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Innovation and the international diffusion of environmentally responsive technology [1]

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Abstract

New evidence is presented on environmental innovation and diffusion over the 1970s and 1980s. At a global level, a substantial amount of innovations occurred. In the United States, Japan, and Germany, the share of environmental patents in all patents varied between 0.6 and 3%, and as such was higher than the corresponding share of pollution abatement expenditure in GDP. Japanese environmental innovation rates were consistently high. Certain plausible connections between environmental regulation and innovation also emerge. Across these three countries and over time, innovation responded to pollution abatement expenditure, an indicator of the severity of environmental regulations. Environmental patenting rates in developing countries were also high, reaching 2% in many years in Brazil. Developing country innovators obtained a non-trivial number of patents, most of which appear geared towards adapting imported technologies to local conditions. However, domestic innovation was only one path to new technologies. 'Imports' of disembodied environmental technologies (foreign patents registered in developing countries) were substantial. Foreign patents were typically 'important' or generic patents; evidence also suggests that such patents protected intellectual property in equipment exported. Developing countries, especially in East Asia, often chose to obtain technologies embodied in pollution abatement equipment.

1. Introduction

The creation and diffusion of environmentally responsive technologies offers the best prospect for lowering pollution with minimal impact on the output of goods and services. Little, however, is known about the nature and extent of environmental innovation and its international diffusion. This paper presents new evidence on environmental innovation and diffusion over the 1970s and 1980s, a period of rapidly increasing public awareness and concern about environmental damage. Environmental innovation includes pollution abatement (end-of-pipe) innovation and new technologies which lower the pro-

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duction of pollutants; the data used here pertain primarily to the former with the exception of alternative energy technologies.

One point is clear: at a global level, a substantial amount of environmental innovation occurred. In the three major industrialized countries (United States, Japan, and Germany) the share of environmental patents in all patents, varying between 0.6 and 3% depending upon the country and year, has been larger than the corresponding pollution abatement expenditure share in gross domestic product (between 0.3 and 1.8%). In Japan, 2 to 3% of the patents granted to inventors during that period can be defined as related to technologies that reduce pollution (see Fig. 1). In Germany, the corresponding percentage rose rapidly over the period from low initial levels to about 2.5%. The United States lagged behind, but even there about 1% of all patents were to environmental technologies. In all three countries, but especially in Japan and more recently in Germany, domestic innovators dominated the patent registrations, consistent with our finding that the extent of country specialization (by specific environmental field) was limited and did not grow over the period studied.

Significant numbers of environmental patents were also registered in developing countries, though a large share of these were to inventors from developed nations. Foreign inventors typically registered their 'important' and broadly applicable patents in developing countries, rather than patents covering technologies tailored to the conditions of a developing country; foreign patents also apparently protect the intellectual property embodied in pollution control equipment exported to developing countries. Developing country inventors themselves do a fair amount of environmental innovation, most notably in Brazil. Countries that have systems of 'petty' or 'utility' patents (Korea and Mexico) also show significant patent activity in the environmental fields, indicating adaptive or minor innovations, based in part upon technologies transferred from the developed nations.

Another route to technology acquisition has been through purchase of pollution control equipment, and hence of the technology embodied in such equipment. Such transfer has occurred especially in East Asian economies, in keeping with their broader propensities to acquire technology through imported equipment. Other developing countries are likely to benefit from emulating such a strategy for two reasons. First, a large and competitive world market for pollution-control equipment and related services exists; estimated presently at more than $200 billion

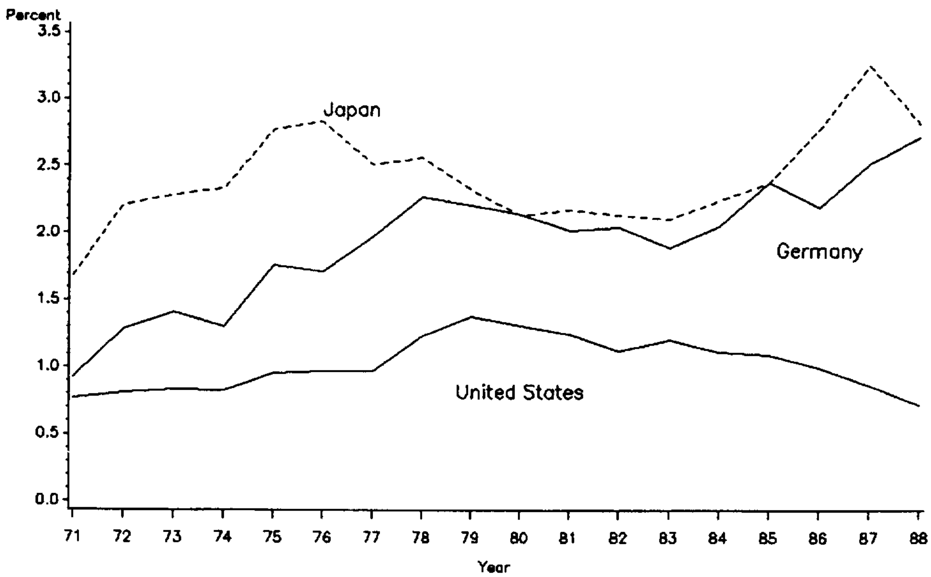

Fig. 1. Environmental patents as a percentage of total patents.

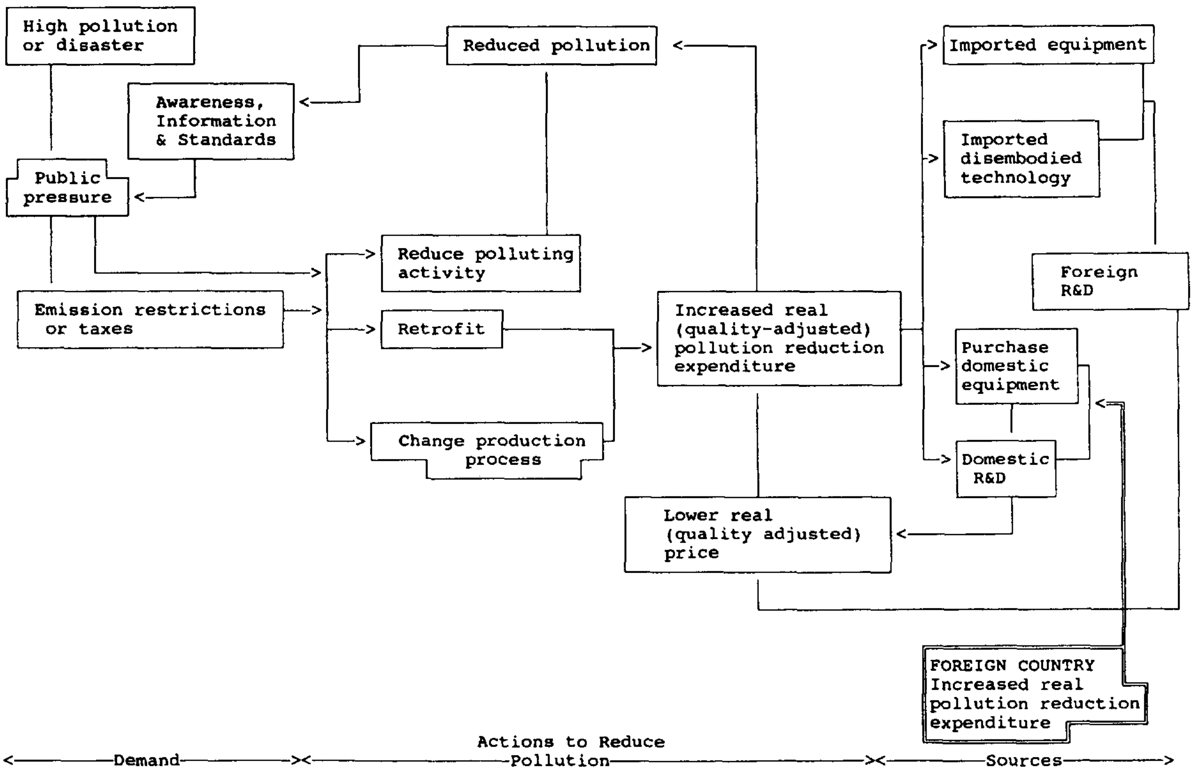

Fig. 2. Institutions and expenditures for environmentally responsive technologies.

year, it is predicted to grow at 5 to 6% year to reach $300 billion by the year 2000 (OECD, 1991). Second, we find that such suppliers of inputs to polluters have been the principal source of innovation for controlling pollution rather than the polluters themselves.

