPR-like thinking by focusing on the distribution of the "margin for growth," a concept similar to Connolly's "ability to destroy." The margin for growth is the difference between the background concentration of ozone and the level set by the standard (see Farrell 1998 pp 4-5 and Figure 1). It represents the allowable ozone concentrations which can be caused by polluting activities (which are often thought of as representing economic growth) before violating an air quality standard. Thus, transboundary air pollution debates can be thought of as questions about who should be allowed to consume the margin for growth, the upwind or the downwind jurisdiction.[18] In the case where the concentration exceeds the standard and there is no margin for growth, the transboundary question can thus be thought of as questions about how much control is needed where, and who should pay for it. Of course, the difficulty in applying CPR approaches to the margin for growth concept is that it involves directionality – sources in an upwind jurisdiction can consume the margin for growth a downwind jurisdiction would like to retain for itself.

3 Concluding remarks

This analysis leads to a few conclusions. The most important of which is that although evocative, the concept of the atmosphere as a commons is not supported in the historical record and largely inapplicable on a theoretic basis. Both historically and theoretically, the concepts of nuisance and public goods are the most commonly used and are the most appropriate approaches to air pollution. Because it is difficult to frame air pollution problems as common property resource issues, CPR regimes are exceedingly rare in application to air pollution. The only real examples are the small number of cap-and-trade systems put into place in the United States. Instead, the traditional approach to managing air pollution has been through litigation and (more often) regulation.

Air pollution litigation and regulation have tended to rely mostly on nuisance and negligence law, and the economic ideas of externalities and public goods. The prevalence of these approaches can be observed in the very commonplace notion of the public's "right to clean air." Further, the basis of almost all air pollution law and regulation is clearly given as the protection of human health, or sometimes the preservation of the environment. The use of the atmosphere is not typically part of the preambles to or bodies of air pollution legislation. And the increasing use of benefit/cost analysis to study air pollution problems and define their solutions is additional evidence of a public goods framing. Another important feature of air pollution regulation is that they have been exceedingly difficult to apply to individual behavior, governments have been much more successful regulating firms than they have been regulating consumers.

Finally, it is clear that the scale of air pollution has increased significantly over the course of the last century, both as a phenomenon and as an issue of governance, and that this increase has been caused by a number of quite different forces. Economic growth has increased the size of anthropogenic activities, leading to additions to existing geochemical cycles large enough to perturb them, and greatly increasing the number of toxic and persistent pollutants emitted to the environment. The globalization of national economies plus scale economies in automobile production and in manufacturing management have lead directly to increases in the scale at which air pollution is best appreciated and managed. And the politics of international pollution flows have also added to the effect.

[18] For a more complete discussion of this concept from a legal perspective, see Revesz (1996 pp2360-2374).

References

101st Congress (1990). Clean Air Act Amendments - Public Law 101-549. Washington, DC, U.S. Government Printing Office.

Anderson, T. and D. Leal (1991). Free Market Environmentalism. San Francisco, Westview Press.

Andrews, R. N. L. (1999). Managing the Environment, Managing Ourselves. New Haven, CT, Yale University Press.

Ayres, R. U., W. H. Schlesinger, et al. (1997). Human Impacts on the Carbon and Nitrogen Cycles. Industrial Ecology and Global Change. R. Socolow, C. Andrews, F. Berkhout and V. Thomas. New York, Cambridge University Press**:** 121-155.

Bailey, C. J. (1998). Congress and Air Pollution. New York, Manchester University Press.

Bedingfield, R. E. (1970).

Bennett, G., Ed. (1991). Air Pollution Control in the Eurpoean Community: Implementation of the EC Directives in the Twelve Member States. International Environmental Law and Policy Series. Boston, Wolter Kluwer Academic Publishers.

Black, H. C. (1980). Black's Law Dictionary. St. Paul, MN, West Publishing, Inc.

