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Executive Summary

This paper considers the challenges to the dissemination of environmental innovation. Following a brief exploration of the legal and regulatory regimes surrounding environmental technologies, the paper examines diffusion mechanisms, market factors, social characteristics and political elements that facilitate and complicate dissemination. Given the importance of innovation to economic development and growth, the diffusion of innovation is of great interest to economists and policymakers alike.

Key Findings:

- Many of the challenges to innovation and the dissemination of technology in general are found in the field of eco-innovation. The three principal problems to be considered are: asymmetric information, market power, and externalities. In addition, uncertainty regarding the qualities of the innovation as well as future prices of inputs will complicate the adoption process.

- The rate of diffusion is dependent on the cost-effectiveness of the new technology. Given this, the firms with the greatest potential profits associated with the innovation will be the first adopters. In addition, new technologies are often capital intensive and associated with size and scale economies, requiring access to investment capital.

- Numerous studies find that the incentives to adopt new innovations are greater with market-based tools than with regulatory tools. In an international context, uncertainty and informational problems are exacerbated and contracting solutions are even more difficult to achieve.

- New technologies frequently challenge existing legal systems in new ways and foster the evolution of the law. However, innovative industries would benefit from greater predictability in the legal realm. This is particularly important since the scope of patent protection, as well as the incomplete enforcement of IP rights, mean that the effective strength of intellectual property rights are determined by the implementation of the legal system.

- Market forces and incentives may facilitate the dissemination of environmental innovations or create insurmountable barriers to adoption. In this context, it is important to be aware of the lessons learned about innovation: innovation responds quickly to incentives; innovation in a given field experiences diminishing returns over time; the social returns to environmental research are high; and the type of policy used affects the nature of new innovations.

- Green technology is characterized by two market failures, the public goods nature of knowledge and environmental externalities.

- While developing nations frequently claim that strong intellectual property rights on carbon abatement technologies hinder developing countries' greenhouse gas abatement efforts, it has been shown that IPRs do not constitute as significant a barrier as claimed since a variety of

technologies exist for reducing emissions. In many cases, IPR protected technologies are not necessarily more costly than those not covered.

- There are a number of characteristics and circumstances of developing nations that hinder innovation: a lack of scientists and researchers, brain drain, small market size, the lack of infrastructure, importantly telecommunications infrastructure, the quality the business environment and governance conditions, bureaucratic climate and the formal/informal regulations regarding economic transactions, cash-strapped governments and inability to make public investments in research and infrastructure.

- Environmental issues are frequently local or regional in nature, so local knowledge and solutions are required. Further, many technologies are highly ecology-specific and while appropriate in one setting may be difficult to employ in another.

- Adoption is facilitated by environmental feasibility as well as cultural and political acceptance. Firms that effectively respond to such pressure and signals are more apt to succeed. It is important to note that consumer perceptions of eco-friendly are unclear, and often hinder diffusion and pricing

- It is critical that technology recipients have the prerequisite knowledge and scientific base to best exploit the information. This includes domestic private and public research laboratories and universities, in addition to a sound basis of technical skills and human capital. Each of these help to reduce the costs of imitation, adaption, and follow-on innovation. The greater the 'technological distance' of a recipient country from the global frontier, the greater the challenge of effectively incorporating information into production systems.

- Technology transfer is enhanced by stronger levels of patent protection, while acknowledging the necessity of complementary factors such as infrastructure, effective government policies and regulations, knowledge institutions, access to credit and venture capital, skilled human capital, and networks for research collaboration. Economic studies have found that while IP protection facilitates trade flows of patented goods into large and middle-income nations, but has no impact on poor countries.

- Like many new technologies, environmental innovations may require significant on-going support, training and assistance with maintenance. It is essential to consider the skills required for continued use and repair of new technologies at the onset of adoption.

This paper reveals that it is a combination of market, regulatory and cultural conditions that contribute to the arena in which dissemination and adoption of environmental technologies take place. Fundamentally for technology transfer to take place in developing nations a number of obstacles must be overcome: uncertainty surrounding the costs and benefits of adoption, asymmetric information on the value of the innovation, financial and skill requirements, externalities, and regulatory barriers. While scholars are still exploring why, where and how adoption takes place, lessons learned indicate that policymakers should seek to reduce uncertainty and foster transparency as they pursue dissemination to developing nations.

Challenges to technology transfer:
A literature review of the constraints on environmental technology dissemination

This is the second in a series of three literature reviews designed to summarize the state of academic knowledge surrounding the economics of environmental innovation. This second paper examines the challenges to the dissemination of environmental innovation. The paper examines diffusion mechanisms, market factors, social characteristics and political elements that facilitate and complicate dissemination. The first paper in this series examines constraints to the development of environmental innovation, while the following paper considers the obstacles to financing.

"There is no master model for technology transfer, but only localized communication strategies for understanding context and culture in effective technology transfer." (Coppola, 2007)

Introduction

The diffusion of new technologies is a difficult process, filled with uncertainty and hampered by both market and cultural factors. Despite obvious advantages over earlier technologies, some innovations are slow to catch on, while others seemingly spread like wildfire. Given the importance of innovation to economic growth and development, the questions surrounding the diffusion of innovation have attracted significant attention from economists. While much has been learned about the diffusion process and the factors that hinder and enhance technology transfer, important questions remain. These issues are perhaps most pronounced in the newest and most technology-intensive industries, including environmental innovation. As noted in the first paper in this series, it is important to keep in mind that many of the challenges to innovation and the dissemination of technology in general are found in the field of eco-innovation. Not surprisingly, several of these challenges are exacerbated in the case of environmental innovation. Again, please refer to the first paper in this series for suggestions on papers reviewing the literature on the economics of innovation.

In order to examine the dissemination of environmental innovation, it is essential to recognize that markets for technology in general are distinct from those for other goods and services. As described by Hoekman, Maskus and Saggi (2004), transactions in technology are characterized by three principle problems: asymmetric information, market power, and externalities. In the context of asymmetric information, technology transfers are fundamentally about trade in information. The difficulty stems from the fact that ex-ante buyers are unable to fully assess the value of the information. This may result in considerable transaction costs or stifle the exchange all together. In addition, innovators frequently have significant market power, stemming from first-mover advantages, patents and other forms of IP protection. As a result, price exceeds marginal cost and the socially optimal level of adoption is seldom reached. Finally, technology transfers are often characterized by externalities, the cost and benefits are not fully internalized. The authors note that the externalities most frequently take the form of uncompensated spillovers. As evidence of this, Fischer *et al*. (1998) show that a categorical ranking of policies in their ability to foster innovation is not possible, but rather depends on a host of case-by-case factors including the innovator's ability to appropriate spillover benefits of new technologies to other firms, the costs of innovation, environmental benefits, and the number of firms producing emissions. Beyond these elements, Jaffe et al. (2001) point out that the uncertainty facing eco-innovation adoption is larger than that for other products and processes. Not only is there uncertainty regarding the qualities of the innovation, but there is uncertainty regarding the future prices of the inputs (energy, pollution permits) on which the value of the eco-innovations critically depend.

While understanding the factors that inhibit dissemination of environmental innovation is essential to policymakers managing the process, it is also critical to examine the factors that may enhance technology transfer. Tidd (2006) describes five characteristic that affect technology diffusion: relative advantage, compatibility, complexity, trialability, and observability. Relative advantage is the perceived superiority of a technology over competing innovations and earlier technologies. Compatibility describes the extent to which the innovation is consistent with needs, experience and values of adopters. Complexity reflects the fact that innovations that are easier to use are more rapidly adopted. Trialability is the degree to which an innovation allows for experimentation and the ability to overcome adopters' uncertainty. Finally, observability touches on the extent to which the benefits of an innovation are visible to others.