What stimulated this growth in new environmental technologies and in the pollution control industry? Though this paper primarily provides a descriptive account of innovation and diffusion of environmental technologies, certain plausible connections between environmental regulation and innovation are also presented. Environmental concerns came to the forefront in the early 1970s, triggered in some instances by specific accidents, as in Japan. Air pollution regulation was followed later in the decade by regulation of water pollution. These regulations have embodied collective goals for levels of pollution abatement. As such, they served as 'focusing devices' for motivating innovations. [2] Regulations, in turn, triggered pollution abatement expenditures. Such expenditures are used in this paper as indicators of 'effective demand' for pollution control. The evidence, though imperfect, is strongly suggestive of an association between pollution abatement expenditures and patenting of environmental technologies in developed countries.

Analysis of environmentally responsive innovation and diffusion has been restricted by paucity of

[2] The term 'focusing device' was coined by Rosenberg (1976). Coase (1988, p. 9) also notes that even in apparently competitive markets, regulations exist to lower transactions costs and hence increase the volume of transactions. The role of regulations for focusing polluters and their suppliers is discussed by Pearce (1990). See also Porter (1990).

relevant data. To this end, we have constructed a patent data set, consistent across time and countries, and also rich in detail on specific environmental technologies and the country origin of innovators. We also define a set of capital goods used for pollution reduction that can be identified in international trade statistics – these are used to examine trade flows in pollution control equipment. Although the novel data permit empirical analysis hitherto not possible, data limitations continue to limit the analysis to a simple description of central tendencies and variance, and preclude sophisticated econometrics. Instead, therefore, we enrich the discussion by drawing upon case-studies.

In the following section (Section 2) we begin by setting out a framework for studying environmental innovation and diffusion. In Section 3, we present trends in, and the composition of, pollution abatement expenditures in the United States, Japan, and Germany and their relation to environmental regulations in those countries. In Section 4, the patent data is first analyzed for the United States, Japan, and Germany to describe the extent and composition of innovation and also to explore the link between pollution expenditure and patent activity. Then, for a larger group of countries, including low- and middle-income countries, patterns of patenting are assessed to determine the relative roles of domestic innovation and technology transfer. Section 5 discusses trade in pollution abatement equipment and its relation to patenting. The various strands are drawn together in the final section.

2. Analyzing regulation, innovation, and diffusion

Fig. 2 outlines a system which leads to improved environmental technologies in a country. It is partitioned into three interconnected modules. The first module describes the ways in which the demand for a clean environment is articulated and translated into specific policies to reduce pollution; the second describes the influence of policies on actions by polluters, including the reduction of the polluting activity or the introduction of pollution-control technologies; and the third describes the mechanisms available to implement the latter choice. Feedbacks exist between the modules. Expenditure leads to innovation. Innovation, in turn, can lower the real quality-adjusted cost of pollution-abatement equipment and materials, giving a further fillip to pollution-abatement expenditure. The expenditure leads to lower pollution, greater awareness of pollution reduction possibilities, and possibly greater public pressure for further pollution reduction.

2.1. *Demand for a clean environment*

The demand for a cleaner environment has thus far been channelled primarily through governments. In countries that passed early environmental legislation, the initial legislation was often spurred by a public outcry over an environmental disaster. The well-publicized discovery in 1978 that homes and a school in Love Canal, New York, were built on an abandoned, and leaking, hazardous waste dump led to the Superfund toxic waste clean-up program. In another instance, the strong public reaction in Japan to widespread respiratory ailments caused by a petrochemical complex at Yokkaichi led to that country's first law on pollution control. Similarly the 1956 Clean Air Act in England was a response to the smog crisis in 1952. This pattern continues (the imposition of tighter legislation in India following the Bhopal incident is a case in point) although recently countries have been more likely to pass legislation in line with international standards without the impetus of an attention-grabbing disaster. As the transboundary nature of much pollution becomes apparent, international demand for environmental control has been an important factor in encouraging governments to act.

Environmental regulations within the OECD are now fairly similar, having converged over time. Most low- and middle-income countries have also passed legislation for pollution control, patterned on OECD regulations. On the whole this is recent legislation although there are some exceptions. For example, Korea established legislation, with standards and monitoring mechanisms, before 1980. India, too, passed environmental legislation for controlling water pollution (1974) and air pollution (1981) relatively early. It appears to be the enforcement of existing legislation rather than its creation which is now the largest concern.

By far the most common type of legislation is 'command and control', legislation which imposes limits on emissions and sometimes specifies clean-up technologies. Although market-based strategies are frequently discussed and are becoming somewhat more in evidence, their use is relatively limited even in developed countries. In March 1993 the US Environmental Protection Agency held its first auction of pollution rights (for SO_2) which was conducted by the Chicago Board of Trade. Deposit refund schemes (widespread for beverage containers, for example) represent another market-based strategy that has proven effective in encouraging recycling (see Environmental Protection Agency (EPA), 1991; and Hahn, 1989, for further examples of market-based strategies).

Governments also use more indirect methods to encourage clean behavior, such as tax breaks or subsidies to R&D in environmental fields, and cost-sharing projects aimed at testing and disseminating information about new control technologies. Government initiatives to promote or mandate environmental accounting, to design and standardize eco-labelling of products, and to monitor and publish data on emissions facilitate public action. As knowledge of health risks spreads, neighbors of polluting firms are taking a more active interest in lowering pollution levels. This does not require formal regulations nor that a country be particularly wealthy. Huq and Wheeler (1992) report that villagers living along rivers in Bangladesh have successfully pressured firms located upstream to undertake at least first-stage effluent treatment, even where such treatment was not required by the government. [3]

The public increasingly expresses its demands for pollution control directly through the marketplace by generating bad publicity for 'dirty' firms and switching purchases to 'green' products and companies. Some firms are taking an pro-active attitude toward pollution abatement, for instance, by marketing environmentally friendly products, designing new accounting procedures that detail the environmental costs of their operations, and putting pressure on supplier firms to comply with environmental criteria in product specifications. [4]

Joint and several liability rulings in some countries have had a profound effect on polluters and anyone associated with them, with some interesting implications for pollution control. US banks, for instance, are increasingly reluctant to make loans to polluters for fear of being charged with responsibility for ecological damage if claims are filed. As a result they have begun to require environmental audits as a routine part of loan procedures (*Financial Times*, November 27, 1991). Similarly, some insurance companies are offering new environmental clean-up policies that are contingent upon the policyholder carrying out environmental surveys and adopting rigorous controls to lower risk (*Financial Times*, October 28, 1992).

2.2. Industry responses

In response to the various pressures arising from environmental concerns, polluters may reduce or eliminate the offending activity. Clearly, no direct technical change follows when the latter choice is exercised by the polluters. In most instances, however, effort is made to reduce pollution while maintaining production, either by installing devices that absorb the pollutants before they are discharged into the environment or changing the production process to lower pollutants generated. The former is often termed the end-of-pipe solution. Process change ranges from the complete re-engineering of a production processes to straightforward measures such as the better avoidance of waste (e.g. through the use of superior measuring instruments and control devices) or the substitution of new, cleaner inputs.

[3] Local activism can also have negative environmental impacts. For instance, Nimby (not in my backyard) movements can delay or prevent the construction of water treatment and waste incineration plants.

[4] There is a potential negative side to the realization by firms that strong environmental regulation can be used as a competitive tool. Some countries have been accused of designing new environmental legislation, with the support of domestic industry, which is geared toward establishing trade barriers. One controversy surrounded Danish legislation requiring that certain drinks be bottled in government-approved containers, and stipulating minimum refill percentages. Foreign firms charged that retrieving the bottles would be more expensive for them than for domestic firms (Office of Technology Assessment (OTA), 1992).

Table 1
Machinery suppliers as a source and user of pollution control technology [a]

Field	Share of patents (%)	
	Originating in machinery sector	Used by machinery sector
Industrial air pollution	81	5
Water pollution	83	2
Vehicle air pollution	36	38
Alternative energy	85	8
Solid waste	73	3
Incineration of waste [b]	33	3
Radioactive waste	59	6
Recycling and reusing waste [c]	18	0
Oil spills	90	1

[a] Figures are based on calculations using the Yale–Canada concordance of IPC classes to industry of use and industry of origin. For details see Kortum and Putnam (1989).
[b] 63% of patents originate in the fabricated metals sector.
[c] 66% of patents originate from the food, drinks, and tobacco sector.

2.3. Sources of pollution control technology

Once a demand is created, the relevant technology may be imported or sourced domestically. In either case, technologies may be obtained in equipment 'embodying' the technologies or in a disembodied form (e.g. blueprints, patent licenses, [5] and consulting services). The flow of capital equipment embodying technical innovations is an important mechanism for technology diffusion since suppliers of capital goods are major innovators and new generations of equipment often embody state-of-the-art knowledge. In the environmental fields identified in the patent data (Appendix) it is the machinery suppliers rather than the users of the technologies who have been the leading source of innovation. Machinery suppliers are estimated to have been the source of about 80% of the patents for the control of industrial air pollution, water pollution, oil spills, and the exploitation of alternative (non-fossil fuel) energy sources (see Table 1). [6] Using case studies of vinyl chloride fabrication, small volume chemicals, PCBs, copper mining, auto fuel economy, and safety, Heaton (1990) shows that 'outsiders' played an important role in technology development. The dynamism of equipment producers is especially relevant to developing countries. Equipment markets are reasonably competitive, leading sellers to impose fewer restrictions and constraints on equipment sales than on the sale of technology through licensing. Whether embodied or disembodied, an importing country must often make some adaptive innovations to use new technology effectively.

