Managing Human-Dominated Ecosystems

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The Global Environment in the Knowledge Revolution*

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1. Summary

Markets are a dominant force in the world economy, in many ways a force for change and progress. During the course of this century market economies have led the race for industrialization, overcoming planned economies and traditional agricultural societies. The rapid expansion of international trade during the second part of the 20th century[1] has led to an extensive extraction of resources in developing nations, resources that are exported and consumed mostly in industrial nations and traded often at prices which are below replacement costs. This pattern of North-South trade in resources underlies the main global environmental problems we face today: biodiversity destruction and the risk of climate change. As the century turns, the market itself is evolving. Two major trends, the knowledge revolution and global environmental stress, lead to new and different types of markets involving a combination of private and public features and to new global challenges[2]. Environmental markets and markets for knowledge-based products[3] will play a pivotal role in the new century. Together they are becoming a critical

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[1] Since World War II world trade increased at least three times more than world production, leading to the globalization of world trade. Even the USA, traditionally an isolated country, has more than doubled the proportion of trade to economic activity so that trade today accounts for 30% of US GNP.

[2] The agenda of the Program on Information and Resources (PIR) at Columbia University is addressed to these two major trends. This research was supported by the Sloan Foundation.

[3] Such as software or biotechnology products.

source of wealth and dynamics of the world economy, and could lead to the creation of a sustainable society. To realize the enormous potential of these new markets, new institutions are needed. This article proposes such new institutions, basing its analysis on a somewhat unexpected connection between intellectual property rights and appropriate property rules regarding the environment. Leading ecologists regard the genetical information encoded in biodiversity as representing the most important value of biodiversity, a form of intellectual property. This paper proposes a new regime for property rights that can encourage both an optimal production of knowledge and at the same time a sustainable use of environmental resources, to help achieve a wide diffusion of the benefits from both.

The vision ahead of us is that of a global economy which is very innovative in the use of knowledge but conservative in the use of resources, a society that is centered on diversity and human capital and offering the prospect of substantial economic progress without damaging the ecosystems that support life on earth.

2. The New Global Markets

Markets are a dominant institution in the global economy. As the century turns, however, the market itself is evolving. Two major trends are environmental markets and markets for knowledge. Environmental markets are starting to emerge as a response to global environmental concerns. The Chicago Board of Trade started trading emissions of sulphur dioxide (SO_2) following the US Clean Air Act and water markets are contemplated in California. The first global environmental market is being created: following our earlier proposal to the UN Framework Convention on Climate Change[4] the 166 nations who are parties to the Framework Convention for Climate Change (FCCC) agreed in Kyoto, December 1997, to create an international framework to trade carbon emission credits among industrial nations.[5] Related proposals were advanced in Barrett (1991 and 1992), Chichilnisky and Heal OECD (1994).

[4] Chichilnisky (1995a and 1995b).

[5] The countries involved in Article 17 of the Kyoto Protocol on emissions trading are mostly industrial nations. Our proposal differs from others in that it points out that differentiated property rights allocations are needed in emissions markets in order to reach efficient solutions in emissions trading. All other proposals consider the allocations of initial endowments as a matter of justice or ethical concerns for distribution. I advanced the proposal for the creation of an international framework for trading emissions permits at an international OECD conference in Paris, in 1993, and in 1994 at a workshop of "Joint Implementation and Beyond" organized under the auspices of the Global Environment Facility (GEF) with the participation of the members of the Bureau of the International Negotiating Committee of the Framework Convention on Climate Change (FCCC) at Columbia Business School in May 1994. In December 1995 the proposal for the creation of an International Bank for Environmental Settlements (IBES) that would organize and regulate emissions trading was presented officially at a keynote address to the Annual Meetings of the World Bank, Washington, D.C., and in various publications proposing blueprints for this trading regime, see Chichilnisky (1996a, b). In November 1997 The Rockefeller Foundation and the Global Environment Facility organized a workshop to discuss the creation of the IBES in Bellagio, Italy. In December 1997, Article 6 of the Kyoto Protocol, paragraphs 1 and 5, formalized the creation of such an international framework. The actual modalities, regulation and monitoring of the trading of emissions was discussed further at the Conference of the Parties (COP4) of the FCCC, which took place in Buenos Aires, November 1998. The PIR at the Columbia Earth Institute organized a follow-up conference for the UN FCCC in April 1999.

Markets for knowledge hold the key to the dynamics of the world economy: telecommunications and electronics, biotechnology and financial products, all involve trading products that use knowledge rather than resources as the most important input.

Markets for knowledge and environmental markets are unusual because they trade a different type of good, which I call "privately produced public goods". These are different from the private goods that characterize traditional markets. With private goods—such as apples or machines—traders can choose what they wish to consume independently of each other. Knowledge and environmental goods are different: the planet's atmosphere is the same for all, and knowledge can be shared without losing it. As explained below, knowledge and environmental assets are not private goods but rather privately produced public goods. Markets trading such goods will be important in the future, because knowledge and environmental resources are key trends in the world economy. These trends lead the transformation that I call the "knowledge revolution"®.

Focusing on these new markets, I analyze here the introduction of new institutions and the policies that can lead the transformation of industrial society into a sustainable society. I focus on a new type of economic organization, involving markets that trade a mixture of private and public goods. These new markets require new regimes of property rights, also proposed here. They carry with them the seed of a society which encourages the creation of knowledge, and could lead to a better use and distribution of knowledge and of the world's natural resources.

3. The Global Environment

The rapid pace of industrialization since World War II contributed to biodiversity depletion and to an unprecedented level of greenhouse gas emissions, both of which have become global concerns. Industrialization is based on energy. All over the world energy has been, and continues to be, based on the burning of fossil fuels, and the attendant emission of carbon dioxide. Scientists now know that carbon and other greenhouse gas emissions can cause climate change. After many years of searching for the causes, a consensus is emerging that industrial activity is the fundamental driving force of human-induced climate change. The success of international markets in propelling industrialization has magnified the use of fossil fuels and other natural resources worldwide. By propelling industrial society forward, global markets have fostered an excessive use of natural resources and the attendant emissions.

The enormous growth in the international market plays a pivotal role in the environmental agenda because this market mediates the relationship between industrial and developing countries, the North and the South. The developing South specializes in resources, which account for 70% of Latin American exports and almost entirely for those of Africa, while the industrial North specializes in products intensive in capital and knowledge. With few exceptions, economic development can be read from the composition of a country's exports. The most successful industrializing nations, the Asian Tigers, have swiftly moved into technology-intensive products,

and have shaped their markets to fit their development needs. Those nations that have been left behind, mostly in Africa and Latin America, have followed resource-intensive patterns of development. The handwriting on the wall is clear: resource-intensive development is not reliable and generally does not work. It should be replaced by knowledge-intensive development. In other words: The knowledge revolution may be the only way into a sustainable future.

The origins of the global environmental dilemmas we face today, while complex, are not difficult to trace. They involve the historical coupling of two different worlds: the industrialized and the developing regions, the North and the South. Since the end of colonialism, international markets have perpetuated a pattern of economic development in which, as already pointed out, the world's less advanced countries play the role of resource producers and exporters. What is not generally known is that this pattern of trade is explained in great measure by the historical difference in property rights between the North and the South. It is well documented that countries in the latter hold most resources as common property; in industrial economies these are on the whole private property. Recently differences in property rights have been invoked successfully in explaining the fact that the South over-extracts natural resources for the international market, selling these below real costs.[6] As a result, the North overconsumes resources and the South overextracts them. In a world where agricultural societies trade with industrial societies, markets magnify the extraction and as a result exports of natural resources exceed what is optimal[6].

4. Ecology and Knowledge

A major challenge today is to find practical paths for sustainable development. This means finding ways to reorient consumption patterns and use of natural resources in ways that improve the quality of human life, while living within the carrying capacity of supporting ecosystems.[7] This requires building a future in which humans live in harmony with nature. We are far from this goal. In many ways the world economy is moving in the opposite direction.

Just as the environmental problems generated by industrial society are becoming a threat to human welfare, however, industrial society started a process of transformation. The rapid pace of this change has led me to call it a revolution. The change is centered in the use of knowledge and for this reason I call it the "knowledge revolution." What characterizes this so-called knowledge revolution?

The question is best answered in a historical context, by contrasting the current situation with the agricultural and the industrial revolutions, two landmarks in so-

[6] See Chichilnisky (1994a, b). An "agricultural society" is a society that has gone through the agricultural revolution but has not completed the stage of "industrial revolution," so most output is raw materials or agriculture. In the "industrial society" most output is industrial manufactures.