In the case of a specific industry, Purvis and Outlaw (1995) examine technological innovation in the context of environmental compliance in industrializing the agriculture sector. The authors identify a number of factors that help explain the rate of technological diffusion and adoption. First, the rate of diffusion is dependent on the cost-effectiveness of the new technology. That is, the earliest adopters will be those firms with the greatest potential profits associated with the innovation. In addition, they notes that new technologies are often capital intensive and associated with size and scale economies. As such, adoption may require access to investment capital. The study also cites Boehlje (1992), which argues that adoption is a function of differing salvage values for the displaced technology across firms, as well as distinct abilities to assess the risks and rewards associated with the innovation.

Fundamentally, different types of environmental policy have distinct impacts on innovation and diffusion. Standards and regulatory measures contrast with market-based incentives. Numerous studies (Zerbe 1970; Downing and White 1986; Milliman and Prince 1989; Jung *et al*. 1996, among others) find that the incentives to adopt new innovations are greater with market-based tools than with regulatory tools. Despite that, it is not surprising the policymaking exerts an influence and matters to technology transfer. Jaffe et al. (2001) conclude that the form of environmental protection policy matters at least as much as its stringency. Command-and-control policies tend to be associated with larger costs and less dynamic progress, while market-based policies encourage each firm or individual to find the best solution to their own situation. Technology standards are particularly troublesome, since there is no benefit to investment in better solutions, or eco-innovation. On the other hand, they may be technology-forcing, providing a ready market to third-party innovations. The balance of policy is also important. Parry et al. (2000) present a theoretical model which shows that the welfare gains from stimulating eco-innovation are much smaller than the welfare losses from inappropriate pollution control. They advocate that current abatement should not be forsaken in the hunt for a dynamically efficient solution via innovation.

In an international context policymaking becomes even more challenging. Uncertainty and informational problems are exacerbated and contracting solutions are more difficult to accomplish. Brock and Taylor (2004) develop models of endogenous growth to show tradeoffs between environment and economic growth. It refers to the enormous literature on the Environmental Kuznets Curve (EKC), where evidence is clear for US and generally supportive for rest of world. By many measures, the environment is improving in many developed nations, as measured by emissions of regulated pollutants, or quality of city air. Those improvements have been relatively cheap, costing at most 1-2 percent of GDP for the US (and similar elsewhere). At the same time, it is important to note that EKC trends tend to be pollutant-specific. In particular, they are most often found for things such as particulates and SO2, cases in which some type of expensive capital equipment is needed to comply with regulations. Alternatively, for CO2, emissions increase with income. For other things, such as the quality of drinking water, the relationship is always positive; higher income is correlated with cleaner water.

In a specific case study, Chandrashekar and Basvarajappa (2001) explore the challenges of technological innovation and economic development for India. They find that the process is complicated by institutional and regulatory constraints. "Piecemeal and ill-thought out approaches to economic reform and privatization as well as vested interests have often come in the way of the diffusion of pioneering technology". The study also notes that trade in technology may be impacted by national security concerns, making exports difficult. They specifically cite trade restrictions on nuclear power, pointing out that globally nuclear power has experienced significant growth.

In addition to the factors that impact the dissemination process, it is important to consider the *how* and *where* of technology transfer. Jaffe et al. (2001) point out that diffusion is a gradual process, regardless of the advantages over the previous generation. There is a well-documented S-shaped curve (Griliches, 1957; David 1966; Oster 1982; Levin et al. 1987; Mansfield 1989; Geroski 2000). The slowness is due primarily to two reasons: heterogeneous adopters and the risk/uncertainty involved in adoption. Models usually adopt one of two main branches of theory, the probit or contagion models. The option value model is an offshoot of the probit model. The speed of both increase with information flow, e.g. learning-by-doing or by proximity to other adopters. Hoekman, Maskus and Saggi (2004) point to the complex relationships between the different channels of technology transfer. "[T]rade and FDI are often complements, whereas FDI and licensing may be either complements or substitutes. Movement of people is often needed to allow trade, licensing or FDI to occur or to increase the efficiency of such transactions." Alternatively, Blackman (1999) describes several studies have found that technological diffusion stimulates additional R&D, and that, in turn, research and development also stimulates diffusion. He argues that "firms' expenditures on adapting new technologies to their particular circumstances and on searching for new technologies – i.e., R&D expenditures – are closely linked to diffusion." Empirical studies have emphasized the roles of firm size, R&D expenditure, market share, market structure, input prices, technology costs, firm ownership, and other institutional factors including policy.

Turning to the *where* of innovation and dissemination, Dechezlepretre et al. (2008) use the EPO's PATSTAT database to investigate where eco-innovations have been patented worldwide since 1978. They consider 13 different classes of technologies with significant global GHG emission abatement potential: 6 renewable energy technologies (wind, solar, geothermal, ocean energy, biomass and hydropower), waste use and recovery, methane destruction, climate-friendly cement, energy conservation in buildings, motor vehicle fuel injection, energy-efficient lighting and Carbon Capture & Storage (CCS). Thus they analyze 273,900 patent applications filed in 76 countries. On average, climate-related patents included in the data set represent 1% of the total annual number of patents filed worldwide.

They note that Kyoto has increased the rate of international patenting in these categories, both pre- and post-Agreement, and between signatories and non-signatories. However, Kyoto has not increased the rate of diffusion or transfer between nations. Patents in climate change technologies are highly concentrated in three countries—Japan, Germany and the USA—which account for two thirds of total patents considered. Japan's counts are first in 12 of 13 technologies (note: probably because of different patent publication law, but the authors try to account for this using average relative patent family sizes). China, South Korea and Russia are respectively the fourth, fifth and sixth largest innovators, but other emerging and less developed nations are not active. These three globally represent about 15% of total patents.

The export rate—measured by the share of patents that are protected in at least two countries—is around 25%. This sounds small, but it is only a few percent below the rate for all technologies. International transfers mostly occur between developed countries (75% of exports). Exports from developed countries to emerging economies are still limited (18%) but are growing rapidly. Their analysis indicate that patent imports are positively correlated with domestic patents in the field (complements, perhaps because imports boost demand for all eco-innovation), but are negatively correlated with domestic share (substitutes, perhaps crowding out).

The authors build an adequate model and estimate it econometrically. The highlights of their findings include the following. They find more local innovations encourage patent imports while education (or absorptive capacity) is less universally significant. In addition, they observe that there is only modest correlation with energy prices. The strictness of IPRs affects certain industries (buildings insulation, wind power, fuel injection and energy-efficient lighting) but not others. Higher tariff rates have a statistically significant negative impact on patent flows in most regressions, suggesting perhaps that transferred technologies are frequently embodied in equipment goods. Strict international capital control does not have any statistically significant effect on patent flows in most regressions. Overall, they do a nice analysis of the spatial concentration of innovation, and of the sectoral patterns over time. Unfortunately, Dechezlepretre et al. (2008) is one of very few studies providing empirical evidence on the diffusion of eco-innovations or the impact of policy on their diffusion.

The following section briefly explores the current legal and regulatory regimes relevant to the environmental innovation landscape. The remainder of the paper is organized around two themes, challenges to the diffusion of environmental innovation and important considerations specific to strategies for technology transfer of environmental innovation. Finally, the concluding section draws out lessons learned for effective dissemination strategies and suggestions for future research.

Current Legal and Regulatory Regimes

Bernauer et al. (2006) define regulation as "to include the full range of legal instruments by which governing institutions, at all levels of government, impose obligations or constraints on private sector behavior. Constitutions, parliamentary laws, subordinate legislation, decrees, orders, norms, licenses, plans, codes and even some forms of administrative guidance can all be considered as regulation" (OECD, 1997a:9). They consider it to include environment-related regulation that considers and impacts the environment (Kemp, 1998:14).