3. Expenditure on pollution control – evidence of demand

One indicator of demand for environmentally responsive innovation is the level of private and public spending on pollution control and abatement. Expenditure is a particularly useful indicator as it encapsulates not just regulation but monitoring, enforcement, and the strength of marketplace signals. Given the imprecision in, and different categories of, expenditure data, comparisons across countries are risky. However, the evidence presented below suggests a similarity in trends and composition across the United States, Germany, and Japan, in particular the prominence of expenditure on water pollution control. The data are also consistent with the general perception regarding the strength of regulation and compliance in the three countries. During the 1980s, differences in the severity of emission standards narrowed. By the end of the period, however, Japan fell 'at the strict end', with not only strict standards, but probably the most extensive monitoring and enforcement systems. Local governments have been particularly assiduous in enforcing pollution standards. The United States was in an intermediate position, and Germany and other European countries were, on average, at the lower end (Kopp et al., 1990). Ger-

[5] Licensed technology may be used for domestic production of equipment. Disembodied refers to the form of technology *as transferred*.

[6] Figures in Table 1 are based on calculations using the Yale–Canada concordance of IPC classes to industry of use and industry of origin. For details see Kortum and Putnam (1989).

Table 2
Pollution abatement expenditure

Year	United States		Germany		Japan	
	Expenditure (1980 $US millions)	% GDP	Expenditure (1980 $US millions)	%GDP	Expenditure (1980 $US millions)	%GDP
1972	14908	0.66	1794	0.27		
1973	17653	0.75	1803	0.26		
1974	18099	0.77	1783	0.26		
1975	19081	0.82	5025	0.73		
1976	19531	0.81	5155	0.71	14164	1.75
1977	18971	0.75	4624	0.62	13962	1.63
1978	20177	0.75	4339	0.56	15940	1.77
1979	20676	0.76	5277	0.66	17664	1.87
1980	22956	0.84	5899	0.73	18149	1.84
1981	20364	0.73	5469	0.67	18931	1.85
1982	18369	0.68	5094	0.63	18365	1.74
1983	16281	0.58	4813	0.59	17615	1.62
1984	18392	0.61	4586	0.54	16250	1.42
1985	19877	0.64	5877	0.68	16127	1.35
1986	20132	0.63	3362	0.38	16509	1.34
1990	22421	0.62	7696	0.77		

Source: OECD (1990, 1993).

many made tremendous strides over the period, however, not only by instituting high standards but by promoting innovative institutional development in areas such as recycling and eco-labelling.

3.1. Public and private expenditures

Table 2 shows pollution abatement expenditures (in 1980 dollars) [7] for the United States, Japan, and Germany by all levels of government, and by private manufacturing and non-manufacturing firms. The figures include investment expenditures on plant and equipment, regulation and monitoring, and research and development. From 1972 to 1976, total expenditure in the United States increased from US$15 billion to close to US$20 billion. It remained at or above that level through 1980, reaching 0.84% of GDP. In 1981–83 spending dipped then returned to previous high levels of absolute spending by the end of the decade, although remaining at a lower percentage of GDP.

Spending in Japan on pollution control rose from US$14 billion in 1976 to a peak of US$19 billion in 1981, somewhat after the peak in expenditure in the United States. In that year, the share of pollution abatement expenditure was 1.85% of GDP. From 1981, spending fell to US$16 billion in 1985 and rose again in the latter half of the 1980s. [8]

Pollution control and abatement expenditures have historically been substantially lower in Germany, both in absolute and percentage terms. From a total of US$5 billion in 1975, spending dipped in 1977 and 1978, and then peaked in 1980 at US$6 billion. In Germany too, expenditure fell in 1981 and contin-

[7] Nominal expenditure was deflated by a capital equipment price index for the US, and wholesale and producer price indices for Japan and Germany respectively. Currency conversions use 1980 exchange rates. Source: IMF, *International Financial Statistics*, various volumes.

[8] This data is less reliable than that of the US since the private investment derives from a yearly survey of enterprises with capital over 100 million yen and includes a varying number of (and different) firms each year. Furthermore, the public expenditure portion of the data is inflated by operating costs.

Table 3
United States pollution abatement expenditures by field [a] (in 1980 $US millions)

Field	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
Air	2106	1990	1569	859	888	1030	1144		1143	1313	1796
End-of-pipe	84%	86%	85%	84%	80%	70%	64%		73%		71%
Change in process	16	14	15	16	20	30	36		27		29
Water	1146	933	839	684	760	811	812		967	1317	1859
End-of-pipe	87%	87%	86%	88%	83%	88%	82%		83%		78%
Change in process	13	13	14	12	17	12	18		17		22
Solid waste	251	239	187	165	211	398	270		457	480	573
Hazardous				31%	36%	66%	49%		54%		40%
Non-hazardous				69	64	34	51		46		60
Total expenditure	3503	3161	2595	1708	1859	2239	2226		2567	3111	4228
Percent of total capital expenditure	5.0%	4.4%	4.1%	3.3%	2.9%	3.4%	3.7%		4.2%	4.4%	5.9%

[a] Expenditure by manufacturing firms with 20 + employees on new plant and equipment. Source: US Dept. of Commerce, 1980–1988 and 1990.

ued down throughout the early 1980s before picking up again sharply in 1985.

The decline evident in absolute spending in all three countries in the early 1980s cannot be simply ascribed to the effects of the recession. Expenditure as a share of GNP fell during those years; and, at least in the United States, for which it is possible to distinguish private equipment expenditure, pollution abatement was given a lower priority in private capital spending in the early 1980s (see discussion below). [9]

We move now from the trends in pollution control expenditure to its composition in the United States and Germany, countries where disaggregated data are available. In the United States, spending on clean water accounted for half to two-thirds of total abatement expenditures over the past 2 decades. As a result, the pattern of expenditure on water mimics that of total expenditures. Spending on industrial air pollution control increased sharply from US$4.5 billion in 1972 to a peak of US$7.5 billion in 1980. Over the 1980s, spending declined due to a hiatus in new capacity construction, dropping sharply in 1983 to less than US$4 billion. Less directly, R&D spending directed toward energy efficiency, with spillovers for air pollution control technology, moved in the same pattern in response to energy prices. In contrast, expenditure on vehicular air pollution, rose steadily from US$0.5 billion in 1972 to US$4 billion annually from 1985 to 1987.

In Germany, too, spending on water pollution control has been the largest share of total expenditure. However, Germany's outlays for air pollution control increased steadily between 1979–1985, from an eighth to a third of total expenditure. In the late 1980s, Germany instituted a major wet scrubber retrofit program, and the high levels of spending continued into the 1990s.

3.2. Private investment

US data are also available for private manufacturing expenditure, specifically on new plant and equipment for pollution abatement in companies with at least 20 employees (see Table 3). These data are much less inclusive than the figures in Table 2, which include, in principle, both government and

[9] The scaling back of public pollution reduction efforts in the United States during the Reagan administration is one explanation (see Viscusi, 1992). However, the decline in real expenditures on pollution abatement also occurred in Japan and Germany. It is not wholly improbable that the weakening of environmental protection efforts in the United States during the early Reagan years had spillover effects in other countries. A concern with competitiveness may have persuaded foreign industrial firms to lower pollution expenditures to match US firms.

private expenditures for equipment as well as for R&D and other pollution control related services, but the trends over time in the totals are the same. The last line of Table 3 shows that the dip in expenditure during the early 1980s was accompanied by a fall in the *share* of pollution control equipment in total capital expenditure. Since 1985, the importance of pollution control equipment has risen every year, with an exceptionally sharp increase in 1990 to a new high of 6% of total capital investment. (The impact on some industries is much greater than the aggregate figures indicate. Expenditure on pollution control equipment is heavily concentrated, with over two-thirds in the paper, chemical and petroleum, and coal industries in 1990.)

An important feature of Table 3 is the breakdown of investment between end-of-pipe and change in process. It shows first that there is a strong bias toward end-of-pipe investments. In the United States (and elsewhere) compliance with regulations is often assumed if a specific end-of-pipe technology is being used, which clearly encourages end-of-pipe solutions. Nevertheless, the table also indicates that there has been a slow but marked increase in the percentage of expenditure classified as 'change in process'. Given that firms reported difficulty in determining when and how much of a change in production process should be attributed to pollution abatement concerns, this shift may be an underestimate. Firms are discovering that changing production processes to avoid creating pollution in the first place can be a cost effective option. One implication of this shift in approach to lowering pollution is that it will become increasingly more difficult to identify an 'environment industry' or firm responses to environmental policies.