[7] This is the definition of sustainability adopted by the Bruntland Report (1987), and is anchored in the concept of development based on the satisfaction of "basic needs," a concept that was introduced and developed empirically in Chichilnisky (1997a and b). Sustainable development is explored also in Caring for the Earth, a joint publication of IUCN, UNEP and WWF.

cial evolution. Neither of the two previous revolutions (agricultural and industr is complete. Across the world we find today pre-agricultural societies populated nomadic hunters and gatherers, and most of the developing world is still within ag ian societies. While the two previous revolutions are still working their way throu human societies, knowledge is becoming a leading indicator of a third wave change. Knowledge means the ability to choose wisely what to do, and how to it. This ability is becoming the most important input of production, and the m important determinant of wealth and economic progress. The key input in t revolution, knowledge, resides mostly in human brains rather than in physical tities such as machines or land. It is worth pointing out that the important inpu *knowledge* rather than *information*. The difference between these two terms is difference between the computer industry, which is based on information techr ogy, and other sectors such as telecommunication, biotechnology and financial s tors, which involve knowledge rather than information technology itself. Informat facilitates knowledge, and inexpensive information fosters new knowledge. It been observed that the key value of biodiversity resides on its knowledge conte

It can be said that knowledge is the content and information is the mediu Knowledge is driving change, and this is facilitated by the medium, informati Information technology is like a fuel for knowledge. Its abundance and inexp sive supply fuels the growth of sectors such as communications, biotechnology a global finance. Information technology fuels knowledge sectors because it p forms the important role of allowing the human brain to expand its limits in production, organization and communication of knowledge. The most import input of production today is not information technology itself: it is knowledge

5. Characterizing the Knowledge Revolution

We may characterize the knowledge revolution as a period of rapid transition at end of which knowledge itself becomes the most important input of production, most important factor driving economic progress and wealth. For example, today knowledge content of biodiversity can improve public health and human welf and is identified as a crucial source of economic value. By contrast, in prior revo tions the most important inputs were land (in the agricultural revolution) and m chines (in the industrial revolution).[9] Knowledge differs fundamentally from land a machines in that it is not "rival" in consumption. More on this in Section 7 belo

The knowledge revolution is already with us. Indicators include the fact t the value of corporations in the stock exchanges of the world is increasingly m sured from their knowledge assets, such as discoveries, patents, brand names a innovative products, rather than from their capital base or physical assets. T means that knowledge-type assets (such as patents) are increasingly regarde

[8] According to leading ecologists such as E. Wilson and T. Lovejoy; presentations to the National Acad of Sciences.

[9] Both land and machines became better utilized because of new knowledge, but the main inputs of pro tion were then land and machines; now it is knowledge itself.

an important source of value of a corporation. At the level of the economy as a whole, knowledge of mathematics and sciences has become a good predictor of national economic progress across the world; an illustration is in Figure 1 below.[10]

In this period of change the USA leads the pack. Today more Americans make semiconductors than construction machinery. The telecommunications industry in North America (USA and Canada) employs more people than the auto and the auto parts industries combined. The US health and medical industry alone have become larger than defense, and also larger than oil refining, aircraft, auto, auto parts, logging, steel and shipping put together. More Americans work in biotechnology than in the entire machine tools industry. Most US jobs in the last twenty years were generated in smaller, knowledge-intensive firms driven by risk capital. In the US, one third of the nation's growth is accounted for by the knowledge sectors, see Figure 1 below,[11] so that knowledge is an increasingly important determinant of economic progress. The knowledge sectors of the US economy already grow several times faster than the rest of the economy, and account for much of the dynamics of its economic growth. Increases in personal spending in the US show the trend clearly. For example, key old economy items such as motor vehicles, major food appliances and clothing grew on average 2.3% in 1997-8, while key new economy items such as home telephone services, entertainment and recreation services, cable TV, brokerage and other financial services and home computers grew on average 12.5%.[12]

Knowledge sectors consume less resources and have less ecological impact than the rest; thus they could decrease environmental damage once they become dominant in the economy; see the figures below. The question is whether the pace and scope of this process of change will foster a sustainable society in a time scale that matters. Encouraging and accelerating this transition is key. The economic transformation depends among other things on the evolution of the new markets for knowledge and for environmental assets. These require special analysis since, as already mentioned, knowledge and environmental assets are privately produced public goods, leading to new types of markets with new challenges and new opportunities for action.

6. A Service Economy?

It is important to differentiate the knowledge revolution from a service economy which used to be thought of as the latest stage of the industrial society. A service

[10] Data from TIMSS: Third Mathematical and Science Study, American Federation of Teachers, American Department of Education.

[11] See also *Business Week*, "The New Economy: What it really means" by Stephen Shepard, Editor-in-Chief, November 17, 1997, p. 40, last paragraph.

[12] See also Business Week, March 23, 1998. This is despite the fact that current systems of accounting undervalue the contribution of electronics, which are extraordinarily productive and offer rapidly lowering costs for their products, so their weighting factor in GDP (market prices) decreases with time. In a nutshell: in the US knowledge products are rapidly becoming the most important input of production, source of value and economic progress. Similar statistics hold in many of the OECD nations. Development of knowledge sectors is slower in Europe than in the US because their financial markets and property rights systems are not as flexible and as well developed and regulated. This is discussed further below.

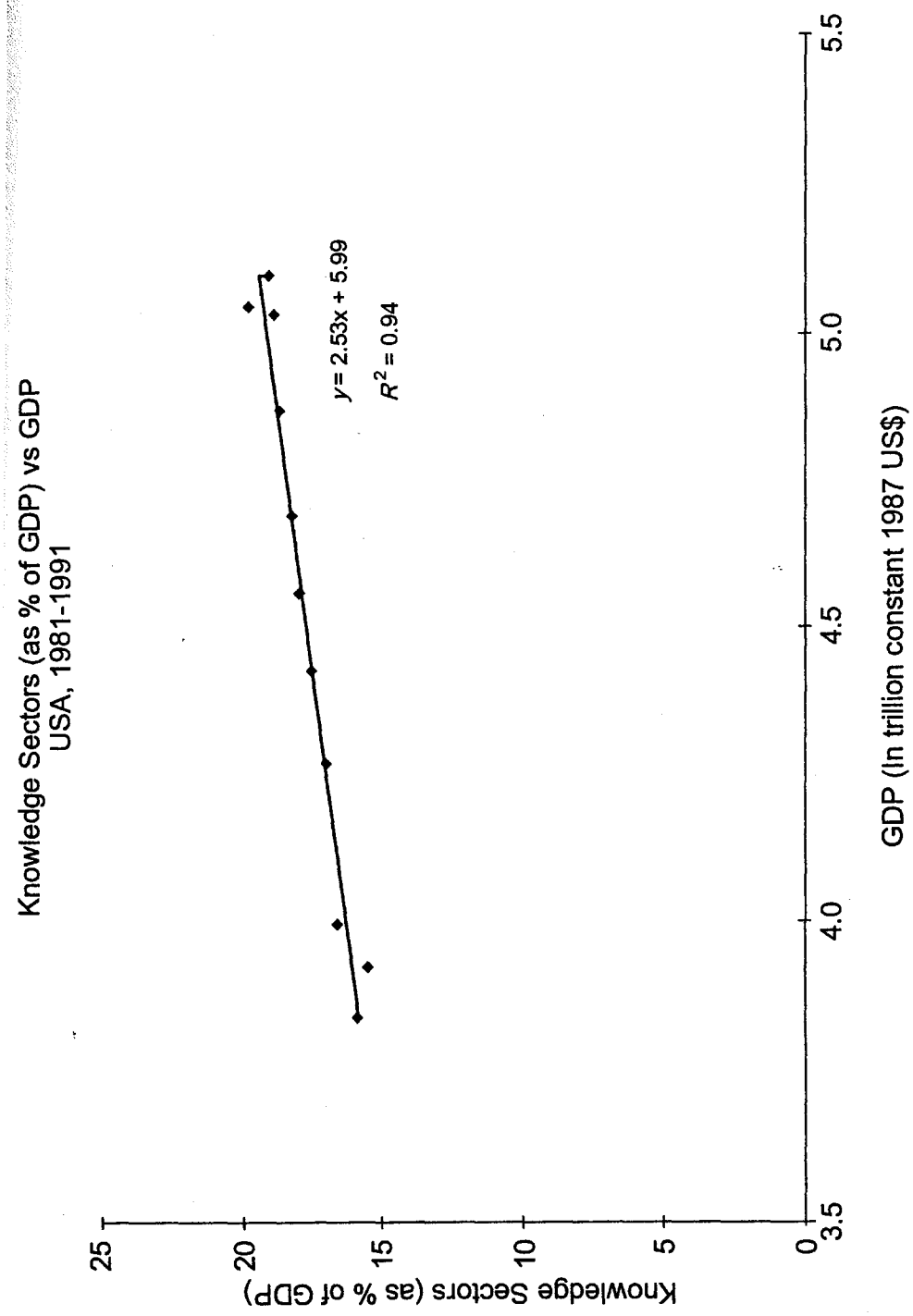
Knowledge Sectors (as % of GDP) vs GDP
USA, 1981-1991
y = 2.53x + 5.99
R2 = 0.94
Knowledge Sectors (as % of GDP)
GDP (In trillion constant 1987 US$)
25
20
15
10
5
0
3.5
4.0
4.5
5.0
5.5

Figure 1.

economy is characterized by the production of services more than goods, and it is similar to a knowledge economy in that knowledge sectors often involve services (such as finance). It is true that services now make up the largest part of advanced industrial economies. However the analogy ends there. An inevitable concern about the service economy is that it could lead mostly to service-oriented labor, such as the labor employed in the food services or in bank processing, requiring little skill and therefore leading to lower wages. The main difference between the service economy and the knowledge society is that in the latter the typical worker is highly skilled and generally well paid. Furthermore the worker's knowledge resides in her/himself and her/his brain and life experience, rather than in the machines that complement labor. Therefore the knowledge economy could result, with proper institutions, in a society that is more human oriented than the industrial or the service society.

A distinct possibility is that in the next century a new society will develop, one that is centered in human creativity and diversity, and which uses information technology rather than fossil fuels to power economic growth. The vision is a human-centered society which is deeply innovative in terms of knowledge and at the same time very conservative in the use of natural resources. The patterns of consumption and resource may not be as voracious as those in the industrial society, and may be better distributed across each society and across the globe. The knowledge society may achieve economic progress that is harmonious with nature. This vision is only a possibility at present. Without developing the right institutions and incentives this possibility may never come to pass, and a historical opportunity may be lost. We need institutions to bridge the gap between a grim present and a bright and positive future. The rest of this paper will address this issue, for which an economic analysis of knowledge and environmental markets is required.

7. Knowledge and Resources as Privately Produced Public Goods

A key connection between knowledge and the environment is that both are public goods that are produced privately. This unusual connection between "public" and "private" aspects can be fruitful in understanding the new institutions needed for a global economy where knowledge and environmental markets acquire increasing importance.