Hutchinson (2006) provides a nice overview of the variety of international legal agreements that touch on transferring climate change technology to developing nations. The international legal regime is replete with generalized obligations for states to transfer green technology to developing nations. He notes that Principle 9 of the Rio Declaration on Environment and Development provides "that '[s]tates should cooperate . . .by enhancing the development, adaptation, diffusion and transfer of technologies, including new and innovative technologies.'" In like manner, Principle 20 provides that "'environmental technologies should be made available to developing countries on terms which would encourage their wide dissemination without constituting an economic burden on the developing countries.'" While acknowledging the importance of patent protection (Chapter 34 of Agenda 21), technology transfer is a common theme. This includes the UN Climate Change Convention, the Kyoto Protocol, and the TRIPS Agreement (a nice outline of the specifics is included in Hutchinson, p.525). Support for carbon abatement takes other forms as well. Morgan (2007) cites the importance of reducing and eliminating subsidies that encourage reliance on, and production of, fossil fuels. He notes that the Kyoto Protocol explicitly requires a reduction of the subsidies that encourage carbon emissions.

International trade is another channel through which technology is disseminated, and subject to a host of additional legal restrictions. Abbott (2007) notes that new standards of protection for intellectual property must be carefully considered due to national treatment and most-favored-nation treatment (MFN) principles. Hoekman, Maskus and Saggi (2004) note that in 2001, "WTO members established a Working Group on Trade and Technology Transfer to examine the relationship between trade and the transfer of technology and explore what might be done under WTO auspices to increase IT to developing countries." Indeed, the relevant legal regimes may differ across developed and developing nations. Correa (2007) writes about the intersection of intellectual property and competition law, placing the issues at hand in the context of developing nations. He emphasizes the importance of preserving competition and market contestability in the area of IPRs, noting that the right balance of competition and IP protection must be achieved through a diversity of policies and regimes. The article elaborates on a number of recommendations that may be employed by developing nations in which such legal regimes are still evolving.

Though not specific to developing nations, the uncertainty that exists in these markets is well reflected in the model of Aoki and Hu (1996). They argue that the uncertainty surrounding the scope of patent protection, as well as the incomplete enforcement of IP rights, mean that the effective strength of intellectual property rights are determined by the implementation of the legal system. Given this, they examine how the legal system impacts incentives to innovate. The authors analyze how firms act strategically, using licensing and litigation to prevent infringement and deter imitation. Aoki and Hu's analysis is particularly applicable to areas of new technology.

New technologies frequently challenge existing legal systems in new ways and foster the evolution of the law. As one would expect, this process can take time and interesting adjustments may take place in the meantime. Consider US stem cell technologies. In the midst of national restrictions surrounding the technology, state governments stepped in to promote technology transfer from academic institutions to industry. Appel and Irvin (2008) describe the California Stem Cell Research and Cures Bond Act as a recent example of a state initiative designed to incubate a new technology-based industry. In November 2004, California adopted Proposition 71 to fund stem cell and medical research facilities over ten years. In another example of the evolving process, Appel and Irvin (2008) analyze the US environmental management and technology systems (EMTS) industry and the laws impacting innovation incentives. The study contrasts the EMTS industry to the emergence of the biotechnology and semiconductor industries. Early on US courts adapted existing law to create a predictable legal structure under which both industries were able to grow and prosper. By contrast, the EMTS industry is largely "based on trade secret and protected expertise commercialized within a consulting – not a manufacturing industry – model, which does not draw equally as well on existing intellectual property law protection and guidance." They suggest that the industry would benefit from greater predictability in the legal realm.

Finally, there is a large literature on the impact of regulation on innovation. Bernauer et al. (2006) investigate evidence on the 'win-win hypothesis' as stated by Porter and van der Linde (1995) as "…properly designed environmental standards can trigger innovation that may partially or more than offset the costs of complying with them". They refer to a large-scale quantitative study of the impacts of environmental regulation (Johnstone et al, 2005), and previous work by Hemmelskamp (1999), Kemp (1997), and Klemmer et al. (1999), Jaenicke et al. (2000), Jacob et al. (2005) which the current study aims to encompass with a common framework. Kerr and Newell (2000) found that stronger regulation encouraged greater adoption of lead reducing technology in petroleum refineries. They also found that larger and more technically sophisticated refineries, which had lower costs of adoption, were more likely to adopt the new technology.

Dissemination

Blackman (1999) provides an overview of the four categories of technology diffusion models: epidemic models, rank models, order models and stock models. Epidemic models are the oldest and likely most influential, based on the idea that the spread of information is key to understanding diffusion. Adoption time varies based on 'infection', the amount and timing of information received, which is a function of the characteristics of individual technologies. Firm heterogeneity explains differences in diffusion patterns in rank models. These models are based on the hypothesis that firms differ with regard to some critical variable that impacts the expected discounted profitability of the new technology, the 'net return on adoption'. Blackman identifies seven critical variables: capital vintage, firm size, beliefs about the return on the new technology, search costs, input prices, factor productivity, and regulatory costs. The premise of order models is that the order of firm adoption determines the net return they receive. Early adopters earn higher net returns than later adopters. Finally, stock models presume that the net return on adoption is a decreasing function of the total stock of firms that have adopted. As more firms adopt, net returns fall. Blackman (1999) argues that the majority of empirical studies on technological diffusion amount to an examination of how diffusion is impacted by firm characteristics. While firm size and market structure have garnered the most attention, the impact of factor prices, factor productivity, infrastructure, vintage of capital stock, macroeconomic variables, R&D expenditures, regulation, and institutional differences have also been considered.

In like manner, Kemp (1997) groups diffusion models into two types: epidemic models (e.g. Griliches 1957) and rational choice models (e.g. David 1969). Kemp (1997) is a volume dedicated to explaining the literature's models of environmental innovation and diffusion, then testing them empirically with case studies. It's good reading for someone moderately familiar with economics and econometrics, and explains methods and results in a historical (as well as policy-relevant) fashion. In particular, the cases use the same data in competing model formats to highlight the differences in results and interpretation. Specifically, he shows that via alternative models, increases in the effluent tax rate encourage adoption of waste-water treatment plants, but not in the way many might predict. Instead of through diffusion speed, instead the tax rate increased diffusion by increasing the population of prospective adopters. The mode of diffusion is one of enabling and encouraging the valuation of the end-product/process, rather than encouraging information flow or regulating. He also concludes that many year-to-year changes are not explained by current models. Adoption is clearly affected by the financial or investment rules of the firms involved, which may operate on heterogeneous principles or timelines.

In terms of country specific studies, Klaassen et al. (2005) uses data from three European nations to estimate the learning curves for wind farm technologies. They estimate the cost impacts of governmentally subsidized expansions, comparing national policies to evaluate their relative effects. Similar data could be found and used to apply this method elsewhere, or for other technologies. Howe (2007) summarizes the Australian position on global warming and environmental policy responses, none of which specifically target innovation. Finally, Kemp (1997) analyzed the diffusion of thermal insulation in the Netherlands 1978-92. Explanation was impossible using a rational choice model, but works quite well using epidemic models of diffusion. He finds that the rate of adoption by owners is not very different from that of renters, probably because of a high degree of rental market penetration by housing corporations. Subsidy programs had little impact on the rate of diffusion, instead providing windfall gains to receivers.

Alternatively, Milliman and Prince (1992) showed that in a theoretical model, auction-based permits offered the largest incentive to adopt. The result holds across heterogeneous firms, and was confirmed by Jung *et al*. (1996), Parry (1998), Denicolò (1999) and Keohane (1999). Emissions taxes are better than permits, which are themselves much better than regulated or command-and-control policies. However, the degree of improvement is shown by empirical estimates to be sensitive to the context (Parry (1998); Requate (1998)).

The literature on the dissemination of innovation includes many excellent reviews. Popp (2008) is a good review of the field for policymakers and regulators. It includes discussion of the provisions of the Kyoto Protocol, and the current state of knowledge surrounding transfer of technologies to less developed nations. Karshenas and Stoneman (1995) is a good literature review of technology diffusion overall.