4. Innovation and diffusion of pollution control technology

In this section we turn to the patent data to investigate the extent of innovation which occurred in the last decades. The data on environmentally responsive innovations presented here (assembled by Evenson et al., 1991) include technology patented in the United States, Japan, Germany and 14 low- and middle-income countries. [10] An innovation is legally protected only in a country in which it is patented. [11] (In other words, an invention patented in the United States is only protected in Korea if it is also patented in Korea.) Thus, some part of the technology crossing borders will show up as foreign patents and knowing the nationality of inventors allows us to identify these flows.

Our patent data cover nine environmental fields: industrial and vehicular air pollution, water pollution, hazardous and solid waste disposal, incineration and recycling of waste, oil spill clean-up, and alternative energy. Relevant patents were identified as follows. In virtually all countries, patents are classified according to the international patent classification system (IPC). This classification system is technology, rather than product, based. The IPC classes corresponding to various types of environmentally responsive innovation were determined in two ways. First, the descriptions of the classes were searched to find those which were appropriate. Second, in the US patent system, a 'keyword' index of terms found in patent document texts is available. Relevant keywords were searched and the corresponding IPC classes of the resulting patents considered for inclusion in our analysis.

In choosing the IPC classes, two sources of possible error arise. If too many are selected, innovations that bear no relation to pollution abatement are included and information about environmental fields may be swamped by movements in the mistakenly included patents. If too few are selected, relevant innovations are left out. In the second case, as long as all environmentally responsive innovation in a field responds to events in a broadly similar fashion, activity in the chosen IPC classes is indicative of overall activity. Totals, of course, would be somewhat understated. An attempt was made to lean in the direction of 'pure' categories and avoid the first type of classification error. A sample of patent abstracts was read as a check on the accuracy of the

[10] These are: Argentina, Brazil, China, Egypt, Hong Kong, Israel, India, Kenya, Korea, Mexico, Philippines, Portugal, Singapore, and Turkey.

[11] One exception is the European Community patent which offers protection in six designated countries.

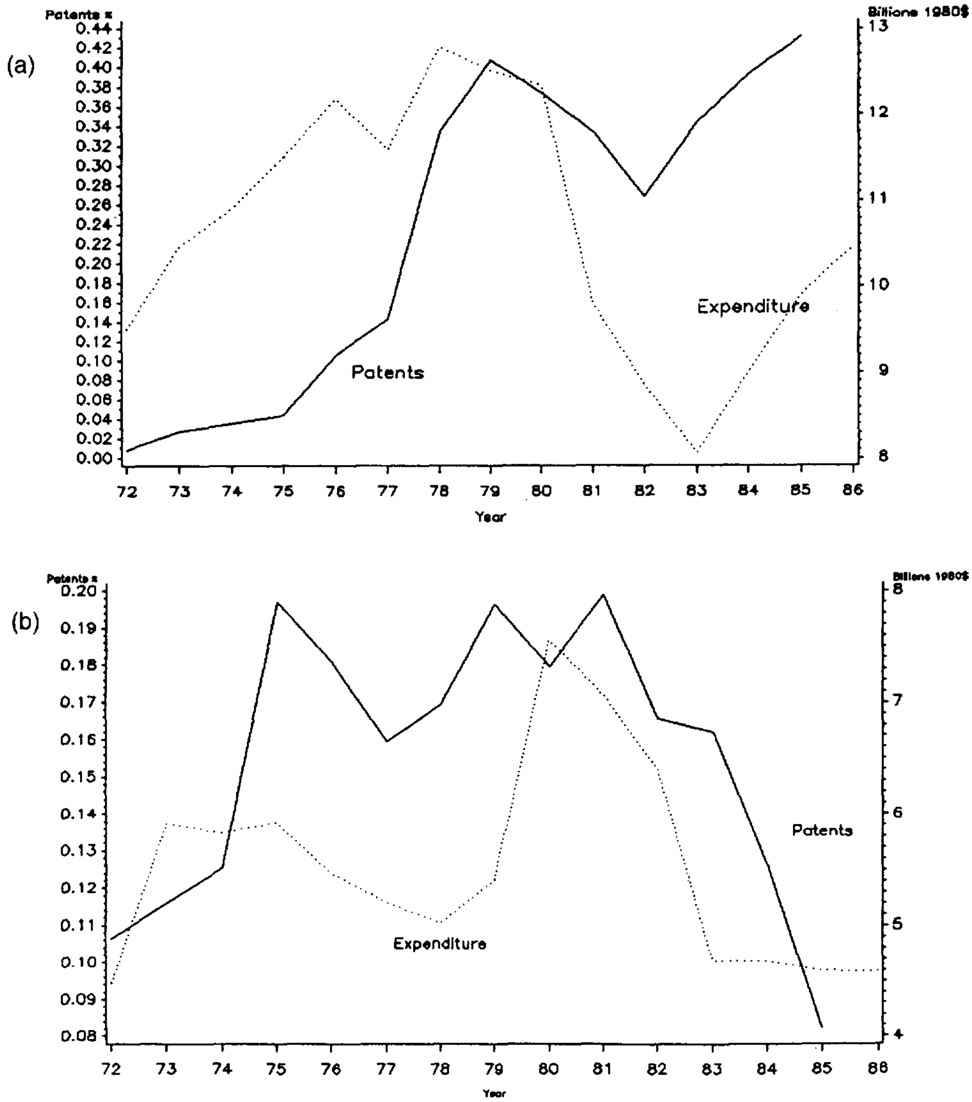

Fig. 3. (a) Water/total patents vs. expenditure (United States). (b) Air/total patents vs. control expenditure.

chosen IPC classes. The Appendix details the final classes grouped into nine fields with class descriptions and the percentage of US patent abstracts in the class with at least one keyword.

Data were obtained from the International Patent Documentation Centre in Vienna. Patents are dated by their priority year, or year of application in the country of origin; for innovations patented in several countries, it is the earliest application year. [12] For most of the developing countries, the data begin in the mid 1970s, a notable exception being China,

[12] In most countries, inventors can not apply for a patent more than a year after the first application has been made due to novelty requirements so these dates would tend to be similar.

which has only recently established a patent system. The final year of data is 1988 in most instances. [13]

In much of the discussion that follows, patenting of various types of innovation is given as a percentage of total patenting in the country. Normalization by total patents is important because the breadth of patents, and hence the number that would be granted for a given innovation, varies across countries. [14] In addition, the propensity to patent may vary with the strength of the patent system and the availability of other means to protect innovations. There can be lags in numbers of patents over time for spurious reasons, such as staffing shortages at patent offices (see Griliches, 1990). The use of ratios avoids all of these potential problems.

4.1. Innovation in developed countries

Throughout the period of the data, Japan patented most intensively among developed countries (although it may soon be overtaken by Germany), reflecting its position as the most stringent environmental regulator. Between the early 1970s and the late 1980s, about 2.5% of Japanese patents were environmentally responsive (see Fig. 1). In particular, a very high percentage of Japan's total patents concerned industrial and vehicular air pollution control in the early 1970s – areas where it imposed early, relatively strict regulations. In contrast, environmental patents in the United States were less than 1% of total patents during most of the 1970s, and, except for a brief interval, they have remained at that level (Fig. 1). The two periods of rapid growth in Germany's environmentally responsive innovations are closely related, first, to very strict regulations introduced in the 1970s and the accompanying jump in abatement expenditure in 1975 and second, to increased expenditure in the late 1980s.

Within countries, the share of environmentally responsive innovations which is related to water pollution control has increased dramatically over time, particularly in the United States and Japan, from 2 to 44% and 12 to 72%, respectively. Detailed emissions standards and technology specification have been more common in water pollution control than in other fields. In the United States, the turning point in water legislation was the 1972 amendment to the clean water act, mandating tough new standards of water quality. Grants of as much as $US50 billion were made in the following years to municipal authorities for clean water projects. The dramatic increase in US patents in this field probably resulted almost entirely from this episode. The ratio of water pollution patents to total US patents was flat in the early 1970s and rose in the late 1970s to a new plateau, paralleling expenditure with a 2- to 3-year lag (see Fig. 3(a)). Similarly, the dramatic fall in water pollution control expenditure during the early 1980s was followed by a dip in patenting. In Germany too the ratio of water pollution to total patents and expenditure moved together, rising in the 1970s and falling in the early 1980s. The linkages are complex, however. As shown in Fig. 2, expenditure could also be stimulated by lower real costs arising from innovation. This could explain the fact that the 1982 upturn in patenting in the US led expenditure increases.