First observe that environmental markets often trade *public goods*, by which we do not mean goods available publicly but rather goods that are not "rival" in consumption. An example is the concentration of carbon dioxide in the planet's atmosphere. Carbon mixes uniformly across the entire world, and therefore its concentration is one and the same for all. In this sense the carbon concentration in the atmosphere is not 'rival' in consumption. The second distinguishing characteristic of environmental markets is that the public goods traded are not standard, since they are generally *privately produced.* By contrast, classic public goods, such as law and order, are produced in a public, centralized fashion: by governments. Many environmental goods are produced by individuals in the course of their everyday

life: for example, through driving cars and choosing to heat our homes we "produce" carbon emissions and therefore influence atmospheric quality. In brief: environmental markets involve *privately produced public goods.*

The parallel with knowledge is now immediate. As knowledge itself becomes the most important input to production in the knowledge revolution, the economy changes because knowledge is also a special type of good. It is called a *public good* by economists, because knowledge can be shared without losing it and is therefore not "rival" in consumption. This is a *physical* property of knowledge, not an economic property, and as such it is quite independent from the organization of society. Nevertheles, the economic rules governing the use of knowledge—for example whether patents can be used to restrict its use—can have a major impact on human welfare and organization; more on this below. Knowledge is also different from conventional public goods of the type that economists have studied for many years, such as law and order or defense, which as already pointed out are typically supplied by governments, in a centralized fashion.[13] While knowledge is a public good at the level of consumption, it is produced mostly by *private* individuals. At the level of production, therefore, knowledge is like any other private good: costly to produce, and the resources used to produce knowledge often cannot be used for other purposes. Producing knowledge requires economic incentives similar to those for producing any other private good.[14] Hence knowledge is a *privately produced public good*,[15] exactly as environmental goods often are.

8. Markets for Privately Produced Public Goods

If current trends persist and markets continue to be a dominant institution in the global economy, we can anticipate that markets for knowledge and environmental markets will acquire increasing importance. However both of these markets trade privately produced private goods and are quite different from standard markets.[16] Such markets require special institutional arrangements:[17] they are efficient under conditions which

[13] Classic work in the area of public goods by Lindahl, Bowen and Samuelson, as well as modern work on the subject, analyze public goods as government policy, rather than in the context of competitive markets; see e.g. Laffont (1977).

[14] It is important to observe that this refers to a purely physical characteristic that is independent of social arrangements, and certainly does not contradict the obvious fact that it is possible to obtain economic gain by monopolizing knowledge within a given institutional environment. It is equally possible to monopolize any public good (air, water) and obtain economic benefits from this if allowed by the social institutions. For example, a bandit can set up by the New York water source and collect for himself a fee from all of those who wish to obtain it until the law catches up with him or her. Patents allow some of this behavior for a limited period of time, which is why they are considered inefficient.

[15] Knowledge means knowing what to do and how to do it. I use here a technical definition of a 'public good,' which does not imply that it is offered by the government. Indeed, in today's societies, knowledge is mostly produced and traded individually.

[16] The study of markets with public goods was formalized later by Foley in a general equilibrium context. The foundations of the modern theory of privately produced public goods can be found in the excellent work of Laffont (1977).

[17] Several proposals have been made in this direction, prominently Lindahl's theory of markets in which different traders pay different prices, a theory which is theoretically flawless but usually fails on practical grounds.

are much more stringent than those under which ensure efficiency in standard markets;[18] see Laffont (1977). Unless they are properly regulated, markets with public goods will lead to inefficient allocation of resources. Economists have shown this to occur because there are "externalities" that are not properly "internalized". Such externalities drive a wedge between the costs from the benefits. Aligning costs and benefits is an essential feature in the successful performance of the market as an "invisible hand". For example, in the case of markets for emissions permits, each trader has an impact on everyone's welfare through their emissions, yet their private actions in choosing how much oil to burn do not take into account the benefits that their emission abatement could produce for others. This miscalculation leads the economy as a whole to underinvest in the public good. In our case, this leads to carbon emissions that exceed what is efficient or optimal. This may well represent today's problems of global atmospheric quality: each country benefits the entire world when abating their carbon emissions. Yet the benefits they receive are only a fraction of the total, thus leading to less abatement than would be optimal for the world[19]. The key to resolving this problem is to find a way to "realign" costs and benefits of environmental decisions as it is the case in private markets, so that those who suffer the costs are in a position to take the actions needed to achieve the corresponding benefits.

To solve the dilemma of inefficiency in markets with public goods, Lindahl suggested using an ingenuous institutional framework involving "personalized" prices, a solution that is theoretically correct but is widely regarded as unrealistic.[20] Another solution involves the government itself determining the quantity of the public good produced, rather than market forces.[21] However this solution does not work when the public goods are *privately produced.* For example, emissions are produced by individuals in the course of their private lives, in burning fossil fuels for transportation or for home heating. It is not reasonable to expect goverments to control how much people drive their cars, or how and how much they heat and cool their homes. Similarly, knowledge production cannot easily be controlled by government action. Therefore government determination of the allocation of privately produced public goods is also impractical, like personalized prices are. New solution are needed today.

9. Property Rights Foster Market Efficiency

This article proposes an alternative way of recovering efficiency in economies with privately produced public goods, one that has not been considered until now: a two-

[18] For private goods.

[19] See Heal (1999) for more details.

[20] In this scheme, different traders pay different prices, depending on how they value the environment in relation to private goods. He showed that when using such prices, markets reach efficient solutions. Lindahl's solution is considered unrealistic, because one trader can "buy" from another the right to pay less, therefore inducing arbitrage and defeating the purpose of charging according to the trader's values. Is scheme could lead to 'black market' operations, and to a totally different outcome from that intended, an outcome that is no longer efficient.

[21] The optimality conditions were also determined by Lindahl, Bowen and Samuelson.

part system involving (1) the creation of *competitive* markets for trading rights in the use of the public goods[22] coupled with (2) specific allocations of initial property rights in the use of the public goods. We show below that, when taken together, these two steps can achieve Pareto efficient allocations of resources in markets involving both private and public goods. Both steps are needed to achieve efficient solutions.

The first step proposed above, (1), is relatively well known and understood today for emissions. Examples are emissions markets where traders are assigned a quota on their emissions, which they can trade freely among themselves. In the case of knowledge, however, the examples are less well known. I propose below the creation of markets for compulsory licences in the use of knowledge such as genetical information encoded in biodiversity. Such licences are substantially different from patents, as explained below, and avoid some of their shortcomings. The traders are assigned initial quotas in the use of knowledge (e.g. a given number of licences) which can be traded at competitive market prices. Both of these examples, emissions markets and markets for licences, illustrate part (1) of the proposed policy, and are relatively straightforward.

Part (2) of our proposal is much less understood. The use of specific initial allocations for ensuring efficiency in markets with public goods is new. The fact that one can reach efficient solutions by specific allocations of property rights (called here "efficient" property rights) is a somewhat unusual observation. It is rigorously based on general equilibrium results which are reported in the Appendix. In the case of emissions markets the new results of Chichilnisky, Heal and Starrett (1993) and Chichilnisky (1993a) show that *some but not all* allocation of initial property rights lead to efficient allocation of resources in emissions markets. This is true even though these are competitive markets. In the Appendix we show that the same result holds in knowledge markets involving markets for compulsory licences which have a structure that is similar to emissions markets.

As already mentioned, the specific allocations of property rights that lead to efficient market solutions are called **efficient property rights**. For the reasons explained above, these property rights regimes are particularly important both in markets with knowledge and in environmental markets, both of which involve privately produced public goods. The knowledge revolution, with additional institutions, can solve global environmental stress. Hence the title of this paper.

The use of property rights regimes to induce efficient solutions is a realistic policy because many property rights on environmental use are still to be determined. Indeed, through the Kyoto Protocol, emission rights on a global scale are in the process of emerging. So are property rights regimes on knowledge or on biodiversity through the United Nations Biodiversity Convention. One hopes that there is still time to develop policies involving efficient regimes of property rights for the environment and knowledge.

[22] In a competitive market all traders face the same prices, so that what is proposed here eliminates Lindahl's markets with personalized prices. Government action in terms of choosing the total level of the public good, as proposed by Lindahl, Bowen and Samuelson, is also eliminated by our condition of competitive markets. Our solution differs therefore from previous ones.

What allocations of initial rights are likely to lead to efficient outcomes? A rule of thumb is that those who own fewer private goods should be assigned proportionately more rights to use the public goods. In other words: as shown in the appendix to this paper and in Chichilnisky (1993a) and Chichilnisky and Heal (1994) market efficiency often requires that the allocations of initial rights to use knowledge or resources should benefit proportionally more those who have relatively lower income. This is a novel result in economic terms, even though it has an intuitive appeal at the policy level. For example, most school systems treat preferentially lower income groups, which often have free or subsidized access to education or to professional training schemes. But this is usually done on equity grounds, not on efficiency grounds. What is unusual here is that we offer a rigorous explanation of why choosing initial allocations that favor lower income groups is important for market efficiency. This is a matter of efficiency, not a matter of ethics. As industrial economies evolve into knowledge economies, access to knowledge becomes essential in determining wealth and welfare.

The application of these results for the case of biodiversity is of special interest. By analogy with the emissions trading system, efficiency suggests that patents or genetical information be replaced by a system of compulsory, negotiable licences that are traded within competitive markets, and with initial rights allocated preferentially to lower income regions or countries. More on this below.