Role of compulsory licensing

Although there is no single standard definition, the World Trade Organization defined compulsory licensing in its briefing notes for the Doha Round as circumstances under which "the authorities license companies or individuals other than the patent owner to use the rights of the patent — to make, use, sell or import a product under patent (i.e. a patented product or a product made by a patented process) — without the permission of the patent owner." (WTO, 2001) It is important to note that compulsory licensing is legal and allowed under the WTO's Trade Related Aspects of Intellectual Property Rights (TRIPS) Agreement, although the Agreement itself does not define the term, provided that certain procedures and conditions are met. Significant controversy naturally surrounds the activity. Compulsory licensing is intended to facilitate more rapid and less costly diffusion of technology, especially in the case of innovations with public good characteristics where a clear public emergency is emerging. The 'taking' of patent rights clearly reduces the profitability of innovation and increases the uncertainty surrounding investment and R&D. In a broader sense, Abbott (2007) notes that "compulsory licensing legislation serves multiple purposes, including facilitating price negotiations with patent holders, allowing authorization of generic imports, and allowing authorization of local production." That change in incentives unambiguously leads to less subsequent innovation in pharmaceutical and other health fields, meaning more expensive (or completely unavailable) long-run solutions to any emergency. In short, compulsory licensing enables existing technologies to disseminate more quickly and cheaply, while discouraging second-generation solutions from developing. Economists conversationally refer to this as a "static solution to a dynamic problem."

The study by Copenhagen Economics (2009) notes that at the Beijing International Conference in November 2008, India and China proposed that the TRIPS flexibilities for the compulsory licensing of medicines be extended to carbon abatement technology. "The argument was that climate is a public good, just like health, and that hence the international community should follow the principle of 'guidance by government – participation by enterprises'." There is ample evidence that compulsory licensing reduces the incentives to innovate in pharmaceuticals, and therefore reduces the pace of innovation in health-related fields (see, for example, Danzon and Towse, 2003; Lybecker and Fowler, 2004; Bate and Boateng, 2007). Those same arguments presumably apply at least in part to eco-innovation as well, although there is no direct evidence. Beyond that indirect evidence, Copenhagen (2009) finds no argument in favor of extending the TRIPS flexibilities due to the number of substitute technologies available, many of which are not protected by IPRs. While many diseases are (at least initially) only treatable with one specific drug, a variety of alternative technologies are available to reduce carbon emissions. Moreover, the Copenhagen Economics study finds that compulsory licensing is likely to serve as a disincentive to investment in environmental technologies.

The uncertainty engendered by compulsory licensing is an important consideration both in the context of incentivizing innovation and also in terms of its dissemination. Aoki and Hu (1996) argue that imperfect patent protection provides firms with an incentive to license to potential infringers or competitors. The licensing occurs precisely because of the uncertainty surrounding patent protection. Through a theoretical model of competition, they demonstrate that the ways in which firms utilize licensing and the terms of the agreement are a function of the costs of litigation.

Mandel (2005) argues strongly against compulsory licensing, suggesting that it is only a potential help in an industry where an innovator is not licensing their innovation enough. The study argues that this should rarely be the case for eco-innovations, innovations which presumably have network externalities or positive spillovers. He further argues that compulsory licensing will reduce the incentive to innovate, which is precisely an exacerbation of the initial problem.

Alternatively, Hutchinson (2006) points to an important argument in favor of compulsory licensing. He notes evidence that in some cases, fear of competition by businesses is a barrier to technology transfer and a reason behind refusal to license technology. Specifically, the study cites examples of climate change technologies in Korea and India. At the same time, he highlights one important complication surrounding compulsory licensing, noting that firms in developing nations "may lack the expertise to develop the technology without more than just the blueprint. In particular, compulsory licensing does not oblige the patent holder to transfer know-how (nor does patent law in general)." Especially in the case of technologies involving significant tacit knowledge, the mere ability to use the patent may be insufficient to make the technology workable.

Role of markets and incentives

Market forces and incentives may facilitate the dissemination of environmental innovations or create insurmountable barriers to adoption. The attributes that work both for and against are concisely described in the works of Popp (2003, 2005, 2006). Popp (2005) describes the key lessons for innovation and dissemination from empirical studies on policy and environmentally-friendly innovation. He enumerates the lessons as follows: innovation responds quickly to incentives; innovation in a given field experiences diminishing returns over time; the social returns to environmental research are high; and the type of policy used affects the nature of new innovations. (Popp 2005, pp.215-219) Popp (2005, 2003) cite the public goods nature of knowledge and the resulting market failures for knowledge, specifically the inability to completely appropriate the returns, as important causes of the underinvestment in R&D. Accordingly, Popp (2003) argues that limiting the impact of market failures through subsidizing R&D and government financed R&D may improve the potential gains from such innovation.

In terms of market failures, Popp (2006) examines government subsidies for innovation in the context of addressing the two market failures that characterize green technology, the public goods nature of knowledge and environmental externalities. He finds that while R&D subsidies do lead to increases in climate-friendly R&D, they address only the public good problem. Since the environmental externality problem is not addressed, there are no additional incentives to adopt the new technologies. As such, policies that directly impact the environmental externality result in greater gains in terms of both atmospheric temperature and economic welfare.

Innovation adoption is a function of economic viability. Pray (1981) describes the technology transfer of the green revolution as viable only after World War II, when rapid population growth increased the prices of grains and the decline of chemical fertilizer prices made fertilizer-responsive grain varieties affordable in new markets. The low food-grain price/fertilizer price ratio made these varieties economically feasible in countries where they previously had not been, leading to adoption. Pray (1981) points out that, in the case of the green revolution, the distribution of benefits was determined by government pricing policies, rather than the nature of the technology or the forces of supply and demand. He argues that government policies determined how benefits were shared between farmers and consumers. Links to labor markets are also featured in the work of Rennings and Zwick (2001) which presents empirical evidence that eco-innovations among 1500 European firms are labor-using, leading to lower employment among small adopting firms and among those firms with expectations of growth. Product innovations use more labor, while process innovations tend to use less labor when compared with the pre-innovation input portfolio. However, the effects are noticeable only at the margin (9% increased employment, 3% decreased).

In another branch of the literature, cost reductions feature prominently in many studies. Jaffe and Stavins (1995) found that consumers were much more sensitive to adoption costs than to energy costs when choosing to adopt energy-efficient innovations for their new US homes. Hasset and Metcalf (1995) confirmed this result, suggesting that it is due to behavioral biases toward proximate events in favor of future events, or due to uncertainty surrounding how future energy prices will evolve. In addition, Blackman (1999) argues that many types of climate friendly technologies (CFTs) both reduce carbon emissions and reduce production costs. Clearly technology diffusion is facilitated if such technologies cut costs and boost exports. “Efforts to promote the diffusion of CFTs are likely to garner widespread support since they represent opportunities to enhance productivity and abate local pollution in the eyes of developing countries, and opportunities to boost exports of equipment and expertise in the eyes of industrialized countries."

Leading up to the 2009 Copenhagen Summit on Climate Change, the Copenhagen Economics study (2009) examines the claim frequently made by developing nations that strong intellectual property rights on carbon abatement technologies hinder developing countries' greenhouse gas abatement efforts. The study finds that IPRs do not constitute as significant a barrier as claimed since a variety of technologies exist for reducing emissions. Based on the cost-per-unit-of-carbon-emission-reduction, IPR protected technologies are not necessarily more costly than those not covered. The authors note that the expensive of some innovative carbon abatement technologies stems from the immaturity of the technology rather than patent protection. Moreover, the study finds that while there is a small number of emerging market economies which account for the majority of patents protected in the sample (99.4%), there is a much larger number of low-income nations that protect very few patents (0.6% of the total sample). Given that patents are virtually non-existent for these technologies is most developing countries, it is difficult to argue that IP protection is a significant barrier to technology transfer. Moreover, if stronger environmental regulations were in place and creating a market for these technologies, there would likely be more patents for clean technologies in developing countries.