Boehmer-Christiansen, S. A. (1989). "Vehicle Emission Regulation in Europe - The Demise of Lean-Burn Engines, the Polluter Pays Principle . . . . and the Small Car?" Energy and Environment **1**(1): 1-25.

Boehmer-Christiansen, S. A. (1990). "Curbing Auto Emissions in Europe." ENVIRONMENT **32**(6): 17-20, 34-39.

Brenner, J. F. (1974). "Nuisance Law and the Industrial Revolution." Journal of Legal Studies **3**(June): 395-411.

Brimblecombe, P. (1987). The Big Smoke. New York, Methuen.

Brown-Weiss, E. (1993). "International Environmental Law: Contemporary Issues and the Emergence of a New World Order." Georgetown Law Journal **81**: 675-710.

Clapp, B. W. (1994). An Environmental History of England. London, Harlow, ENGLAND.

Cleveland, J., B. Kleiner, et al. (1976). "Photochemical air pollution: transport from the New York City area into Connecticut and Massachusetts." Science **191**: 179-181.

Coase, R. H. (1960). "The Problem of Social Cost." Journal of Law and Economics **III**(October): 1-44.

Colbeck, I. and A. Mackenzie (1994). Air Pollution by Photochemical Oxidants. New York, Elsevier.

Connolly, B. (1999). Asymmetrical Rivalry in Common Pool Resources and European Responses to Acid Rain. Anarch and the Environment. J. S. Barkin and G. E. Shambaugh. Albany, NY, State University of New York Press**:** 122-149.

Cox, R. A., A. Eggelton, et al. (1975). "Long-range transport of photochemical ozone in north-western Europe." Nature **225**: 118-121.

Davidson, C. I. (1979). "Air Pollution in Pittsburgh: A Historical Perspective." APCA Journal **29**(10).

Davies, J. C. and B. S. Davies (1975). The Politics of Pollution. Indianapolis, IN, Bobbs-Merrill.

Decker, C. E., L. A. Ripperton, et al. (1976). Formation and transport of oxidants along Gulf Coast and in Northern U.S. Research Triangle Park, NC, U.S. Environmental Protection Agency.

Dietrich, W. F. (1996). "Harmonization of Automobile Emission Standards Under International Trade Agreements: Lessons from the European Union Applied to the WTO and the NAFTA." William and Mary Environmental Law and Policy Review **20**: 175-221.

Esposito, J. C. (1970). Vanishing Air: Ralph Nader Study Group Report on Air Pollution. New York, Grossman Publishers.

Farrell, A. (1998). Environmental Assessment and Policy in Follower Nations: Air Pollution in Spain. GEA Discussion Paper. Cambridge, MA, Harvard University.

Farrell, A. (2000). "The NOx Budget: A Look at the First Year." Electricity Journal **March**: 83-92.

Farrell, A., R. Carter, et al. (1999). "The NOx Budget: Costs, Emissions, and Implementation Issues." Resource & Energy Economics **21**(2): 103-124.

Farrell, A. and T. J. Keating (1998). Multi-Jurisdictional Air Pollution Assessment: A Comparison of the Eastern United States and Western Europe. Cambridge, M, Belfer Center for Science and International Affairs, Harvard University**:** 74.

Foster, V. and R. W. Hahn (1995). “Designing More Efficient Markets: Lessons From Los Angeles Smog Control.” Journal of Law and Economics **38**(1): 19-48.

Friedman, L. (1973). A History of American Law. New York.

Friedman, T. L. (1999). The Lexus and the olive tree. New York, Farrar, Straus, Giroux.

Grinder, R. D. (1980). The Battle for Clean Air: The Smoke Problem in Post-Civil War America. Pollution and Reform in American Cities, 1870-1930. M. V. Melosi. Austin, TX, University of Texas Press**:** 83-103.

Haagen-Smit, A. J. (1950). “The Air Pollution Problem in Los Angeles.” Engineering and Science **XIV**(Dec.): 7-13.