10. Property Rights Regimes for Environmental Markets

What are 'environmental markets' and how do they work? Environmental markets work by creating and allocating property rights on the use of environmental resources, local or global, and allowing them to be traded.[23] They encourage conservation by increasing the cost associated with resources, thus discouraging their use. For example, carbon dioxide markets assign a price to the right to emit the gas into the planet's atmosphere. Therefore they add a cost to the use of the atmosphere to emit greenhouse gases: This can be the cost of purchasing permits when one exceeds one's allotment. Or it can be the opportunity cost of using one's allotment rather than selling it at the market price. In all cases, environmental markets make resources more expensive and discourage their use. They can therefore induce more rational use of resources globally.

Environmental markets come in many forms. One can trade rights to the use of water bodies such as aquifers, or to the use of the atmosphere of the planet for disposing of greenhouse gases. Traders can be individuals or corporations. They can also be countries. Environmental markets already exist in the US: permits to emit sulphur dioxide are traded on the Chicago Board of Trade. Following the US Clean Air Act, electric utilities were assigned rights to emit SO_2 up to an overall

[23] This is an idea in the tradition of Coase: one of the earliest developments in environmental markets is Dales (1930), more recently e,g. Barrett (1992), Chichilnisky (1993a) and Chichilnisky and Heal (1994, 1995).

level. They were also given the ability to write contracts to trade these rights in open markets.

Environmental markets are a growing trend. In the Kyoto Protocol in December 1997, 166 nations endorsed the global trading of emission reduction certificates by industrial nations,[24] the first step in the creation of a global market for emissions trading. Article 17 of the Kyoto Protocol provides a new scheme, which is still in an embryonic form, following a proposal that was advanced to the diplomats of the Climate Conventions by the scientists of Columbia's Program on Information and Resources to the United Nations Framework Convention on Climate Change in May 1992.[25] This extended to a global domain the trading on sulphur emissions that emerged in the USA after its Clean Air Act, and opened a new era in market economics. Our proposal to the United Nations Framework Convention on Climate Change differed from others in that we showed that special allocations of rights to emit by different countries would be needed to achieve efficient allocations in competitive emissions markets.[26] Until then it was assumed that a competitive emissions market would be automatically efficient, and all considerations of allocations of property rights were restricted to the realm of ethical concerns for justice and redistribution. In showing that property rights allocations are a precondition for efficient emissions markets, we showed that these markets behave very different from standard markets where equity and efficiency are divorced from each other.

Environmental markets differ from standard markets in that the "invisible hand" must reconcile two major concerns in today's society: equity among the traders and the efficient operation of markets. As shown below both equity and efficiency are closely intertwined in environmental markets because these markets trade goods that have a combination of private and public features, where each trader's behavior is linked to the whole. The issue supports an intuitive concern for equity, which has been apparent in the environmental movement since its beginnings. The appendix provides results showing that such intuition is not misplaced.

11. Property Rights Regimes for Markets with Knowledge

To produce new knowledge, its creators need incentives. Incentives could involve artificial 'scarcity', by restricting the use of the knowledge by others. Patents on new discoveries work in this fashion, by restricting others' use of knowledge. This creates inefficiencies because any restriction in the sharing of knowledge is suboptimal, because knowledge can be shared at no cost. So restrictions on the use of knowledge are inefficient after knowledge is created. However, without some re-

[24] Formally Annex B nations.

[25] See Chichilnisky (1993a) and (1995b.)

[26] Because of the connection between efficiency and equity in emissions markets, we proposed the creation of an International Bank for Environmental Settlements (IBES) in 1993 to the UN Framework Convention on Climate Change, and made a similar proposal at an invited keynote speech the Annual Meetings of the World Bank in 1995.

strictions there may be no incentive to create *new* knowledge. I call this the paradox of knowledge. This paradox is at the heart of the success of the knowledge society, of its ability to bring human development for many and not only wealth for a few.

New property rights regimes are needed to deal simultaneously with the need to share the use of knowledge for efficiency, while at the same time preserving private incentives for production. The appendix contains a technical summary of how this would work in practice within competitive markets.

I propose substituting patents by a system of *licences* which are allocated in a specific way that ensures optimal use of knowledge, and which are then traded, in a *competitive* fashion, along with all other goods in the economy. In this new scheme, the right to use knowledge is unrestricted (licencing is compulsory) and by law everyone has access to it; however, users must pay the creator each time they use this knowledge. Since the licences are traded in competitive markets, they ensure that the creators of knowledge are compensated for their labor in a way that reflects the demand for their products and therefore their usefulness for society. Prices are uniform and set by competitive markets. Since licences are compulsory, they make knowledge available to all. In this sense, this regime differs fundamentally from patents because, in principle, patents can be used restrict the use of knowledge.[27] No restriction in the use of knowledge is allowed in the system I propose. However, a key issue is the initial distribution, property rights, use and applicability of the licences, to which we now turn.

It is clear that a system of licences on knowledge products (e.g. operating systems for software, biological information, how-to-do-it systems) could in principle preserve or even worsen today's uneven distribution of wealth in the economy. This is because the knowledge economy has a built-in incentive for the creation of monopolies. Indeed, any knowledge-based corporation is a "natural monopoly," a technical term used to indicate that the cost of duplicating knowledge products (such as a software products) is very small, and therefore the larger the firm the lower are its costs. This is an extreme case of "increasing returns to scale" where larger firms have an advantage over their competitors, and therefore can prevent entry by newer and smaller competitors. Such natural monopolies are frequent in the knowledge society. How to avoid concentrating knowledge in the hands of very few?

The system of property rights proposed here takes into account these possibilities. It establishes how the initial distribution of property rights on licences is a crucial element in achieving efficient solutions. The solution is to achieve a distribution of property rights on licences that is negatively correlated with the property rights on private goods, and beyond this to ensure that markets for knowledge act competitively. The results in the appendix make this proposal rigorous within a standard model of a market economy.

[27] Patents *can* be negotiated and licenced, but they do not *have* to be. Owners of patents are legally entitled not to licence their use, effectively creating a "monopoly" during the period of the patent's life. Compulsory licences do not create monopolies.

How can such a system of property rights become accepted? This concern parallels that proceeding the introduction of laws to ensure fair trade, a matter on which natural monopolies have offered and continue to offer much resistance and which is eventually overcome by society as a whole.

There are substantial economic incentives for corporations to accept fair trading and the systems of property rights that we propose, although more business education is needed before widespread acceptance. For example, those producers that benefit in principle from increasing returns to scale could support a system of licences in which the lower income segments of the population are given proportionately more rights to use knowledge than the rest. Consider as an example the case of worker training schemes. Because knowledge is so important for the productivity of society as a whole, and produces positive "externalities" on all producers, there is an incentive to develop a skilled pool of workers. Corporations know that the knowledge owned by skilled workers is essential to the success of their knowledge industries.

In a proposition presented in the appendix, it is shown that for an efficient market solution, one that cannot be improved so as to make everyone better off, lower income traders (individuals or nations) should be assigned a larger endowment of property rights in the use of knowledge. This means a larger amount of licences to use knowledge must be assigned to lower income countries or groups. The scheme is new but realistic. Similar systems are already in place in industrial societies. An example is the auctioning of use of airwaves by the US Federal Government in Washington, D.C.: minorities and women are given substantial discounts when they participate in auctions for the purchasing of property rights on the airwaves. In certain cases this involves a 40% discount of the auction prices.

12. Licences: We Make It, We Take It Back

The system of property rights proposed here, while unique in its economic formulation, is reminiscent of a development that is already taking place in the US corporate world. It is connected with environmental issues that have a public good aspect, such as the disposal of materials involved in heavy industrial products, vehicles and electronic equipment. Leasing vehicles (a form of licences for use) and electronic equipment is now a thriving business that hardly existed twenty years ago. For example, one of the largest packaging companies in the world, Sonoco Products Co., started taking its used products off customer's hands after its CEO Charles Coker made a pledge in 1990: "we make it, we take it back." The policy has already been adopted by the car industry in Germany, where car manufacturers are responsible for disposing of the vehicles that the customers return at the end of their useful life, due to environmental concerns. Another example arises in the floor covering industry. Ray Anderson, CEO of Atlanta-based corporation Interface, the largest maker of commercial carpeting, has set up as a goal to create zero waste while making a healthy profit, and takes back the used products that it sells to recycle them. The mission of

their businesses, all these business people say, is to sell licences to use *services*, rather than the ownership of products. In other words: rather than selling TVs, selling licences to viewing services; rather than selling vehicles, selling rights to use transportation services, rather than selling carpets, selling rights to the comfort and visual services that carpets provide. Licencing has the advantage that the producers have an incentive to minimize waste and environmental damage—for example, the waste produced by wrapping or by defunct car bodies—as they will be responsible for it. These business people see licencing services as the way to the future, particularly when they are confronted with paying for the disposal of industrial waste.

Implicit in this new system of property rights is an idea that we share: *licencing the use of services* rather than *owning the products that deliver those services*. The products in the corporate examples just described share another common characteristic with our economic approach: they have some of the characteristics of public goods that produce negative environmental "externalities." Knowledge, as we saw, also produces externalities, although positive.

Knowledge, as we saw above, has much in common with environmental assets: it is a privately produced public good. Knowledge products have been licenced for many years, although this has been done in a case-by-case manner, without securing the competitiveness of the market for licences, and without securing the distribution of property rights that would ensure efficient outcomes. In this sense, the new developments in industry reported here move in the same direction as the system of property rights, involving licences, proposed in the appendix and discussed above. *These new systems of property rights can be thought of as a step forward and institutionalization and economic formalization of licencing and leasing systems that have recently emerged in advanced industrial economies.*

13. Impacts of Property Rights on Knowledge

Rules to govern the use of knowledge lead to threats and opportunities for human development, both directly and through the possible changes in the patterns of consumption of goods and services. They can determine the impact of human societies on the environment and on resource use, as well as determine inequalities across the world economy. The way we use and distribute knowledge casts a very long shadow on human societies.