The same primary pattern emerges in industrial air pollution. In the United States, the ratio of such patents to total patents increased in the mid-1970s following the growth in air pollution abatement expenditure in the early years of the decade (see Fig. 3(b)). Further, the drop in expenditure in 1983 was followed by a decline in the patent ratio in 1985. In Germany, the steady spending increases beginning in 1979 were matched by an increase in the ratio of industrial air pollution to total patents beginning 2 years later.

The most dramatic evidence of an expenditure/innovation link in the environmental fields is in the area of alternative energy. Interest in sources of alternative energy was widespread during the late 1970s and early 1980s as a result of increases in oil

[13] In all countries it takes several years before all patents from a given cohort which will ever be granted complete the process. The data were collected in 1991 so, for example, 1988 patents granted in 1992 are not included. This truncation bias was adjusted for by using the age structure of granting in the US and inflating the last years of data accordingly. Germany and Japan have a delayed examination period which considerably lengthens the granting period. For these two countries the adjustment is insufficient and the numbers of patents in the later years is biased downward.

[14] The amount of innovation, in terms of private or social value, which is covered by a patent, even within one country, can vary tremendously.

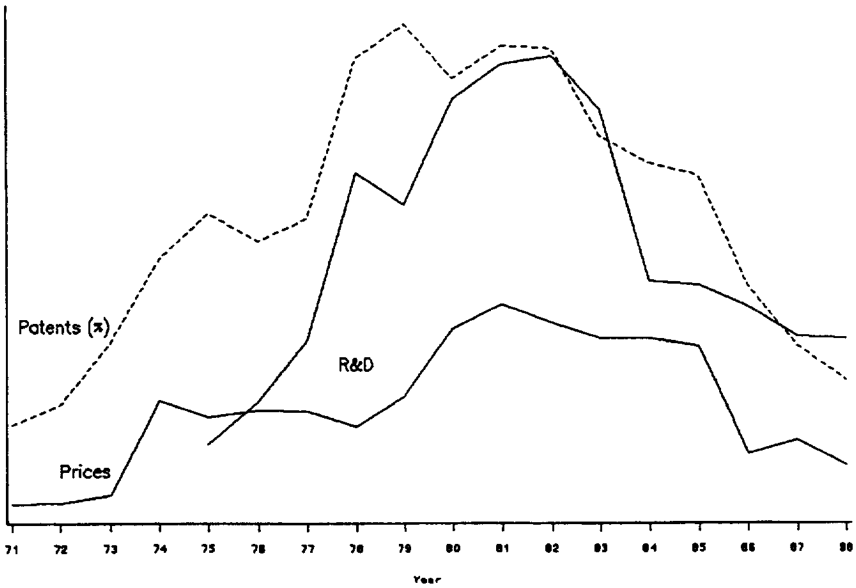

Fig. 4. Alternative energy. Patents, energy prices, R & D. Note: patents (%) is alternative energy patents / total U.S. patents. Sources: R & D funding. Chemical and Engineering News (various February issues).

Table 4
Sources of foreign patents by nationality of inventor [a,b]

Source	Industrial air				Water				Vehicle air			
	1972	1977	1982	1986/7	1972	1977	1982	1986/7	1972	1977	1982	1986/7
United States												
Japan	48%	28%	11%	38%	0%	21%	15%	23%	38%	82%	90%	35%
Germany	36	38	64	28	0	21	41	35	45	12	7	51
Other OECD	16	31	25	31	100	49	38	28	18	6	4	11
Other	0	0	0	3	0	9	6	3	0	0	0	2
Foreign/total in field	21%	32%	28%	32%	20%	33%	34%	26%	40%	66%	68%	65%
Japan												
United States	50%	46%	42%	64%	48%	44%	50%	83%	47%	33%	60%	100%
Germany	25	15	42	14	7	22	17	15	47	33	30	0
Other OECD	20	31	16	14	44	44	17	15	7	22	0	0
Other	0	0	0	0	0	0	17	0	0	0	0	0
Foreign/total in field	20%	13	19%	14%	27%	9%	6%	6%	15%	9%	10%	11%
Germany												
United States	37%	34%	45%	15%	40%	20%	22%	19%	35%	34%	70%	19%
Japan	48	34	16	27	10	14	11	3	50	48	11	27
Other OECD	13	32	37	58	50	61	57	71	15	8	20	46
Other	1	0	3	4	0	4	8	6	0	0	0	8
Foreign/total in field	71%	47%	38%	26%	50%	49%	37%	31%	52%	50%	56%	26%

[a] The percentages may not sum to one due to rounding.

[b] For Germany and Japan the last column year is 1986 to avoid possible biases due to differential truncation error across nationality of patentee.

prices and government expenditures on R&D reflected this interest (see Fig. 4 for the United States). In all three countries, the ratio of alternative energy to total patents climbed steeply from 1972 to 1982 and dropped off sharply thereafter.

Vehicular air pollution is the major exception to the link between innovation and expenditure. In the United States, spending rose continually from the early 1970s, while the share of vehicular air pollution patents in total patents *fell* from 1973 through 1985. The explanation may be that the number of cars required to comply with the regulations (which apply only to new cars), has increased. At the same time, the technology in this field, primarily catalytic converters, was developed in the early 1970s, when auto emissions restrictions were imminent, and has not changed in any major way over the period. This may be because regulations are acting as a constraint on innovation in this area. It may also be because new innovations for lowering vehicle air pollution are focused on entirely new forms of technologies, such as electric cars or new materials, which are not captured in the data.

4.2. Diffusion: trade in technology within OECD countries

The extent of foreign patenting is a crude measure of technology transfer and Table 4 presents some 'trading' patterns in environmental technologies. In the United States, about two-thirds of vehicular air pollution patents have been granted to foreigners since the 1970s (see Table 4), suggesting substantial trade in this area of technology. In contrast, foreign nationals have received 20 to 30% of industrial air and water patents, the foreign share having risen slightly over the period. On the other hand, in Japan and Germany the share of new technology coming from foreign innovation has fallen, and dramatically so. In the water pollution field, foreign inventors' share of patents fell from 27 to only 6% in Japan, and 50 to 31% in Germany. In the air pollution field the share of German patents granted to foreigners plummeted from 71% in 1972 to 26% in 1986.

The volume of trade in technology depends upon the volume of trade in goods and services, differing innovation capabilities, and on the extent of international specialization in various areas of technology.

Table 5
The standard deviation of environmental field ratios

	1971–75	1984–88
Industrial air pollution	0.069	0.075
Vehicular air pollution	0.044	0.036
Water pollution	0.096	0.145
Incineration of waste	0.051	0.028
Solid waste disposal	0.037	0.044

The link between trade in goods and innovation is discussed below when we consider developing countries. The decline of foreign inventors' shares of patents in Japan and Germany points to the possibility that these countries are becoming more adept at innovation. The unusually large share of vehicular air pollution patents granted in the United States granted to German and Japanese inventors points also to a more effective innovation response in Germany and Japan, particularly in light of the fact that the United States was the first country to implement strict vehicle emissions regulations. Here we have a case of regulation in one country spurring innovation in other countries, with more impressive outcomes than in the regulating country itself. The large volume of automobiles exported from Japan and Germany to the United States, being subject to stringent environmental regulations, no doubt contributed to pressure on German and Japanese automobile producers and their suppliers. [15] The data indicate that a decline in specialization is not a factor driving the fall in foreign patenting. We see this by noting that, absent any specialization, one would expect that the ratio of, say, water pollution patents to total environmental patents would be the same for all three countries. The variance in ratios would be zero. With increasing specialization the ratios would become more divergent and the variance would increase. In fact, ratio variances for all fields, while not zero, changed little over the period. For the major environmental fields, the standard deviation of the field ratios averaged over the years 1971–1975, and over the years 1984–1988, were as shown in Table 5.

[15] And sure to be enforced under the eye of the US car manufacturers since regulations can make useful trade barriers.