Haagen-Smit, A. J., E. F. Darley, et al. (1951). “Investigation on injury to plants from air pollution in the Los Angeles area.” Plant Physiology **27**: 18.

Haagen-Smit, A. J. and M. M. Fox (1954). “Photochemical ozone formation with hydrocarbons and automobile exhaust.” Journal of the Air Pollution Control Association **4**: 105-109.

Hayes, S. P. (1998). Explorations in Environmental History. Pittsburgh, University of Pittsburgh Prress.

Hov, O., E. Hesstvedt, et al. (1978). “Long-range transport of tropospheric ozone.” Nature **273**: 341-344.

Hurst, J. W. (1956). Law and the Conditions of Freedom in Nineteenth Century United States. Madison, WI.

Husar, R. and J. D. Husar (1990). Sulfur. The Earth as Transformed by Human Action. B. L. Turner, W. C. Clark, R. W. Kateset al. Cambridge, MA, Cambridge University Press**:** 409-421.

Isaksen, I. S. A., O. Hov, et al. (1978). “Ozone generation over rural areas.” Environmental Science and Technology **12**: 1279-1284.

Johnson, S. L. and D. Pekelney (1996). “Economic assessment of the regional clean air incentives market: A new emissions trading program for Los Angeles.” Land Economics **72**(3): 277-297.

Jones, C. O. (1974). Clean Air: the politics of pollution. Pittsburgh, PA, Pittsburgh University Press.

Jones, K. C. and P. de Voogt (1999). “Persistent organic pollutants (POPs): state of the science.” Environmental Pollution **100**(1-3): 209-221.

Joskow, P. and R. Schmalensee (1998). “The political economy of market-based environmental policy: The US acid rain program.” Journal of Law and Economics **41**(1): 37-83.

Keating, T. J. and A. Farrell (1998). Problem Framing and Model Formulation: The Regionality of Tropospheric Ozone in the US and Europe. GEA Discussion Paper. Cambridge, MA, Harvard University.

Krier, J. and E. Ursin (1977). Pollution and Policy: A Case Essay on California and Federal Experience with Motor Vehicle Air Pollution 1940-1975. Berkeley, CA, University of California Press.

Lents, J. M. and P. Leyden (1996). “RECLAIM: Los Angeles' New Market-Based Smog Cleanup Program.” Journal of the Air & Waste Management Association **46**: 195-206.

Lubove, R. (1995). Twentieth-Century Pittsburgh: Government, Business, and Environmental Change.

Markham, A. (1994). A Brief History of Pollution. New York City, St. Martin's Press.

Martinez, J. R. and H. B. Singh (1979). Survey of the role of NOx in non-urban ozone formation. Research Triangle Park, NC, U.S. Environmental Protection Agency.

Middleton, J. T., J. B. Kendrick, et al. (1950). “Injury to herbaceous plants by smog or air pollution.” Plant Disease Report **34**: 245-252.

Mitchell, R. B. (1999). International Environmental Common Pool Resources: More Common than Domestic but More Difficult to Manage. Anarachy and the Environment. J. S. Barkin and G. E. Shambaugh. Albany, NY, State University of New York Press**:** 26-50.

National Research Council - Committee on Tropospheric Ozone Formation and Measurement (1991). Rethinking the ozone problem in urban and regional air pollution. Washington, DC, National Academy Press.

Office of Technology Assessment (1989). Catching Our Breath: Next Steps for Reducing Urban Ozone. Washington, D.C., U.S. Government Printing Office.

Patton-Hulce, V. R. (1995). Environment and the Law: A Dictionary. Santa Barbar, CA, ABC-CLIO.

Pearce, D. and R. Shaw, Eds. (1992). The MIT Dictionary of Modern Economics. Cambridge, MA, MIT Prese.

Portney, P., Ed. (1990). Public Policies for Environmental Protection. Washington, DC, Resources For the Future.

Raufer, R. (1998). Pollution Markets in a Green Country Town: Urban Environmental Management in Transition. Westport, CT, Praeger Publishers.