A historical comparison helps to explain this process. In agricultural societies the way humans regulated the ownership of land, which was then the most important input to production, led to social systems such as feudalism. Ownership of land had therefore a major impact on human welfare and on economic progress. Similarly in industrial societies the way humans organize the use of capital, which is its most important input of production, leads to very different social systems such as socialism and capitalism. Indeed, these two systems are defined by the rules on ownership of capital. In socialism ownership is in the hand of the gov-

ernments or other public institutions, and in capitalistic systems capital is in private hands. Property rights on capital have mattered a great deal, and have led to global strife in most of this century. Since capital is the most important input of production in industrial society, it is clear that property rights on capital had an enormous impact on the organization of society, on economic progress and on people's welfare.

Similarly in the knowledge society the way humans organize the use of knowledge, which is the most important input to production, will determine human welfare and economic progress across the world. This means that human institutions that regulate the use of knowledge, such as property rights and markets for knowledge, will become increasingly important. However, as we saw knowledge is a different type of commodity than land or capital: it is a public good. Markets with public goods, and other economic institutions such as property rights on public goods, are still open to definition and require much economic analysis. Markets themselves will operate differently in the knowledge economy, because the nature of the goods traded is different. There will be new challenges and new opportunities.

14. The Ecological Impact of Knowledge-Intensive vs. Resource-Intensive Growth

It is critical to distinguish two patterns of economic growth, two extreme cases of which are a spectrum of possibilities: economic development that is *knowledge-intensive*, and that which is *resource-intensive*. The former simply means achieving more human welfare with less material input. The latter means achieving more production by means of more material use. These two categories were introduced in Chichilnisky (1995a, 1994b).

There are excellent historical examples of the two patterns of development, and of the differences they induce on economic growth. As already mentioned, East Asian nations fit the knowledge-intensive paradigm, while Latin American countries and those in Africa, fit well the pattern of resource-intensive growth. On the whole knowledge-intensive development strategies succeeded, while resource-intensive development patterns lost ground. Chichilnisky (1997) studied the historical patterns focusing on East Asian nations that are now called the Asian Tigers, including Japan, Korea and Taiwan, and later those called the Small Tigers, such as Singapore, the Philippines, Hong Kong and Malaysia. These focused on exports of technology-intensive products such as consumer electronics and technologically advanced vehicles, and overturned the traditional economic theory of "comparative advantages." In contrast with East Asian nations, Latin America and Africa followed a resource-intensive pattern of development and lost ground.

15. Scenarios of Development in the North and the South

As already mentioned, the most dynamic sectors in the world economy today are not resource-intensive; they are, rather, knowledge-intensive, such as software and hardware, biotechnology, communications and financial markets (Chichilnisky 1994b, 1995a). These sectors are relatively friendly to the environment. They use fewer resources and emit relatively little CO_2. Figure 2 below illustrates this in the US economy. Knowledge sectors are the high-growth sectors in most industrialized countries.

Some of the most dynamic developing countries are making a swift transition from traditional societies to knowledge-intensive societies. Mexico produces computer chips, India is rapidly becoming a large exporter of software, and Barbados has recently unveiled a plan to become an information society within a generation (Fidler 1995). These policies are a natural extension of the strategies adopted earlier by the Asian Tigers, Hong Kong, Republic of Korea, Singapore, and Taiwan (Province of China), who have achieved extraordinarily successful performance over the last twenty years by relying not on resource exports but rather on knowledge-intensive products such as consumer electronics. By contrast, Africa and Latin America emphasized resource exports and lost ground (Chichilnisky 1994b, 1995a, 1995-1996).

The lessons of history are clear: not to rely on resource exports as the foundation of economic development. Africa and Latin America must update their economic focus. Indeed, the whole world must shift away from resource-intensive economic processes and products. In so doing, fewer minerals and other environmental resources will be extracted, and their price will rise. This is as it should be because today's low resource prices are a symptom of overproduction and inevitably lead to overconsumption.

Not surprisingly, from an environmental perspective one arrives at the same conclusion: higher resource prices are needed to curtail consumption.

Producers will sell less, but at higher prices. This is not to say that all will gain in the process. If the world's demand for petroleum drops, most petroleum producers will lose unless they have diversified into other products that involve fewer resources and higher value. Most international oil companies are investigating this strategy. Examples are British Petroleum and Shell.

The point is that nations do not develop on the basis of resource exports, and at the end of the day development can make all better off. As the trend is inevitable, the sooner the transition to the Knowledge Revolution, the better.

The data and a conceptual understanding of how markets operate lead to the same conclusion. Economic development cannot mean, as in the industrial society, doing more with more. It means achieving more progress with fewer resources.

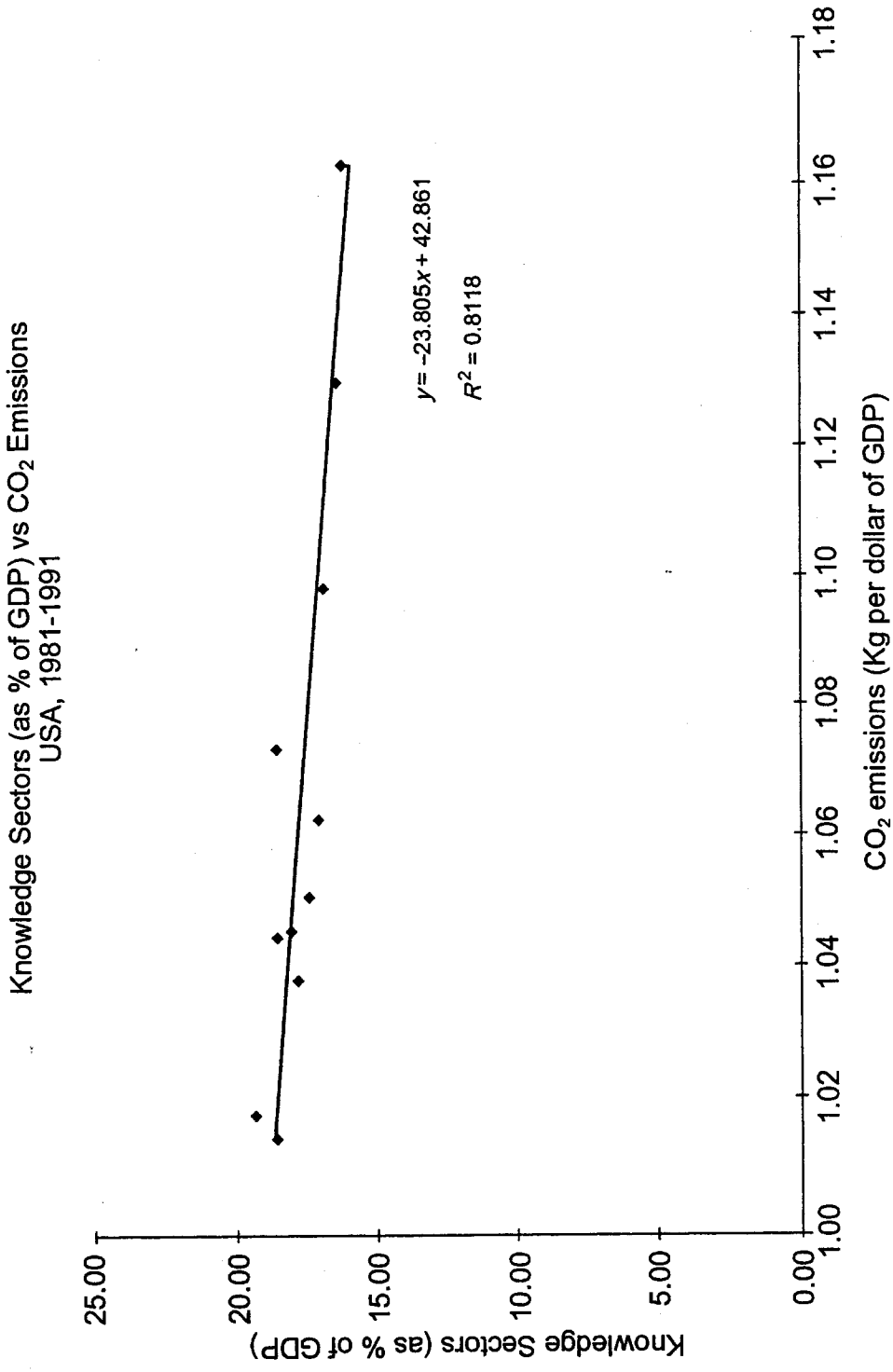
Knowledge Sectors (as % of GDP) vs CO_2 Emissions
USA, 1981-1991
$y = -23.805x + 42.861$
$R^2 = 0.8118$
Knowledge Sectors (as % of GDP)
25.00
20.00
15.00
10.00
5.00
0.00
1.00
1.02
1.04
1.06
1.08
1.10
1.12
1.14
1.16
1.18
CO_2 emissions (Kg per dollar of GDP)

Figure 2.

16. Policy Questions

(1) Should the World Trade Organization link environmental property rights to the trade regime? (2) Against the background of a free trade regime, is a movement in the direction of privatizing of resources always welfare improving? (3) What is the role of property rights on equity and efficiency? This section will offer answers based on the findings reported above and in the appendix.