Costs are also examined in empirical work. Rose and Joskow (1990), Boyd and Karlson (1993) and Pizer *et al.* (2001) all found that increased fuel prices encourages adoption of fuel-saving innovations at industrial facilities in different industries. Also consider Brunnermeier and Cohen (2003) who use panel data models across US manufacturing industries to find that between 1983 and 1992, environmental innovation responded very clearly (with a one-year lag) to increases in pollution abatement expenditures, but increased monitoring and enforcement activities related to existing regulations did not provide any additional incentive to innovate. They also found some empirical evidence that environmental innovation is more likely to occur in industries that are internationally competitive. As mentioned earlier, the study also refers to similar conclusions by Lanjouw and Mody (1996) and Jaffe and Palmer (1997).

Drawing on examples from the agriculture sector, Purvis and Outlaw (1995) describe the potential importance of economics of size. The study points out that if large scale is necessary for adoption, the result may be industry concentration. "By their experimentation, large-scale producers can take leading roles in demonstrating the efficacy of new technologies. If such cutting-edge technologies are workable and affordable only for facilities that achieve certain economies of size, then over time the industry can become dominated by industries that can afford to comply."

Important considerations arise from both the supply and demand side, as noted by Kemp and Soete (2000). On the supply side, technological opportunity and appropriability affect this field of innovation in a fashion similar to other fields of innovation. On the demand side, innovation faces much higher hurdles here. First, there are problems related to knowledge and information, including who is responsible for costs, and how to price damage. Second, there is uncertainty about actual costs, consumer values, and policy platforms now and in the future. Third, many eco-innovations are process in nature, but aim to market to the end consumer without necessarily lowering costs, making them a strange commodity.

The complications surrounding these strange commodities are furthered by government interventions in the market and their tinkering with incentives. Naghavi (2006) presents a theoretical model showing how "tariffs levied on polluting goods could result in less global pollution than harmonization of environmental standards by inducing more pollution abatement R&D". Arrow et al. (2004) refer to three reasons that natural resources may be underpriced: unclear property rights, externalities and government subsidies. They refer to the 1992 World Development Report by the World Bank which showed that in 29 of 32 LDCs surveyed, subsidies had caused the price of electricity, water and fossil fuels to fall below cost (not even including externality costs). The similarly report that the International Energy Agency (1999) "has estimated that in India, China and the Russian Federation, full-cost pricing would reduce energy consumption by 7, 9 and 16 percent, respectively… where most of the departure from social cost pricing is attributed to energy subsidies". They refer to Myers and Kent (2000) for estimates of aggregate global subsidies on the use of environmental and natural resources.

Observations on particular countries are considered in the following studies. Malueg (1989) and Kerr and Newell (2000) showed that the program in the US to phase out leaded gasoline using tradable permits led to a more efficient use of resources than pure regulation would have. Keohane (2001) confirmed the same result using the example of the US Clean Air Act system of tradable permits. In an interesting contrast, Friedman (2006) argues that China has one political advantage over the US, that it can make decisions against special interests and all bureaucratic obstacles or worries about voter backlash and simply order a change. If the US could do that for one day, and institute responsible regulations, standards, education, infrastructure and prices, then our system would make sure that they are enforced via legal action if necessary. Friedman also suggests that short-term tax credits, to be renewed each year, are devastating for small and emerging industries, because they don't allow full-scale production and increase risk. Firms can't invest without a guaranteed market.

The role of government intervention is also described by Sachs (2003) who concisely enumerates on the characteristics and circumstances of developing nations that hinder innovation in developing countries. He notes that scientists and researchers tend to congregate geographically in universities, research parks, and scientific hotbeds like Silicon Valley. In addition, brain drain has intensified with globalization. Poor countries are also handicapped by their small market size, cash-strapped governments and inability to make public investments in research and infrastructure. (Sachs 2003, p.136) Sachs notes that while there are very few examples of nations that were low innovators a generation ago which are highly innovative today, in those that are, both markets and conscious industrial policy played important roles. "[P]romotion of a knowledge economy or innovation-based economy is not only a market phenomenon, but also a process of industrial policy and government investments in science, technology, and higher education."

Finally, legal incentives are also important features of the innovative landscape. Aoki and Hu (1996) explore the impact of the legal system on the incentive to innovate under uncertain patent protection. They analyze conditions under which an innovator decides to license their technology to prevent imitation. This takes place when "(1) the legal costs and probability of winning make the patent owner unable to credibly threaten with an infringement suit; or (2) the patentee credibly threatens to sue, but the potential infringer's legal cost is so low that he is willing to go to court." Under these conditions, the innovator will license the technology and share the market. In essence, the market structure is determined by the uncertainty surrounding patent protection and by legal enforcement.

The incentives surrounding the diffusion of environmental innovations take a variety of forms. They naturally occur in the market and are shaped by market structure and uncertainty. A noted in the Copenhagen Economics study (2009), technological capacity and market size are prerequisites for stimulating domestic innovation and technology transfer. Technology transfer is also delayed and speeded by the forces of government intervention and the markets for substitute and complementary goods. The economic literature provides a wealth of studies examining each of these elements and yet providing plenty of inspiration for additional works and further empirical study.

Importance of appropriate technology

The appropriate nature of technology is a subtle, yet essential, consideration in the analysis of the dissemination of innovation. Though far from obvious, the varied considerations surrounding the appropriateness of technology are intimately linked to its success or failure. As noted by Pray (1981), similarities between the innovator and adopter are essential. He illustrates this claim with evidence from the Green Revolution. "The type of transfer that occurred during the green revolution depended on the agroclimatic similarity of the adopting country with the country of origin and also on the sophistication of the local research system. The initial diffusion of HYVs [high yield varieties] in India, Pakistan, Turkey, and Malaysia was largely a material transfer because their agroclimatic conditions were similar to Mexico and the Philippines." Pray goes on to note that a study of what determined the acceptance of this technology determines that success may require acceptance by both government and by firms. The benefits to both are key to acceptance and diffusion of new technologies.

In a cross-country study, Popp (2006c) compares innovation for SO_2 and NO_X pollution control in the US, Japan and Germany. He finds that when regulations are enacted, local inventors respond by increasing patenting activity for relevant technologies. This result even holds true in the last country to adopt regulation (Germany for SO_2, US for NO_X), suggesting that these innovators are adapting existing innovations from other countries. This claim is supported with evidence from patent citations. The explanation may be traced, in part, to the quality of coal which varies across countries. Control technologies need to be adopted to work with the locally-available coal. As such local innovations matter for these technologies. Another example in which the appropriate technology context is particularly relevant to the environment may be found in Lanjouw and Mody (1996). They find that there are more adaptive patents for water pollution than for air pollution. This is explained with the observation that air pollution uses expensive capital equipment that may be imported to developing countries, while water pollution technologies must function under local geological conditions.

In a similar vein, the theoretical work of Adler (2001) asserts that many environmental issues are local or regional in nature, so require local knowledge and solutions. Adler (2001) advocates 'competitive federalism as a promising alternative to rigid, inefficient national regulation and regimentation'. His work is published under the auspices of the American Enterprise Institute, which asserts that "competitive federalism attempts to mimic, in the political arena, the dynamics of a well-functioning economic market." Adler asserts that the environmental regulatory system in the US suffers from inefficiency, excessive rigidity, poor prioritization and other problems characteristic of a command-and-control system. He advocates a national policy of 'ecological forbearance', where states would petition the EPA for waivers of particular requirements in order to pursue state-level innovation and experimentation. Rather than rely on a patchwork system of prescriptive policies which may slow innovation and impose non-trivial costs, a new system might encourage (or at least permit) states to deviate from the national norm in pursuit of better solutions. Sachs (2003) also stresses that many technologies are highly ecology-specific. Technologies appropriate for one ecological environment may be difficult to employ in another. "The diffusion of technology from the advanced to the lagging countries, so important in the process of catching up, works best when the laggard shares the same ecological zone as the leader . . . and works most poorly when the laggard is geographically isolated and in a distinct ecological zone."