These figures may be compared to the maximum possible standard deviation of 0.577 (which would result if one or two countries innovated exclusively in a field that inventors in other countries ignored completely). They suggest that there has been no significant *change* in the degree to which these three

Table 6
Source of patents in selected non-OECD countries

Source	China [a] (1984–88)	India (1974–88)	Brazil (1971–88)	Hong Kong (1971–88)	Korea utility (1976–88)		Mexico utility (1979–88)	
(a) Total environmental patents								
Domestic	179	143	705	0	243	590	17	34
United States	31	101	484	16	62	1	28	27
Japan	30	5	50	18	100	16	0	1
Germany	13	49	384	1	7	0	8	15
Other OECD	25	77	535	21	24	0	15	17
Other	1	9	22	0	0	0	3	0
Total	279	384	2180	56	436	607	71	64
Foreign/total in field	36%	63%	68%	100%	44%	–	76%	–
(b) Industrial air pollution patents								
Domestic	29	12	43	0	46	21	2	3
United States	13	26	84	6	16	0	7	7
Japan	11	2	9	1	7	0	0	1
Germany	5	14	60	0	3	0	1	3
Other OECD	11	11	61	1	2	0	2	2
Other	0	1	3	0	0	0	0	0
Total	69	66	260	8	75	21	12	16
Foreign/total in field	58%	82%	83%	100%	36%	–	83%	–
(c) Water pollution patents								
Domestic	70	16	174	0	64	238	5	15
United States	5	6	90	5	12	1	9	10
Japan	6	0	12	3	41	7	0	0
Germany	2	3	48	1	3	0	3	0
Other OECD	4	12	128	9	3	0	2	6
Other	0	1	3	0	0	0	1	0
Total	87	38	455	18	123	246	20	30
Foreign/total in field	20%	58%	62%	100%	47%	–	75%	–
(d) Alternative energy patents								
Domestic	31	54	165	0	23	53	6	3
United States	8	43	102	3	12	0	6	2
Japan	3	0	7	11	18	9	0	0
Germany	5	28	80	0	0	0	3	3
Other OECD	2	30	92	2	6	0	4	0
Other	0	4	8	0	0	0	2	0
Total	49	159	454	16	59	0	21	2
Foreign/total in field	37%	34%	64%	100%	61%	–	71%	–

[a] China also grants utility models. All of them have been to Chinese nationals.

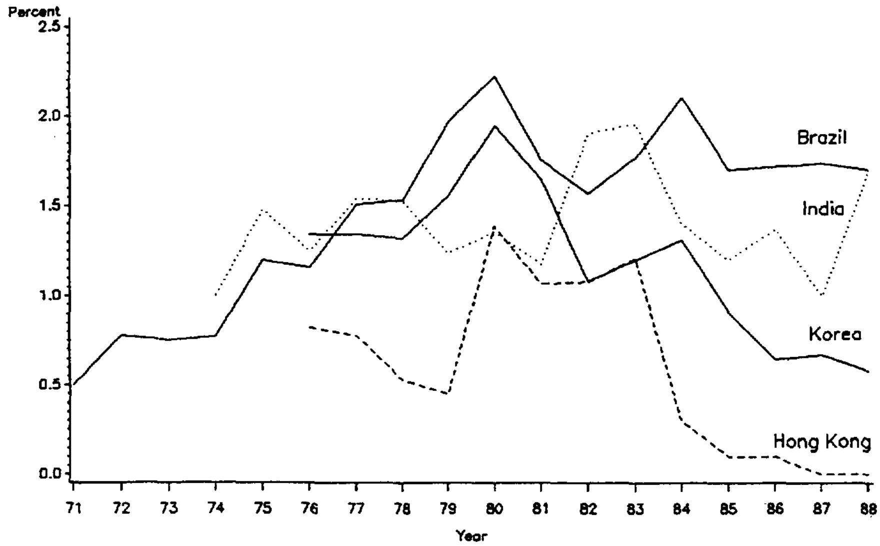

Fig. 5. Environmental patents as a percentage of total patents.

countries specialize in various fields and furthermore that the three countries have a fairly similar composition of innovation. [16] If an early lead in a particular technology area confers an advantage on the leader, one might have expected to see increasing specialization over time as these advantages were exploited. Thus it is interesting that this does not appear to have occurred.

4.3. Environmental technology outside the OECD

While the preponderance of patents are granted by developed countries, it is certainly not the case that patenting environmental innovations has been the monopoly of the developed countries. Within developing countries, Brazil has been the clear leader: over 18 years, between 1971 and 1988, Brazil granted 2180 environmental patents. India granted 384 patents in the 15 years between 1974 and 1988; Korea granted 436 in 13 years between 1976 and 1988; and China, with a relatively new patent system, had granted 279 patents by 1988. Table 6 shows the number of patents in selected low- or middle-income countries and their sources.

Korea, Mexico, and China also award utility patents, or so-called petty patents, which are of shorter duration than regular patents and do not require the same inventive step. In China, the number of utility patents awarded is 743, which is over two and a half times the number of regular patents. All Chinese patents were awarded to domestic inventors, indicating the large scope for local, adaptive innovations.

The trends in environmental patenting within developing countries are interesting. From low levels in the early 1970s, Brazil and India experienced a rapid increase in the share of environmentally-responsive patents to total patents (see Fig. 5, which includes only regular patents and does not include utility models). About 2% of Brazilian patents in more recent years have been environmentally responsive, the corresponding proportion for India (and China) is 1.5%. The high Brazilian proportion is greater than the ratio for the United States (1%) and only slightly below the high ratios achieved in Japan and more recently in Germany. This indicator of Brazilian efforts towards pollution reduction is consistent with its innovative institutional design and heavy pollution reduction expenditures.

[16] Note that finding no increase in the level of specialization in innovation does not preclude increasing specialization in production or trade. Further, no increase in specialization in the categories of data used here also does not preclude increasing specialization in narrower categories of technology.

In contrast, in the newly industrializing economies (NIEs) of East Asia, the share of environmental patents in total patents declined significantly to about 0.5% in Korea and to virtually zero in Singapore and Hong Kong. In Korea, the absolute numbers of environmentally responsive patents continue to be high, but the proportions are small because innovation efforts are being focused on other areas more directly relevant to international competitiveness in high-technology industries. As we shall see below, imported pollution-control equipment has substituted for the low emphasis on innovation.

4.4. The importance of foreign patenting

The prominence of foreign patenting in low- and middle-income countries varies greatly across countries, from 100 (Hong Kong) to 36% (China). The relatively low share of foreign patents in China is likely a result of the recent establishment of the system, and the procedural difficulties and doubts about enforcement that newness entails. The Korean ratio of foreign patents is close to that of China, with less than 50% being foreign patents; Mexico, in contrast, has 76% foreign patents; and Brazil and India fall in between.

We interpret these data to mean that, although the preponderance of technology related to pollution control comes from developed countries, the developing countries are actively innovating. The evidence suggests, however, that much of this innovation is to adapt imported technologies to local conditions. Very few patents are granted in the OECD countries to developing country inventors (see Table 4), which implies that their innovations are of local, rather than general, usefulness. Also suggestive is the fact that by far the largest number of utility (petty) patents are granted to domestic inventors.

Examining specific environmental fields, we find that an especially large percentage of industrial air pollution patents are issued to OECD inventors. Such innovations may be more widely applicable than innovations in other areas. It may also be the case that the technology involved is relatively complex or that it is incorporated in factory equipment imported from OECD countries. Korea, the developing country in our sample with the most sophisticated industrial base, does have a relatively high share of domestic patents in industrial air pollution. In contrast, many water pollution control patents are held by domestic inventors in less developed countries. This is not surprising since these innovations are often for water treatment plants that operate under many different types of conditions.

4.5. The identity of foreign patentees

It is of interest to identify the OECD countries which patent in the different developing countries because these patterns are related to the international trade in pollution control equipment.

India, Brazil, and Mexico have granted at least a third and often more than half of all foreign patents to US nationals. Japanese inventors rarely patent in these countries; in fact they received *no* patents in Mexico during the indicated period. In addition, virtually no patents were granted to inventors from developing countries. Most of the other surveyed low- and middle-income countries not presented in the table display this pattern. China is similar but with the addition of a large Japanese presence: Japanese inventors received about the same number of patents as Americans. The East Asian NIEs, however, are very different: Japanese inventors dominate and German inventors have no presence at all. In Korea, for example, most of the patents granted to foreigners were to Japanese inventors (52%) and none were to Germans.

Looking at the individual fields a few anomalies present themselves. Unlike for the other environmental fields, Japanese inventors do not figure highly in industrial air pollution control patents in the East Asian NIEs and most patents are granted to Americans. On the other hand, Japanese inventors take an unusually large share (70%) of Korean patents to foreigners in the field of water pollution control. Alternative energy technologies are patented quite heavily by Americans and Germans in most countries.

In those environmental fields not displayed in Table 6, the developing countries granted fewer patents. The distribution across nationality of inventor followed roughly the same pattern as the totals. One exception, which highlights the role of subsidiaries as a source of patents, is in vehicular air pollution. Here, Germans patented as much as Americans in Brazil. Volkswagen is the major automobile manufacturer in Brazil, having entered the market in 1958 before any of the American automobile companies. Degussa, a German metals and fine chemicals firm, is its sole supplier of exhaust catalysts and probably holds many of the patents seen in the data. [17]

4.6. Do foreign patents represent major or adaptive innovations?

Since the developing countries appear to import a substantial amount of environmental technology from developed countries, one might ask whether such technology is appropriate to their conditions. To what extent is the technology originating abroad designed specifically for the importing country? To what extent does it require adaptation? To investigate this question we use 1982 patent family and citation data drawn from the water pollution field. [18] A patent family consists of patents granted in different countries that cover the same innovation. Thus the size of the family indicates how widely an innovation is used. [19] Another measure of a patent's importance is the number of times it is cited in subsequent patent documents. Patent documents cite previous patents as antecedents, so the number of times a patent is cited in subsequent patents is an indicator of how much innovation it spawned. Early or basic innovations are cited often; adaptive innovations less so.