It is well known that ill-defined property rights lead to resource overuse, and ultimately cause the destruction of the resource base itself. This has been called the "tragedy of the commons." Recently it has been shown that the commons problem is amplified by international markets (Chichilnisky 1994a, b). Since property rights on resources are lacking in the South, an expansion of resource trade may damage the environment and decrease welfare (Chichilnisky 1994a, b). In this sense, the pattern of North-South trade that we observe, which is largely responsible for the world's overuse of natural resources, originates from a historical situation involving the coupling of two types of nations through the international market: developing nations that have traditional institutions and common property rights on resources (the South) which are used as "open access" during the process of industrialization, and others with better defined private property rights on resources (the North).[28] Liberalizing international trade in this case amplifies the *tragedy of the commons* in the South: resources are overextracted and exported to the North at prices that are lower than optimal.[29] The North consumes more resources than is optimal.[30] The result is a misallocation of the world's resources, which are undervalued and overused. As already mentioned, this is a main source of the global environmental dilemma we face today. It explains the crisis in *biodiversity* destruction, and the problem of *climate change*. Both are based on the overuse of resources: forests in the first case, and minerals such as petroleum in the second. Both are overextracted in the South, exported at prices which are below real costs, and overconsumed in the North.[31] These results offer a positive response to questions (1) and (2) presented above. However, below we see that in certain cases the answer can be negative. One can say precisely when the answer is positive and when it is negative—more on this below.

[28] Although somewhat unconventional at the time, the Chichilnisky (1994a, b) results have become increasingly popular. They are based on economic theory and a historical fact: that industrialization proceeds by increasing privatization of resources. Natural resources such as forests, mineral reserves and biodiversity are often held as common property in the developing countries of the South, but as private property in the industrialized North. As a result resources in the South are used on a "first come first served" basis. The economic theory developed in my article explains that this leads to their overextraction and to a false impression of resource abundance and 'comparative advantage.' The reality can be quite different.

[29] Optimal prices are those that would prevail in the Pareto optimal solution: the equilibrium of a benchmark economy which is indentical to the one considered here but is perfectly competitive and has private property rights, see below.

[30] The definition of 'optimal consumption' parallels that of optimal prices: it is the consumption that would prevail in a general equilibrium model which is identical to that considered here but with no market failures.

[31] For data on this issue see *World Resources and the Environment* (World Resources Institute, 1994-5) and Chichilnisky (1995-6) "The economic value of the earth's resources."

This historical interpretation of the environmental problems we face today leads to another natural question: would it suffice to privatize natural resources in the South in order to resolve the overuse of environmental resources across the world? We identify below in which cases it does, and when it does not. In the former case the World Trade Organization should link environmental property rights to the trade regime and in the latter case it should not. This also gives an answer to questions (1) and (2) posed above. More precisely: privatizing in the South—namely the creation of private property rights on environmental assets—may not by itself solve the problem of overuse of natural resources in the world economy.

- In nations with common property regimes, international trade can lead to the *underuse* or to *overuse* of resources. The outcome depends on whether the common property regime affects inputs or outputs. Environmental assets are usually inputs, which is the reason liberalization does not work. In the case of outputs, for example software, the situation can reverse the outcome.
- Within free trade regimes, privatizing may or may not improve welfare. It can fail to do so when the goods privatized are environmental assets. Examples include the global market for carbon emissions created recently by the Kyoto Protocol.
- The distribution of property rights among the traders can be decisive in achieving efficient outcomes. Giving more rights to lower income groups can increase overall efficiency. This is relevant for the global negotiations in climate change.

These issues are analyzed in the appendix within a model of North South trade similar to one introduced in 1981(Chichilnisky 1981, 1994a). This differs from a standard trade model in that resources in the South are held as common property.

Below I draw also on historical evidence for these new questions, involving contemporary history. In Kyoto, December 1997, 166 nations agreed to assign ceilings on industrial countries' emissions of greenhouse gases, i.e. property rights on the use of the atmosphere,[32] and on a system of trading these property rights that I proposed in 1994 to these policy makers.[33]

17. Are Emissions Markets Efficient?

Consider a resource which is extracted from a *commonly owned pool* in the South: for example, petroleum residing on national soil. According to Chichilnisky (1994),

[32] The so-called Annex 1 countries.

[33] I.e. the Bureau of the International Negotiating Committee (INC) of the Secretariat of the Framework Convention of Climate Change (FCCC). As mentioned above, this proposal was presented at a seminar sponsored by the Global Environment Facility (GEF) and organized by the author and Professor G.M. Heal at Columbia University School of Business in May 1994. In December 1995 the proposal was officially presented at a keynote address to the Annual Meetings of the World Bank, and it was subsequently published under the auspices of UNESCO and UNDP in September 1995, see Chichilnisky (1995b).

this would lead to excessive extraction of petroleum in the South and to its specialization in petroleum even when it has no comparative advantage; to lower international prices for petroleum, and to overconsumption of petroleum in the North.[34] An example that comes to mind is Mexico trading with the US. Mexico exports petroleum to the US but is known to have rather shallow reserves that are expected to run out soon in the next century. The US imports most of its petroleum from Latin America (Mexico, Venezuela and Ecuador) and its consumers pay prices that are 2.5 times lower than those paid by their German or Japanese counterparts. Corresponding to this, the US consumes today about 25% of all petroleum produced in the world and is less efficient in the use of petroleum (about 40% less) than is Germany or Japan. At the same time the US generates 25% of all the carbon dioxide emitted in the world. Not surprisingly, it has been a reluctant party in the global climate negotiations to decrease carbon emissions.[35]

The following formalizes the introduction of property rights, and shows how this may not lead to Pareto efficient outcomes. In the example just described the price of petroleum extracted from a common property pool is too low when compared with a benchmark economy with private property rights on the resource pool. The common property problem may be difficult to correct because governments in the South own the soil in which the resource resides, and sovereign rights make it difficult to interfere. Alternatively, petroleum reserves may be shared by several landowners who own the land, a case covered by the US Hot Oil act. This case would require new legislation within the country, and there may be difficulties in interfering with sovereign legal institutions. In any case, because of common property rights there is an excessive extraction of oil. Corresponding to this, there are excessive emissions of carbon dioxide, which are a byproduct of burning fossil fuels.[36]

While property rights on the soil may be difficult to change, it is possible to address directly the problem of excessive emissions of carbon dioxide. This can be achieved by an international agreement fixing a total ceiling on emissions, and giving to each country or region a right to emit that adds up to this total. Regions can trade their rights among themselves. Such a procedure amounts to assigning private property rights on the use of the atmosphere to the regions, and allowing them to trade.

This procedure could resolve the problems emerging from the common property of oil, by assigning property rights on the emissions of carbon which are associated with burning oil. The result would be the creation of an international market on carbon emission rights. This is what in contemplated in the Kyoto Protocol: 166 nations have agreed to this solution for Annex I countries in December 1997.[37] The question is whether this solution leads always to efficient allocation of resources.

[34] All compared to the benchmark case that is, as discussed above, taken as the 'optimal.'

[35] Annex I nations, see Article 6 of the Kyoto Protocol.

[36] The term 'excessive' means, as before, exceeding what is optimal under an optimal solution corresponding to a private property rights regime.

[37] See Article 6 of the 1997 Kyoto Protocol.

The answer is generally negative: the solution is typically not Pareto efficient, although there are cases where efficiency is obtained.

To understand why the solutions may not be efficient consider the simplest case: a North-South economy where each region produces one good y using one input of production x: energy (petroleum). The more energy is used, the more carbon dioxide CO_2 is emitted, i.e. the less is 'abated,' and the higher is the concentration of carbon dioxide in the atmosphere. Carbon dioxide diffuses very uniformly and stably, taking from 60 to 100 years to break down. As a result the whole world is exposed to the same atmospheric concentration of CO_2. Define the level of abatement or 'quality of the atmosphere' a as the inverse of the concentration of carbon dioxide: the more carbon is emitted, the worse is the atmosphere's quality.

Better atmospheric quality means a more stable climate and therefore more welfare, so the utility functions of the regions increase in a; they also increase with the level of consumption of goods, y. In this situation, atmospheric quality is a public good which is available to everyone in the same 'quantity,' and is therefore not 'rival' in consumption.[38] However a is not produced by the government as are classic public goods such as law and order. The quality of the atmosphere a is a *privately produced public good* because driving a car, or using energy are private activities. Every individual in the North-South economy affects the composition of the atmosphere, and in this sense 'produces' the public good a. For the purposes of this section, the most relevant aspect is that due to its physical characteristics[39] a is available to everyone in the same amount: individuals cannot choose different atmospheric qualities. This links closely the consumption of different individuals in a way that does not occur with standard private goods, and requires special allocations of property rights in order to reach efficient solutions.

In a nutshell: despite the privatizing of the global commons (the atmosphere) a competitive equilibrium of the North-South model may or may not satisfy the additional Lindahl-Bowen-Samuelson condition for efficiency which derives from the fact that a is a public good. Therefore:

- Despite the privatizing of atmospheric use, the competitive market equilibrium may not be Pareto efficient. This is due to the physical characteristics of the atmospheric concentration in CO_2, which is the same across the planet, thus making a a privately produced public good. Property rights policies can lead to efficient solutions.

To show how an equilibrium in these markets may be Pareto inefficient, it suffices to provide an example. In the following diagram 1 the first market equilibrium is Pareto inefficient: this is shown by exhibiting a second market equilibrium in which both regions, the North and the South, are both strictly better off. The horizontal

[38] This is a definition of a public good.

[39] CO_2 mixes very thoroughly and stably across the planet's atmosphere, so its concentration is the same the world over. Sulphor dioxide does not have this property.

axis denotes quantities of the private good y_i and the vertical axis measures abatement a_i and the quality of the atmosphere, a. Here $i = 1, 2$ denotes the region (North and South). There is an initial allocation of emissions rights as indicated in the vertical axis for the North and the South. The first equilibrium has permit prices denoted "initial prices"; at those prices each region maximizes profits by producing at the respective levels of initial production, and using energy corresponding to an abatement level denoted initial abatement. At the initial allocation the North has an excess of permits which it sells to buy additional private goods; region one exports permits to import private goods, and the opposite is true for region two. At an equilibrium both markets clear. This equilibrium is inefficient in the sense that both regions can be made better off within the existing ceiling on emissions, as shown in the diagram. The first situation depicts a situation similar to a prisoner's dilemma, in that both traders are in an inferior position. A second initial allocation of rights corresponds to a lower ceiling on emissions and leads to higher utility levels for both regions, thus moving the traders to a Pareto superior position. Note that in the second situation more rights to emit are given to the South and fewer to the North than in the first, and *the total level of emissions in the second equilibrium is within the limits of the first equilibrium, but the welfare of both traders is higher in the second equilibrium.* This example illustrates why privatizing may not lead to Pareto efficient solutions, as we wished to show.