Finally, technology lock-in is a well-documented story, occurring where there are increasing returns to adoption (David, 1985). For innovations which work as a system, there is also the strong possibility of positive externalities of adoption (e.g. ATMs, fax, computer OS, VHS). In such cases, an appropriate role for policy is to delay the adoption of standards until sufficient information about the future timepath has been revealed. Besen and Farrell (1994), Katz and Shapiro (1994), Liebowitz and Margolis (1994) and Farrell and Saloner (1985) all analyze cases involving network externalities. Policy might also help to set standards, to help disparate market interests to coalesce around a common interest in a new framework (e.g. USB format).

Culturally, Environmentally, and Politically Appropriate

The diffusion of environmental innovations is facilitated by environmental feasibility as well as cultural and political acceptance. Firms that effectively respond to such pressure and signals are more apt to succeed. A wide array of economic studies has analyzed these different facets of adoption. The importance of social pressures is emphasized by Blackman and Bannister (1998) in their analysis of the pressures by other firms and community groups in the adoption of cleaner fuels for brick kilns in Mexico. Berrone et al. (2007) proposes that firms react to normative pressures from their peers alongside regulatory pressures. Finally, Baylis et al. (1998) explore the possible reasons for adoption of eco-friendly innovations via EU case studies. Larger firms clearly felt more social pressure, but conformity to laws was the overriding reason for adoption.

Beyond social pressure, Wong et al. (1996) show that consumer perceptions of eco-friendly are unclear, and often hinder diffusion and pricing. Lapan and Moschini (2004) analyze innovation and the case of genetically modified (GM) products. Their work points to the importance of public acceptance and effective regulations, as well as the consequences for international trade. They demonstrate that the introduction of genetically modified products may lower welfare because of the cost externality that results from certifying and verifying such products. In addition, regulations on genetically modified products may impose artificial costs on the trade in GM products, lowering efficiency and redistributing welfare.

Economic studies have focused on both surveys of large numbers of firms, as well as industry case studies. Craig and Dibrell (2006) used a survey of a sample of 396 firms to determine whether family-based firms were better at eco-innovation. They used a poorly described five-item scale for environment from Klaassen (2001), and a similarly vague innovation construct introduced in Davis et al. (2002). Results are simple and show that family firms are more attuned to their natural environment and related policies. Again, the data would be interesting to analyze in a new model with better tools. In another large scale study, Frondel et al. (2004) use a survey of OECD data across 4186 firms and find that more than ¾ of all abatement measures adopted are for cleaner production rather than end-of-pipe reasons. Estimation results indicate that regulatory measures and the stringency of environmental policies are positively correlated with end-of-pipe technologies, while cost savings, general management systems, and specific environmental management tools tend to favor clean production. Naturally, there are differences across nations and between firms and industries.

As for case studies, Calef and Goble (2005) compare the policy encouragement during the 1990s of electric vehicle diffusion by California and France, California's approach being very public and adversarial, France's being quiet and without public participation. They argue that California's stringent regulation spurred the development of innovative hybrid and fuel cell vehicles more effectively than the French approach. They state that regulation "in California is an example of *technology-forcing*; it required the regulated industry to produce and sell efficient electric vehicles, within a set period of time, even though the technology was not fully developed when the regulations were created." Despite the success of this policy, it is important to note that the original Californian policy called for zero emission vehicles, which does not describe hybrid vehicles. The intent of the policy was to incentivize truly electric powered vehicles. When the automakers couldn't produce them, the standards were weakened so that they could be met with partial zero emission vehicles, such as hybrids. Calef and Goble provide an interesting review of the importance of cultural and political context when considering diffusion mechanisms.

In another study, Larson (2001) analyzes fuel cell technology. The study suggests that it may be adopted in less developed nations before developed nations, since the need is greater. In the absence of a reliable power infrastructure, fuel cells could follow the path of cell phones. As the least capital-intensive system (compared to stringing transmission lines from a central generation plant to remote areas), it may very well win based purely on lower upfront costs.

In the context of developing nations, Johnson and Evenson (2000) examine diffusion to Africa. In a study of technological spillovers to agriculture and productivity, they argue that the slow diffusion in Africa may be traced to their small markets with low technological infrastructure. "[F]oreign research is less applicable in sub-Saharan Africa, and thus has lower impacts than in other regions. If sub-Saharan Africa had enjoyed even the average level of foreign spillovers, growth would have been much faster, but it is unrealistic to hope for a huge increase, due to the costs involved in developing technological infrastructure and the constraints of climate and other distance measures."

Aubert (2004) studies the process of promoting innovation in developing countries and describes the importance of developing technologies that accommodate local conditions. "A typical example is technology which maintains the autonomy of local communities such as autonomous sources of energy and low cost efficient telecom infrastructure – and thus prevents the destructuring of societies through urban concentration." In order to facilitate innovation opportunities in developing nations, Aubert (2004) argues for the diffusion of technology and knowledge, through a number of channels: "metrology, standards and quality control, extension services (for manufacturing and agriculture), information and training programs, demonstration and pilot projects." He identifies a major problem as the lack of contact between research bodies and local communities in developing nations, which is primarily a function of financing for these research entities.

Importance of Science Base

While the availability of technology is a necessary condition for dissemination, it is also critical that the recipients have the prerequisite knowledge and scientific base to best exploit the information. As described by Hoekman, Maskus and Saggi (2004), "Countries tend to acquire international technology more readily if domestic firms have local R&D programs, there are domestic private and public research laboratories and universities, and there exists a sound basis of technical skills and human capital. All this reduces the costs of imitation, adaption, and follow-on innovation." The authors argue that the greater the 'technological distance' of a recipient country from the global frontier, the greater the challenge of effectively incorporating information into production systems. The absorptive capacity of a nation has also been considered via labor markets. Hoekman, Maskus and Saggi point out that "[s]ome studies have found that intra-national labor turnover from MNEs [multinational enterprises] to local firms is limited, while others find the opposite. An explanation is that in countries where local firms are not too far behind MNEs in technical terms, labor turnover is more likely. Thus, the ability of local firms to absorb new technologies is a determinant of whether labor turnover is a means of technology diffusion."

In an historical illustration of this point, Pray (1981) describes the importance of Ford Foundation and Rockefeller Foundation support in providing initial funding for International Agricultural Research Centers. He notes that their financial support speeded the spread of the technologies of the green revolution. The importance of local scientific knowledge is reinforced by Pray's (1981) results. "One of the most important factors in determining which governments participated in the green revolution first was the strength of the local research program."

Sachs (2003) examines global divisions in innovation and technological advance, utilizing US utility patent data to distinguish between technology innovators and the non-innovators. The "top ten innovating countries account for around 94% of all the patents taken out in the US in the year 2000, yet these countries have a combined population of only around 14% of the world's population. It's roughly a 96-fold higher ratio of patents per capital in the top ten countries than in the rest of the world (94/14 divided by 6/86). . . [T]he bottom 128 countries. . . have 63% of the world's population, but only 1174 patents in the year 2000, or just 0.75% of all the patents taken out in the US that year."