If patents granted in developing countries protect innovations that are specifically tailored to conditions in those countries, we would expect that they are less valuable innovations since they address the requirements of a smaller market. On the other hand, if we find that the patents granted in developing countries protect more important innovations which are patented widely, then we can infer that those innovations are not tailored to specific technological needs of the developing countries but are more broadly applicable innovations originally created for the developed country markets.

Two sets of patents were considered. The first set consists of 50 patents originating in an OECD country but with no family members in Korea or Brazil. The second set of 50 patents originate in an OECD country and have a family member in either, but not both, Korea or Brazil. This second set is interpreted as consisting of innovations that have a higher propensity of being patented in a less developed country (Korea or Brazil). We want to know if the second set of patents (the ones with a developing country bias) protect innovations that are more or less important than the innovations protected in the first set.

Two claims can be made if important innovations, as distinct from developing country-specific innovations, constitute a relatively large proportion of the patents in developing countries. First, the difference between the mean number of family members in the two data sets will be greater than one, with the mean number higher for the second set. Second, the mean number of citations made to patents in the second set will be greater than in the first set.

Looking at the data, the mean family sizes of the two groups are quite different:

Mean family size Group 1 = 7.8 (standard error 4.7)

Mean family size Group 2 = 12.8 (standard error 4.6) with Korea or Brazil.

However a t-test of the null hypothesis that the mean for Group 2 minus the mean for Group 1 equals one cannot be rejected at standard levels of significance against the alternative that the difference is greater than one (P-value = 0.23, degrees of freedom = 98). Similarly, while the mean citations also differ:

Mean citations Group 1 = 5.1 (standard error 5.3)

Mean citations Group 2 = 6.6 (standard error 7.2), the large amount of variation within each group, leading to large estimated standard errors, prevents rejection of equality of the group means. Nevertheless, both sets of point estimates suggest quite strongly that a relatively large proportion of the innovation from the OECD patented in developing countries protects major innovations rather than in-

[17] Information supplied by Hans Mathieu.

[18] The data were drawn from Derwent, Ltd.'s World Patent Index online database.

[19] Sometimes a patent is taken out for strategic reasons on an innovation which is not subsequently used in the country – the goal being to prevent others from using it. In such cases, a patent does not indicate actual use. However, it does show that the innovation could *potentially* be useful in the country.

novations specially tailored for the country in question. This implies that transfers of technology to developing countries are likely to require some adaptive innovation.

5. Trade in pollution control equipment

As noted in Section 1, for countries seeking to import technology, two options exist. They can import the ideas, some of which are patented; they can also import equipment that embodies the ideas. These two forms can be substitutes or complements. This section reviews flows of technology embodied in the form of capital equipment and relates them to the patenting patterns discussed above.

The Standard International Trade Classification (SITC) and the national trade classification systems which feed into the SITC do not lend themselves readily to an analysis of trade flows in pollution abatement equipment. We have identified a set of equipment that we believe represent some part of pollution control equipment. In deciding on the list of equipment to include, we consulted with experts at the US Bureau of Census with regard to the US data and were satisfied that at least for that country our classification was reasonable. Because it is not possible to disentangle water and air pollution control equipment they are considered in the aggregate. [20] The SITC classes included are: (SITC rev2, 1976–1987) 7436 gas, liquid filters; 8744 instruments; 87 483 other measuring; 87 489 electric measuring; 8743 gas, liquid control; 8749 instrument parts.

These categories include not only end-of-pipe equipment (filters) but also equipment, such as instruments and process controllers, that enhance process efficiency while also lowering the emission of pollutants. The same caveats apply as with the patent data. These classes are clearly not a comprehensive list of equipment related to water and air pollution control and some non-related equipment is included. As with patents, the focus is on trends and ratios rather than on absolute amounts.

[20] Data are from the ComTrade international trade database of the United Nations Statistical Office.

5.1. Determinants of international equipment flows

Whether a country imports equipment to lower pollution depends upon the strength of environmental regulations and also on the importance accorded to equipment import relative to other means of dealing with pollution abatement (see Fig. 2). The importance of environmental regulations in motivating equipment imports was highlighted in an OECD (1991) survey of 107 exporters of clean technologies and 137 potential importers in developing countries. Importing firms cited environmental regulation as the primary motivating consideration, and exporters said that demand was low in countries that lacked sufficient regulation to require such technologies.

This link between purchase of imported equipment and response to regulatory pressures is corroborated by the aggregate evidence, where pollution abatement expenditure is used as a proxy for regulatory pressure. As with patenting, changes in the level of equipment imports by the United States, Japan, and Germany follow quite closely the trends in total pollution abatement expenditure discussed in Section 2. Imports increased steadily from 1976 to 1980–1981. Imports by Japan and Germany then fell for several years before beginning a rapid rise from 1985. In the United States, imports were flat in the early 1980s, picked up sharply in 1984 and then continued to rise.

Table 7
Recipients of air and water pollution equipment imports

Country	1978 (%)	1981 (%)	1984 (%)	1987 (%)
United States	9.0	10.6	14.9	13.4
Japan	6.9	7.2	7.6	6.2
Germany	14.8	12.2	11.0	12.0
Other OECD	64.1	59.1	54.2	53.3
Brazil	0.0	1.0	0.4	0.3
China	0.0	0.0	0.0	3.5
India	0.5	0.5	0.9	0.8
Mexico	0.0	0.0	1.3	0.7
Singapore	0.0	2.1	2.2	1.9
Taiwan	1.6	1.6	1.8	2.0
Korea	2.5	2.1	2.9	3.5
Other	0.5	2.7	1.8	1.5

Source: United Nations, Comtrade Database. Geneva.

The tendency to import pollution control equipment also depends upon country policies that influence the propensity to import capital equipment more generally. Among less developed countries, the use of imported equipment as a means of technology transfers varies considerably. In many industrial sectors, the East Asian NIEs have used imported equipment as a major source of technology. For example, imported equipment accounted for between 20 and 24% of gross domestic capital formation in Korea over the 1970–1990 period. In contrast, it was only about 5% of investment in India. The share of imported equipment was never high in Brazil and has declined over time to India's levels. Mexico lies somewhere in between the East Asian NIEs and the large continental economies of China, India, and Brazil.

Not surprisingly, the patterns are similar for imports of equipment for pollution control (see Table 7). Korea and Taiwan began to import pollution control equipment at a relatively early date and continue to record large shares of world imports relative to other non-OECD countries. Korea's share rose from 2.5% in 1978 to 3.5% in 1987 and for Taiwan the increase was from 1.6 to 2.0%. Singapore has also been a relatively large importer during the 1980s. As with other types of equipment, China began importing late, appearing in the data after

Table 8
Sources of air and water pollution abatement imports

Source	1978 (%)	1982 (%)	1987 (%)	1976 (%)	1982 (%)	1987 (%)
	United States			Japan		
United States	–	–	–	72	77	69
Japan	16	17	24	–	–	–
Germany	17	13	16	6	6	9
Other OECD	55	56	43	17	16	19
Other	12	14	17	5	1	3
	Germany			Other OECD		
United States	27	28	24	40	35	26
Japan	4	4	9	1	4	8
Germany	–	–	–	23	16	20
Other OECD	66	66	64	–	–	–
Other	2	2	3	3	5	6

	1987 (%)			
	Brazil	India	China	Mexico
United States	43	30	33	67
Japan	8	12	30	4
Germany	20	21	11	14
Other OECD	21	35	21	10
Other	8	3	6	6
	Korea	Singapore	Taiwan	Israel
United States	30	47	37	47
Japan	51	20	39	4
Germany	7	7	8	15
Other OECD	11	18	14	33
Other	1	8	2	1

Source: United Nations, Comtrade Database. Geneva.

1985, but purchased 3.5% of imports in 1987 – on par with Korea and above the level of other non-OECD countries. (The emphasis on imports of environmental equipment in China is high relative to overall imports of capital equipment.) Imports of pollution abatement equipment by Brazil and India are characteristically low.

5.2. Links between international sources of equipment and patenting

Turning to the sources of imports rather than aggregate trends sheds more light on the extent to which foreign patents represent transfers of disembodied technology and to what extent they are simply mechanisms to protect technology embodied in equipment.