In the diagram 1 provided below there are two ceilings on emissions; a second lower ceiling on emissions is allocated between the North and the South in a manner that favors the South, leading to increased efficiency for both North and South. This example illustrates the connection between the initial rights and the efficiency of the market.[40] This is in contrast with the standard markets with private goods, where *any* initial allocation of property rights leads to efficient outcomes.

The result is somewhat surprising in two ways, each pointing in the opposite direction from the other. For environmental economists, the result is surprising because markets with emission permits are generally thought to be efficient independently from the distribution of initial endowments.[41] This is true for certain types of emissions which can be treated as private goods, such as the particulates that tarnish laundry appearing in a well known example developed by R. Coase. But the physical characteristics of carbon emissions change the nature of the problem, since the atmospheric concentration of carbon, as discussed above, is a public good. In this case Coase's arguments do not work, and efficiency can be lost. This observation explains the difference between the results presented here and Coase's results, but makes the results surprising for another reason. The second reason is that markets with public goods seldom have Pareto efficient equilibria. This is a well known fact for

[40] A general result along these lines was obtained by Chichilnisky, Heal and Starrett (1993): they established that there exist a small set (measure zero) of allocations of property rights from which a market trading private goods as well as privately produced public goods achieves a Pareto efficient allocation.

[41] See for example Chapter 3 of Baumol and Oats's excellent book on the subject.

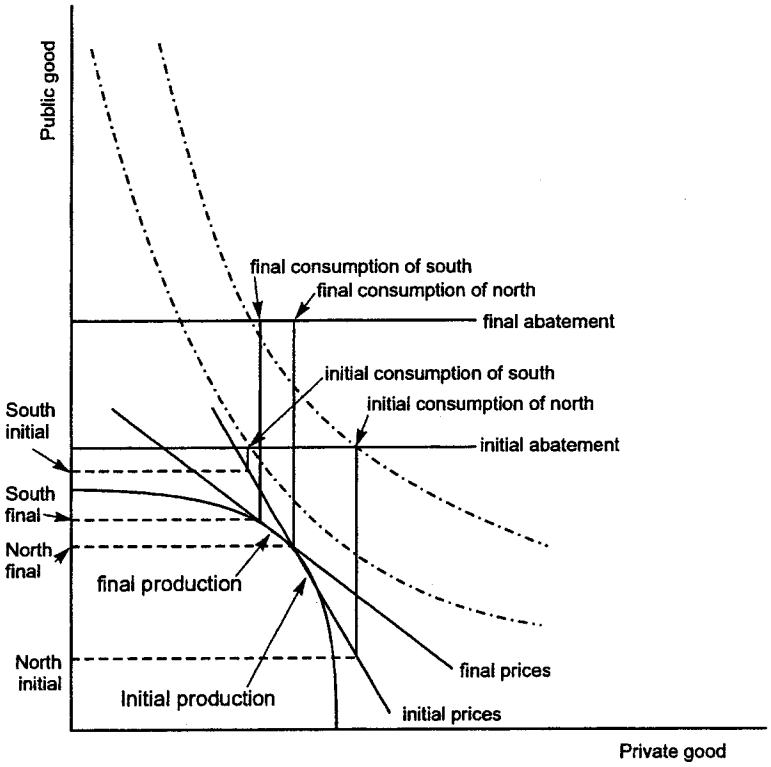

Diagram 1.

public economists. General results in this area until now are due to Lindahl and later Foley within a general equilibrium context, involving in both cases an extension of the market to include 'personalized' prices. Lindahl's solution requires that prices should reflect the characteristics of the traders, effectively multiplying the number of prices and equations in the market by the number of traders. As already mentioned, this allows 'arbitrage' by which traders 'sell' to each other the use of their personalized prices.

A classic result is that with personalized prices, markets with public goods always reach Pareto efficient allocations. The result obtained by Chichilnisky, Heal and Starrett (1993) suggests that rather than using personalized prices (and therefore introducing a large number of markets) one can reallocate property rights and obtain generically first best Pareto efficiency. Diagram 1 above illustrates how reallocating property rights among the two regions can improve efficiency and benefit both the North and the South.

18. Equity and Efficiency

We saw specific cases where privatizing does or does not lead to efficient outcomes. The free market solution may leave room for improvement for both the North and

the South. International coordination can therefore lead to superior outcomes for all trades.

The following diagram 2 takes a particularly simple case and develops a 'thought experiment' that helps to see why efficiency requires that those with lower endowments of private goods should generally be given a larger endowment of the public good—in this case, more rights to emit. The diagram is an Edgeworth box in which two traders trade two goods. In the standard case, every point in the box is an allocation of private property rights that, after trading takes place, leads to a Pareto efficient market equilibrium in the 'contract curve'. Now consider a new economy, where one of the goods is a public good, measured on the vertical axis. Now most of the efficient allocations on the contract curve cannot be realized in practice, because they involve traders using different amounts of the public good which is physically impossible. Therefore we must restrict our attention to those allocations within the contract curve in which both traders consume the same amount of a. Now observe that the initial endowments of rights that lead to such allocations allocate more public goods to those who own fewer private goods, as they are located on the budget line which is negatively sloped.

The inverse relation between property rights on private and public goods that was just discussed, and that is needed for efficiency, could play a useful role in the follow-up to the Kyoto negotiations.

Several countries have expressed the need for a policy of so-called "differentiation" involving the need to spread equally the burden of abatement. Australia advanced such a proposal in 1998; within the European Union such differentiation has already been incorporated: countries such as Portugal can increase their emissions by 40% while the December 1997 proposal for the entire EU was to decrease its overall emissions by 15%. This proposal to share the burden equally is consistent with the inverse connection between rights to emit and rights to private goods explained here. Our result is based on efficiency, e.g. the desire to achieve the agreed reductions on emissions with the minimum loss of welfare. The main point of this section is that these two issues, equity and efficiency, are closely connected in a market with privately produced public goods. This could lead to a valuable source of common interest between North and South as the negotiators assemble in The Hague in November 2000.

19. People-Centered Development: Opportunities and Threats

The knowledge revolution could develop in different ways, depending on the way our institutions and policies unfold. Knowledge has the capacity of amplifying current discrepancies in wealth, because it can lead to natural monopolies such as those that arise due to the adoption of operating systems[41] or other standards. In the North-South context, knowledge sectors could amplify the differences in wealth between the North and the South. If this occurs, then the low resource prices from developing countries will persist, since they are caused in part by the necessity to

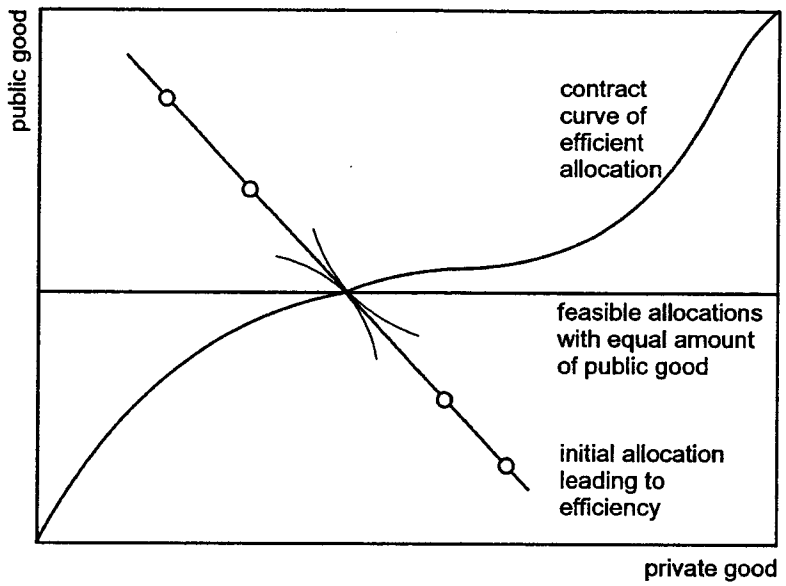

Diagram 2.

survive at low income levels within a difficult international market climate. It has been shown that with current institutions of property rights, anything that leads to more poverty leads to increased resource exports from developing countries (Chichilnisky 1994a).

On the other hand, knowledge sectors could flourish in those developing nations that have skilled labor. Several developing nations are, or could be soon, in that position. For example, the Caribbean and Southeast Asia are a case in point, as are many areas in Latin America (Harris 1994).

The main issues are to

- abandon the resource-intensive development patterns that these nations have followed for the last fifty years, with the support and encouragement of the Bretton Woods institutions such as the World Bank and the IMP, and
- seek to establish the institutions (property rights, financial structures) that could lead them to overcome the "comparative advantages" mirage, avoid the heavy stages of industrialization, and "leap frog" into the knowledge society.

Heavy accumulation of capital (financial or physical) is not needed for most knowledge sectors. What is needed is highly skilled labor, of the type that does not require expensive machinery or heavy capital investment in plants, and good managerial ability, all knowledge inputs that rely on a pool of abundant skilled labor. A good example is Bangalore, India's software industry, which produces about $2 billion of exports today.