In an examination of non-innovators, Aubert's 2004 study identifies several significant weaknesses in the innovation environment of developing nations. Specifically, he identifies low educational achievement, the lack of infrastructure, importantly telecommunications infrastructure, and the quality the business environment and governance conditions. Aubert expresses particular concern for the bureaucratic climate and the formal/informal regulations regarding economic transactions. He also points out that in many developing nations, the absence of a scientific foundation is exacerbated by the exodus of skilled citizens from the developing world to OECD nations. "Up to one-third of R&D professionals from the developing world reside in the OECD area." Although a variety of factors certainly play a role in technology transfer, rich human capital and a strong scientific base are clearly important. As argued by Hoekman, Maskus and Saggi (2004), fundamentally "openness is not sufficient – there needs to be absorptive capacity and ability to adapt foreign technology, both of which are related to human capital endowments and investment in R&D intensive industries."

Strategies for effective technology transfer

Hoekman, Maskus and Saggi (2004) analyze policy options for technology transfer to developing countries. While acknowledging that designing an optimal policy mix is difficult and likely country-specific, they identify some rules of thumb for policy intervention (see table 1 below). They argue for liberal trade policies for all types of countries, noting the policy is associated with higher total factor productivity. "Spillovers from technology-intensive imports exist at the aggregate, intra-industry, and inter-industry levels." The study emphasizes that broad policy initiatives are essential for domestic gains from technology transfer, consisting of "building human capital, expanding national innovation systems, and effectively protecting IPRs, which may be critical for fostering innovation and supporting trade in knowledge".

Table 1: A 'Rule-of-Thumb' Typology and Examples of ITT Policies
(Hoekman, Maskus and Saggi 2004)

	Trade in goods	FDI	Trade in knowledge (licensing)	IPRs	Temporary movement	General technology policies
Own policies in:						
Low-income countries	Liberal access	Inward investment promotion	Improve information flows about public domain and mature technologies	Basic protection and minimum standards	Incentives for education abroad	Basic education; improve infrastructure; reduce entry barriers
Lower middle Income countries	Liberal access	Inward investment promotion	Improve information; limited incentives for licensing	Wider scope of protection; employ flexibilities	Incentives for education abroad and training-related movement	R&D support policies; improve public-private collaboration
Upper middle income countries	Liberal access	No active policy	No active policy	Full TRIPS	Encourage two-way mobility	R&D support policies
OECD policies towards:						
Low-income countries	Subsidize 'public good' type imports	Incentives for outward flows exceeding those for FDI to LMICs (see below)	Subsidize transfer of public domain and mature technologies	Forbearance in disputes; differential pricing for exports of IPR products; assistance in competition policy	Preferential access; subsidies for education and temporary employment	Support for public and public-private research facilities; incentives for universities to accept DC students in STI disciplines
Lower middle income countries	No controls	Incentives that equal those granted for domestic disadvantaged regions	Assistance in establishment of joint venture partnerships; matching grants	Differential pricing of public good type IPR protected goods; assistance in competition policy	Wider access for education and training and temporary employment	Fiscal incentives for R&D performed in developing countries (DCs) and temporary employment of DC scientific personnel and engineers.
Upper middle income countries	No controls	No incentives	No active policy	No active policy	Encourage mode 4 type mobility	No active policy

Numerous economists have examined the strategies for effective technology transfer. Important insights are found in the handful presented here. First, Sachs (2003) distinguishes between two important end users of science and technology and notes that the innovation systems in poor countries are failing along all dimensions. On the one hand, some technology is commercialized by the private sector, embodied in goods and services ultimately purchased by consumers and businesses. Alternatively, other technologies are used in the provision of public goods and are most frequently used by government agencies and other nonmarket organizations. In exploring how countries may effectively diffuse technologies from abroad, Sachs concludes that "the most effective strategy for that purpose has been the integration of the national economy into world production. Countries that have been able to attract foreign direct investment in export-led sectors have been the most successful in achieving rapid technological upgrading."

Hutchinson (2006) cites a large literature exploring the claim that technology transfer is more likely if recipient nations have strong intellectual property rights. He notes the finding that IP protection facilitates trade flows of patented goods into large and middle-income nations, but has no impact on poor countries. In a similar vein, Park and Lippoldt (2008) empirically analyze the impact of strengthened IPRs in the developing world. The study finds that technology transfer is enhanced by stronger levels of patent protection, while acknowledging the necessity of complementary factors such as infrastructure, effective government policies and regulations, knowledge institutions, access to credit and venture capital, skilled human capital, and networks for research collaboration. (Park and Lippoldt 2008, pp.28-29)

In a study on the role of education in innovation adoption in agriculture Lin (1991) explores why education has a positive impact on the adoption of new technology. While a new technology may generate higher productivity or reduce costs, "the changes in the production process involved in the adoption of a new technology may bring risks resulting from imperfect information and the possibility of committing errors. Because education enhances one's ability to receive, decode, and understand information, . . . [it is]hypothesized that education may facilitate the diffusion of new technology."

Aubert (2004) identifies two global drivers for innovation in developing nations: the revolution in telecommunications and scientific advances. Telecom advances in particular have facilitated trade, reduced distance across the world, and linked the most remote areas to centers of commerce. These themes are echoed in Teece (1998) who points out that as global markets have become increasingly liberalized, trade barriers have been eliminated and restrictions on knowledge transfers have evaporated. Given this, firms are no longer able to earn extra-normal returns by capitalizing on trade restrictions. Combined with lower transportation costs, competition has increased and information about market opportunities diffuses virtually instantaneously. However, the impact is not entirely negative. Open trade regimes will facilitate the diffusion of knowledge and technology. As described by Hoekman, Maskus and Saggi (2004), "Firms should have undistorted access to capital equipment and imported inputs that embody foreign knowledge."

Beyond the studies that focus on effective dissemination strategies, a rich literature examines specific policy alternatives and technology attributes that may impact the dissemination of environmental innovations. A great number of studies are very briefly described here to provide an indication of what the body of work contains, and to provide a large set of resources for further investigation.

Early on Carraro and Siniscalco (1994) called for more modeling of technological change, particularly endogenous to the system. Several studies have since answered the call examining endogenous technological change. Bosetti et al. (2006a) formulate and calibrate a global model with economic and environmental policies, prices and endogenous induced technological change. The model could be applied to test alternative policy formations and alternate sets of assumptions. Van der Zwaan et al. (2002) present another model with endogenous technological change. In a similar vein, Buonnano et al. (2003) build an elegant model to test the cost and environmental impacts of the Kyoto protocol. They include exogenous policies and endogenous technological change. This model could be parameterized to test alternative policies.

Gerlagh and van der Zwaan (2003) present a CGE to estimate costs of limiting global temperature change, and include endogenous technological change. This piece extends the application in Gerlagh and van der Zwaan (2006) and may be useful for policy analysis. In another study, Gerlagh et al. (2008) simulate the response of research to environmental policy, recognizing that the optimal policy depends on the stage of the environmental problem. While the results are difficult to summarize here without a full mathematical model, their summary states it quite clearly: "In the early stages of an environmental problem, abatement research should be subsidized at a high level and this subsidy should fall monotonically over time to stimulate initial R&D investments. Alternatively, with a constant R&D subsidy, patents' length should initially have a very long life-time but this should be gradually shortened. In a second best situation with no deployment subsidy for abatement equipment, we find that the environmental tax should be high compared to the Pigovian levels when an abatement industry is developing, but the relative difference falls over time. That is, environmental policies will be accelerated compared to first-best." Since the piece is purely theoretical, its credibility would be strengthened with robustness tests for functional form at least.

Another collection of studies is focused specifically on the Porter Hypothesis and tests of its validity. Mohr (2002) builds a model in which the Porter hypothesis may be true. He draws a parallel to the infant industry argument. In another approach, Ricci (2004) builds a model in which environmental regulation can improve productivity and economic growth (supporting the Porter hypothesis). The avenues of impact are: increased productivity of inputs, better education, economies of scale in abatement, expectations of a better environment encouraging greater household savings and therefore cheaper investment, and stimulated overall R&D because it is a clean activity. Roediger-Schluga (2004) is a very readable survey of the evidence for the Porter hypothesis, from description of regulations and innovations to a review of the evidence on the determinants of innovations and diffusion of eco-innovations. He then outlines a possible policy configuration bringing the supply of regulation (politicians and bureaucrats) to the demand (or lack thereof, from firms and organizations and consumers).