The sources of pollution control equipment vary widely (see Table 8). Looking first at the developed countries, in 1987, the United States imported about 25% from Japan, 15% from Germany, and 40% from other OECD countries. The United States is remarkable for importing from a much wider variety of sources than other countries, including 17% from outside the OECD, primarily Singapore, Taiwan, Korea, and Brazil. In contrast, Germany and Japan imported almost 97% from OECD countries. Japan relies heavily on the United States for imports while Germany sources more often from other OECD countries. There has been very little trade between Germany and Japan or between other OECD countries and Japan. The composition of developed country imports changed over the 1978–1987 period, with the United States becoming less important and Japan more important. In the United States, imports grew not only from Japan but also from non-OECD countries.

Recalling who patents in each of the countries, these trade patterns suggest that trade and patenting need not go hand-in-hand. Most pronounced is the fact that Germany and Japan appear to be much more important to each other as sources of patents (disembodied technology) than as sources of equipment imports. For instance, Japanese inventors held 34% and 14% of German industrial air and water patents, respectively, yet Japan was the source of only 4% of related equipment imports. The comparable figures for German inventors were 15% and 22% of Japanese patents, with Germany the source of just 6% of Japanese equipment imports.

Operating in the opposite direction, while the United States sources up to 17% of its pollution-abatement equipment imports from non-OECD countries, the US rarely awards patents to non-OECD inventors. This suggests either that the non-OECD countries export low-technology environmental equipment to the United States, or that they are hosts to OECD companies whose nationals hold patents in the United States.

In contrast to the situation among developed countries, among the developing countries the links between equipment trade and international patenting are close. The low- and middle-income countries, except Korea, source the largest part of their imports from the United States (see Table 8). [21] Japan successfully exports to the East Asian NIEs and to China. It also has a 12% share of Indian imports, double the mid-1970s level. Japan does not figure prominently in the imports of Brazil and Mexico. Conversely, Germany has a smaller presence in the Asian countries but a substantial share of the import markets of Mexico and particularly Brazil. In contrast to the situation with intra-OECD trade, the United States increased its share of purchases by the East Asian NIEs at the expense of the Japanese. Taiwan and Korea aside, the low- and middle-income countries buy a significant share of their imports from non-OECD countries. Except for the absence of patent activity between the developing countries, these import patterns closely mirror foreign patenting patterns.

While not conclusive, the link between sources of equipment and patents for less developed countries does suggest that most patenting in these countries is done to protect imports of equipment with embodied technology. There is no evidence (as seen between Germany and Japan) of patenting between countries in the absence of trade.

[21] Imports to the low- and middle-income countries are fairly small. As a result, the exact percentages of imports by source fluctuate substantially across years. However, the 1987 figures in Table 8 are a fair representation.

6. Concluding comments

The new data presented here provide empirical evidence that the increasing interest in environmental protection over the 1970s and 1980s led to the development of new pollution control technologies. Trends in innovation, as represented by patenting, have reflected corresponding domestic regulation and spending on pollution control, though there are indications in the data that innovation in a country responds also to regulations in other countries (for example, Japanese and German innovation in response to US vehicle emissions regulations).

Among developing countries, Brazil has been in the forefront in environmental innovation with about 2% of patents being awarded in environmental fields. At the other extreme, East Asian NIEs have seen very low shares of environmental patents in recent years, although Korea continues to award a significant absolute number of environmental patents.

A large portion of the patents granted by the low- and middle-income countries are to developed country inventors. Our analysis shows that the foreign innovations patented in developing countries are not, by and large, tailored for the specific country but are rather technologies with wide applicability. Relative to innovations protected primarily in developed countries, those patented in developing countries have a larger family size and a higher level of citations. Developing country innovators have shown a propensity to adaptive innovations, as in Mexico and Korea where utility patents show significant environmental activity. Such adaptive innovation will continue to be important, especially in the water pollution area, where the technology tends to be localized.

Patents can act as a protective mechanism for both disembodied technology or for technology embodied in machinery. To the extent that foreign patents in developing countries protect export markets of their holders, trade flows and foreign patenting essentially measure the same technology transfer. If patents protect only disembodied technology, on the other hand, then foreign patents represent an additional amount of technology being transferred over and above that embodied in equipment flows. The correspondence between sources of equipment and sources of foreign patents in developing countries suggests (although it does not prove) that most of the patents in such countries are intended to protect export markets. There is limited indication of disembodied technology transfers. For the developed countries, however, this is not the case; the relationship between Japan and Germany shows a much higher level of mutual patenting than trade in equipment.

While the trends in equipment imports are likely to follow regulatory pressures (and pollution abatement expenditure), the levels of environmental equipment import depend also on general trade patterns and policies. East Asian NIEs are more dependent upon equipment imports (both in the aggregate and for pollution control) than are Brazil, India, and Mexico.

In this paper we have considered only the *extent* of regulation, as measured uni-dimensionally by expenditure, and its impact on innovation and diffusion. Equally important may be the *form* of regulation. Judging the effectiveness of different strategies for stimulating innovation is complicated by the fact that environmental policies, where they exist, have tended to be very similar both across countries and time. It will be an interesting area of future research to examine whether the market-based regulatory schemes presently being implemented in some countries give a further boost to the creative new ways of combating pollution.

Appendix. Pollution related IPC classes by field

Below are the international patent classifications (IPC) for each of the nine fields with corresponding search keywords. The percentage of US patent documents in each IPC class with at least one keyword is given in the first column. The second column gives the number of patents in the data for each IPC class.

Table A.1

Classes		Percent with a keyword	Number
(1) *Industrial air pollution. Keywords: treat, scrub, remove*			
B01D-53/34	Chemical purification of waste gases	85	24958
B01D-53/36	Chemical purification of waste gases by catalytic conversion	53	7649
C10K-1/3	Purifying/modifying gases containing carbon monoxide	60	4088
		100	1177
C10L-3	Adding materials to fuels or fires to reduce smoke	0	1166
F23B-5	Burning uncombusted material...	33	796
F23J-3	Removing solid residues i.e. soot blowers	80	1751
F23j-15	...devices for treating smoke or fumes	57	4026
		63	45611
(2) *Water pollution. Keywords: treat, waste, sew*			
C02F-1	Treatment of water, waste water, sewage	53	37756
C02F-3	Biological treatment of water, ww, sewage	88	17419
C02F-7	Aeration of stretches of water	80	676
C02F-9	Multistage treatment of water, ww, sewage	71	2342
E03F	Sewers; cesspools	38	12176
		62	70369
(3) *Vehicle air pollution. Keywords: exhaust*			
F01N-3	...apparatus for purifying, treating exhaust	88	16528
F01N-5	Exhaust, devices profiting by exhaust...	100	892
		89	17420
(4) *Solid waste. Keywords: treat, waste, refus, garbage, remov*			
B02C-8/40	Disintegrating by knives, disin. garbage	100	1919
B09B	Disposal of solid waste	77	5481
B65F	Gathering or removal of refuse	73	13279
C10B-53	Distructive distillation – solid materials	75	3268
		75	23947
(5) *Incineration of waste. Keywords: incineration, waste*			
F23B-7	...other solid fuel combustion apparatus	44	895
F23G-5	Incineration of waste	67	9177
F23G-7	Incinerators...for industrial waste	79	8139
		64	18211
(6) *Alternative energy. Keywords: wind, solar, waste, fuel, heat*			
C10J	Production of gas from carbonaceous...	53	11318
E04D 13/18	Roof covering aspects of energy collectors	100	344
F03D	Wind motors	76	8412
F24J-2	Use of solar heat eg. solar collectors	49	5294
		57	25368
(7) *Oil spills. Keywords: remove, spill*			
E02B-15/04	Cleaning the surface of open water from oil	55	4799
		55	4799

Table A.1 (continued)

Classes		Percent with a a keyword	Number
(8) *Radioactive waste. Keywords: hazard, radioactive*			
0G21F-9	... treating radioactively contaminated material	62	15080
		62	15080
(9) *Recycling and reusing waste. Keywords: recycl, reus, recover, waste, refuse*			
A23K-1/06	Feeding-stuffs from brewers waste	100	387
A23K-1/08	Feeding-stuffs from waste of diary plants	0	466
B29B-17/00	Recovery of waste plastics	25	1047
B30B-9/32	Consolidating scrap, compacting used cars	67	1275
C04B-7/24	Hydraulic cements from residues or wate	100	315
C04B-11/26	Cements from phosphogypsum or waste	100	195
C05F	... Fertilizers from waste	24	10031
C08J-11	Recovery or working up of waste materials	44	2299
C10L-5/46	Solid fuels based on sewage	0	381
C10M-11/00	Working up used lubricants based on oils	100	1088
C22B-7	Working up raw materials other than ores	46	5113
D21B-1/32	Defibrating waste paper	25	721
D21C-11	Regeneration of pulp liquors	56	3795
D21F-1/66	Re-use of pulp-water	40	694
		42	27787

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