Regens, J. L. (1993). Acid Deposition. Keeping Pace with Science and Engineering. M. Uman. Washington, DC, National Academy Press**:** 165-188.

Research Triangle Institute (1974). Investigation of Ozone and Ozone Precursor Concentrations at Nonurban Locations in the Eastern United States. Research Triangle Park, NC, US Environmental Protection Agency**:** 72.

Research Triangle Institute (1975). Investigation of rural oxidant levels as related to urban hydrocarbon control strategies. Research Triangle Park, NC, U.S. Environmental Protection Agency.

Roth, P., S. Zieman, et al. (1993). Tropospheric Ozone. Keeping Pace with Science and Engineering. M. Uman. Washington, DC, National Academy Press**:** 39-90.

Rothbard, M. N. (1924). Conservation in the Free Market. Egalitarianism as a Revolt Against Nature and Other Essays. R. A. Childs. Washington, DC**:** 114.

Russell, A. (1997). "Regional photochemical air quality modeling: model formulations, history, and state of the science." Annual Review of Energy and the Environment **22**: 537-588.

Schlager, E. and E. Ostrom (1992). "Property-Rights Regimes and Natural Resources: A Conceptual Analysis." Land Economics **68**(3): 249-62.

Schmalensee, R., P. Joskow, et al. (1998). "An Interim Evaluation of Sulfur Dioxide Emission Trading." Journal of Economic Perspectives **12**(3): 53-68.

Seinfeld, J. H. and S. N. Pandis (1998). Atmospheric chemistry and physics : from air pollution to climate change. New York, John Wiley.

Smil, V. (1985). Carbon nitrogen sulfur : human interference in grand biospheric cycles. New York, Plenum Press.

Smil, V. (1990). Nitrogen and Phosphorus. The Earth as Transformed by Human Action. B. L. Turner, W. C. Clark, R. W. Kateset al. Cambridge, MA, Cambridge University Press**:** 423-436.

Smith, K. (1993). Fuel Combustion, Air Pollution Exposure, and Health: The Situation in Developing Countries. Annual Review of Energy and Environment, Annual Reviews, Inc. **18:** 529-566.

Smith, K. R. (1994). Looking for Pollution Where the People Are. Honolulu, HI, East-West Center**:** 8.

Soroos, M. R. (1997). The Endangered Atmosphere: Preserving A Global Commons. Columbia, SC, University of South Carolina Press.

Stasiuk, W. N., Jr. and P. E. Coffey (1974). "Rural and urban ozone relationships in New York state." Journal of the Air Pollution Control Association **24**: 564-568.

Stavins, R. (1997). "What can we learn from the grand policy experiment? Lessons from SO2 allowance trading." JOURNAL OF ECONOMIC PERSPECTIVES **12**(3): 69-88.

Stern, A. C. (1982). "History of Air Pollution Legislation in the United States." Journal of the Air Pollution Control Association **32**(1): 44-61.

Tarr, J. (1996). The Search for the Ultimate Sink: Urban Pollution in Historical Perspective. Akron, OH, The University of Akron Press.

Tarr, J. and C. Zimring (1997). The Struggle for Smoke Control in St. Louis. Common Fields: an environmental history of St. Louis. A. Hurley. St. Louis, Missouri HIstorical Society Press**:** 199-220.

Vukovich, F. M., W. D. Bach, et al. (1977). "On the relationship between high ozone in the rural surface layer and high pressure systems." Atmospheric Environment **11**: 967-983.

White, W. H., J. A. Anderson, et al. (1976). "Formation and transport of secondary air pollutants: Ozone and aerosols in the St. Louis air basin." Science **194**: 187-189.

Wolff, G. T., P. J. Lioy, et al. (1977). "An investigation of long-range transport of ozone across the midwestern and eastern United States." Atmospheric Environment **11**: 797-802.

Yergin, D. (1991). The Prize: The Epic Quest for Oil, Money, and Power. New York, Simon & Schuster.