Costantini and Crespi (2007) test the hypothesis that stronger environmental regulation creates a comparative advantage in those nations in the production of eco-innovation. They posit that the 'pollution haven' hypothesis is the opposite, where low regulation areas become low cost producers of all goods (but what about comparative advantage?). Using a 1996-2004 sample of 20 OECD exporting nations and their trade flows with 148 importing nations, they use a gravity model augmented with environmental policy variables to test the impact of regulation on trade flows in goods related to energy and energy savings alone. Environmental policy is proxied by CO_2 emissions, current environmental protection expenditures both of the public and the private sectors, the percentage of revenues from environmental taxes on total revenues, and public investments on environmental protection. Innovation is alternatively measured as the number of patents in the energy sector, the number of total patents from residents, or the percentage of research and development expenditures. The model could be tested more thoroughly in the estimation, but the general results show the expected signs (e.g. nations with more stringent environmental regulation had stronger exports of environmentally-related products.

An additional stream of work has grown up around the work of Nordhaus (1994), the source of the DICE (Dynamic Integrated model of Climate and the Economy) model. Nordhaus (2000) is the expansion of that original model to variations. Nordhaus (2002) is a description of the enhanced DICE models which include technological change. They can be calibrated to simulate policy alternatives on a regional or global level. Popp (2004) includes induced innovation in the DICE model, and permits simulation of alternative policy measures. Popp (2006) includes a backstop technology.

In a broader sense, economists have examined a variety of regulations and policy choices that impact technology transfer. The following studies are an excellent representation of this body of work. Wilcox (1984) shows that regulation and fuel prices impact the fuel efficiency of automobiles. Requate (1998) shows that comparing taxes and permits depends critically on the parameters, so the social preference on policy should be situation-specific. In a more recent study, Popp (2003) looks at patenting before and after the passage of the Clean Air Act in 1990. Patents before the Act acted more to lower costs than to increase environmental effectiveness, while innovations since then have had a marked impact on the effectiveness of scrubbers (flue gas desulfurization units). These results stem from the fact that between 1978 and 1990, new plants were required to install scrubbers that removed 90% of SO_2. Thus, innovation lowered the operating costs of scrubbers, but there was no need to improve the environmental effectiveness. In contrast, after the Clean Air Act of 1990, which started permit trading for SO_2 emissions, further reduction of emissions was rewarded by the ability to sell excess SO_2 permits.

Empirical work in this vein includes Rehfeld et al. (2006) analyze firm-level data in the EU to show that the certification of environmental management systems has a significantly positive effect on environmental product innovations. In another empirical study, Arimura et al. (2007) use 4200 firm-level observations across the OECD to study the propensity for firms to do environmentally-related R&D. In a simple Tobit estimation, they find that subjective perception of the stringency of environmental regulation is a strong predictor of environmental R&D. Firms with an environmental accounting system are likewise more likely to do more R&D. The availability of technical assistance programs is a strong contributor as well. Large firms (measured by number of employees), and firms experiencing sales growth are both more likely to do R&D. There is also a strong nation-specific effect. Montero et al. (2002) is a case study description and analysis of a market-based environmental program in Chile. The program was hampered by transaction costs, regulatory uncertainty, and incomplete enforcement, but still provided flexibility to adapt to new market conditions.

Finally, a large number of studies examine other aspects of dissemination theory. Cowan and Hulten (1996) review the case of technological lock-in which sidelined the electric vehicle. Bosetti et al. (2006b) use another calibrated model to find the relationship between R&D investments and learning-by-doing, between energy-saving and fuel-switching. There is a potential for applied sensitivity analysis here. In an empirical study, Frondel et al. (2004) use a survey of OECD data across 4186 firms and find that more than ¾ of all abatement measures adopted are for cleaner production rather than end-of-pipe reasons. Estimation results indicate that regulatory measures and the stringency of environmental policies are positively correlated with end-of-pipe technologies, while cost savings, general management systems, and specific environmental management tools tend to favor clean production. Naturally, there are differences across nations and between firms and industries. Brunnermeier and Cohen (2003) use panel data models across US manufacturing industries to find that between 1983 and 1992, environmental innovation responded very clearly (with a one-year lag) to increases in pollution abatement expenditures, but increased monitoring and enforcement activities related to existing regulations did not provide any additional incentive to innovate. They also found some empirical evidence that environmental innovation is more likely to occur in industries that are internationally competitive. They refer to similar conclusions by Lanjouw and Mody (1996) which considers an earlier time period, and Jaffe and Palmer (1997) whose analysis establishes that R&D expenditures rather than patenting are significant.

Alternative mechanisms

The body of literature comparing alternative mechanisms for the dissemination of environmental innovation is strikingly recent. The notable exception is Jaffe el at. (1995) which presents a good summary of the US industrial tradeoffs between productivity and environmental responsibility. Valuable studies that have appeared more recently include Press (2007), Kverndokk et al. (2005), Manne and Richels (2004) and Glachant et al. (2008). Press (2007) is a literature review of the impact of regulation on environmental protection, but also on competitiveness and innovation and capital movements. With a broader focus, Kverndokk et al. (2005) compare policies, carrot and stick, to implement least-cost innovations for environmental change. They raise the interesting point that subsidies to alternative energy on the grounds of spillovers may be welfare-reducing if they crowd out other just slightly less efficient or desirable technologies.

Turning to econometric models, Manne and Richels (2004) uses a CGE model to compare alternative models of pollution regulation. While Glachant et al. (2008) analyzes the effectiveness of The Clean Development Mechanism (CDM), a portion of the Kyoto Protocol which allows member industrialized nations to develop or finance projects in other nations in exchange for emissions credits. The analysis uses records on 644 registered projects, describing them and doing econometric analysis of their drivers. Their econometric analysis consists of a logit analysis of whether or not transfer occurred as part of the project, and they find that "transfer likeliness increases with the size of the projects, and transfer probability is 50% higher in projects implemented in a subsidiary." More work with this dataset is definitely warranted.

Importance of follow-on support, training

In many cases, the transfer of technology is only the beginning of the learning process. Environmental innovations, like other new technologies, may require significant amounts of on-going support, training and assistance with maintenance. The required skills for continued use and repair of new technologies should be considered at the onset of adoption. Aubert (2004) notes that "medium technology industries (such as automotive) are often more demanding in terms of required technical skills than high tech industries (such as electronics), because a large part of the components have to be produced locally, while high tech elements, of lighter weight, can be more easily supplied from abroad. In this connection, it is generally the industries supplying materials and components which benefit, on the domestic front, most from technology transfer and skill upgrading from FDI." In an industry specific example, Chandrashekar and Basvarajappa (2001) focus on the Indian food processing industry to describe the importance of downstream infrastructure and technologies. The authors point to the dearth of such elements as a significant barrier to the development of the industry and its export potential.

Conclusions and policy implications

The dissemination of environmental innovation is dependent on fostering a receptive environment and incentivizing the transfer of technology. A combination of market, regulatory and cultural conditions contribute to the arena in which dissemination and adoption take place. Fundamentally for technology transfer to take place in developing nations a number of obstacles must be overcome: uncertainty surrounding the costs and benefits of adoption, asymmetric information on the value of the innovation, financial and skill requirements, externalities, and regulatory barriers. The mysteries surrounding where and how quickly new technologies are adopted are being unraveled in a growing body of economic studies. Nevertheless, significant challenges remain and policymakers would be well advised to reduce uncertainty and operate with transparency as they endeavor to facilitate dissemination for developing nations.

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