20. Conclusions

Market-driven industrialization and the historical differences in property rights on resources in the North and the South are at the core of today's environmental problems. Almost paradoxically, markets could be part of the solution. In many cases, new markets for knowledge and environmental markets could help achieve a sustainable economy, and alleviate some of the worse imbalances in the distribution of global welfare, provided new regimes of property rights are adopted. This article suggests what forms these new property rights regimes could take.

Knitting together several issues into a coherent whole, this article has suggested responses to the following questions: Why has the global environment become such a concern today? What has led to a worsening of the environmental problem in the last fifty years? The response here is the tremendous success of the industrial revolution and its voracious appetite for energy. Are the developing nations, indeed the poor people of the world, central to a resolution of the problem? What are the connections between equity and efficiency in markets for knowledge and resources? The response here is that the overuse of natural resources is a North-South issue, deriving in part from differences in property rights over resources in the two regions. What is the role of international markets? Under today's conditions will the trend towards trade liberalization lead to a sustainable use of the world's resources? What policies are more likely to lead to a new form of industrialization that is innovative in the use of knowledge and conservative in the use of resources? What policies are more likely to lead to a new form of industrialization that is innovative in the use of knowledge and conservative in the use of resources? The response here are the new institutions such as licences for the use of knowledge and the environment, suggested here.

21. Appendix

21.1. The literature

Markets with privately produced public goods were studied by Laffont (1977) and others in a partial equilibrium world. This appendix looks at the problem in a general equilibrium framework, namely when all markets, for private and public goods, occur simultaneously and interact. The problems that occupy us here are not new, but the solutions proposed here have not been proposed before. The results presented below build on recent results in Chichilnisky (1993a), Chichilnisky and Heal (1994) and Chichilnisky, Heal and Starrett (1993) and Chichilnisky (1996c, 1997a). The main results are the connections that emerge between efficiency and the distribution of property rights in markets with privately produced public goods. This connection represents a major departure from standard markets, in which equilibria are always efficient. Here the distribution of property rights matters. It is decisive in ensuring that the market achieves efficient allocations.

21.2. Efficient ways of privatizing the atmosphere

This section demonstrates that even if the use of the atmosphere is privatized, and the rights to use it are traded in a competitive market, the solutions may not be Pareto efficient, showing how different initial allocations of property rights help achieve efficient allocations. The general equilibrium methodology used in Chichilnisky (1994a) is modified to incorporate these issues following Chichilnisky and Heal (1994) and Chichilnisky, Heal and Starrett (1993).

21.3. Environmental markets

A world market economy in which emission rights are traded along private goods is modeled as follows. There are two regions, North and South denoted by $i = 1, 2$. In each region there is a production function converting energy into private goods,

$$y = \phi_i(a_i),\ i = 1, 2.$$

This leads in each region to a production possibility set exhibiting a tradeoff between more production of consumption goods, y, and a real number a_i measuring abatement or decrease in emissions and thus a better atmosphere and climate:

$$\frac{\partial}{\partial a_i}\phi_i(a_i) < 0,\ \ i = 1, 2.$$

The welfare of each region is represented by a utility function depending on two variables, consumption of private goods y, and the public good a, $u_i: R^2 \to R$, which is an increasing function of both. There is the same level of atmospheric quality in both regions, corresponding to the sum of abatement in both regions denoted, $a = \sum_{i=1}^{2} a_i$:

$$u_i(y_i, a) = u_i\left(y_i, \sum_{i=1}^{2} a_i\right),\ \ i = 1, 2.$$

Each region is assigned initial property rights $\bar{a}_i$, $i = 1, 2$, on the use of the atmosphere so as not to exceed a total internationally agreed ceiling $\bar{a}$:

$$\sum_{i=1i}^{2} \bar{a}_i = \bar{a}.$$

Under this assignation of *property rights*, region i can use an amount of energy (petroleum) that abates $\bar{a}_i$ of carbon dioxide. The amount of energy used by region i is denoted a_i; if the region uses more energy and emits more carbon than its rights allow, i.e. if $a_i \leq \bar{a}_i$, then it has to purchase 'permits' to emit, namely the difference $\bar{a}_i - a_i$; if instead the region uses less energy and emits less carbon than $\bar{a}_i$ it can sell the excess permits to the other region, namely $a_i - \bar{a}_i$.

The price for goods is set equal to one, and the (relative) price of permits is denoted π. The price π is set by market forces as the price that clears all markets, for goods and for permits.

A market equilibrium is defined as follows. Each region $i = 1, 2$ chooses how much energy to use, respectively how much to abate, a_i, with the aim of maximizing utility. The region can afford to consume what it produces plus what it can purchase from the sale of unused permits, or minus what it spends on the purchase of additional permits. Markets are competitive, so the relative price π is taken as a given by each region.[42] Formally: in a market equilibrium each region chooses how much to abate a_i so that to maximize the utility of consumption of y

$$Max(u_i(y_i, a)), \tag{21.1}$$

where the value of consumption y_i satisfies

$$y_i = \phi_i(a_i) + \pi(\bar{a}_i - a_i), \tag{21.2}$$

i.e. y_i equals the value of production plus (minus) the value of exports (imports) of permits. In an equilibrium all markets clear:

$$\sum_i a_i = \bar{a}. \tag{21.3}$$

In summary: the North-South model is defined by giving four parameters and several behavioral rules. The four parameters are property rights and technologies: a_i and ϕ_i, $i = 1, 2$. The equations formalizing the behavior of the economy are 21.1, 21.2 and 21.3. The solutions to these three equations define a market equilibrium for the North-South model, and determine the value of the following variables:

- energy (permits) used by each region, a_i, $i = 1, 2$.
- goods produced by each region, $\phi_i(a_i)$, $i = 1, 2$.
- goods exported (imported) by each region, $y_i - \phi_i(a_i)$, $i = 1, 2$.
- permits imported (exported) by each region, $\bar{a}_i - a_i$.
- price of permits π.
- welfare levels in the two regions, $u_i(y_i, a)$, $i = 1, 2$.

It is now straightforward to verify that although the use of the atmosphere has been privatized, and the rights to use it are traded in a competitive market, the solutions may not be Pareto efficient. The reason is that, due to its physical characteristics, the atmospheric quality a is a public good which is available to all in the same amount, thus linking the consumption of the individuals and presenting a more demanding situation from which to reach efficiency. In particular the Lindahl-Bowen-Samuelson conditions for first best optimality in the allocation of public goods are needed *in addition* to the market equilibrium conditions (21.1),(21.2) and (21.3).[43] In addition to the standard marginally conditions which hold at the market equilibrium[44] the *sum* of the marginal rates of substitution must equal the (common) mar-

[42] Namely the region behaves as if it does not influence prices.

[43] See also Chichilnisky, Heal and Starrett (1993).

[44] The marginal rate of substitution equals the marginal rate of transformation equals relative prices.

ginal rate of transformation which in turn equals the price between a and y, i.e. the permit price π.

21.4. Markets with knowledge

This section presents a general equilibrium model of a market with knowledge.[45] As explained above, knowledge is a privately produced public good. In this sense the model presented below is a model of a market that trades private goods as well as a privately produced public good, in this case, knowledge.

There are two traders, North and South, denoted by the index $i = 1, 2$ respectively, each producing two goods: one private good (x) and another a privately produced public good (a) representing *knowledge*. Each trader h has finite resources (24 hours a day) which are allocated to produce either private goods or knowledge. For each trader $i = 1,2$ there is a tradeoff between producing more private goods and producing more knowledge. However, more knowledge leads to higher productivity. Formally for $i = 1,2$:

$$x_i = g_i(a_i, a), \text{ with } \partial g_i/\partial a_i < 0, \text{ and } \partial g_i/\partial a > 0.$$

where

$$a = \sum_{i=1,2} a_i, \text{ or } a = \sup_{i=1,2}(a_i).$$

Each trader or region has property rights $\Omega_i \in R^2$ on private goods and owns licences that allow them to use knowledge, $a_i \in R$. Traders derive utility from the use of private goods x:

$$u_i(x_i),$$

Through compulsory negotiable licences, knowledge is available to all. Traders may use their licences to access knowledge or may sell their licences in the market. If they wish to use more knowledge than their licences allow, they buy more licences in the market.

Markets for licences are competitive: everyone pays the same price for the same licence; prices are determined by equating supply and demand, and no trader can influence market prices.

The next step is to define a market equilibrium with knowledge. The equilibrium of the market is defined as follows. It consists of

- A price π^*, the relative price between private goods and licences to use knowledge,
- For each trader $i = 1, 2$ a level of initial allocation of property rights on licences to use knowledge in the economy $\bar{a}_1, \bar{a}_2$,

[45] This model is authored by Chichilnisky—it differs from the emissions markets model in several ways, in particular the utility function here does not depend on the public good a as before, and the budget equation below.

- For each trader i a level of consumption of private goods x_i,
- For each trader i knowledge production a_i^*,

so that:

- Each trader i allocates time optimally between the production of knowledge and the production of private goods,
- Each trader maximizes welfare within a budget defined by prices and property rights:

$$Max\, u_i(x_i)$$
$$s.t.\ x_i = g_i(a_i^*, a^*) + \pi^*(\bar{a}_i - a_i^*),$$

i.e. the value of consumption equals the value of production plus the value of licences bought or sold, and

- Markets clear

$$\bar{a}_1 + \bar{a}_2 = a_1^* + a_2^*.$$

A competitive equilibrium determines endogenously a number of prices and quantities:

- the initial allocation of property rights on knowledge in each trader or region;
- the level of production and of consumption of private goods and of knowledge by each trader or region,
- the level of trade of private and knowledge between the parties, as well as
- the terms of trade between the private good and knowledge, π^*, which is the market price of the licences.

The price π^* can be thought of as a market-determined licence fee on using knowledge, since it is a monetary value that must be paid for using knowledge above the level allowed by the initial allocation of property rights.

21.5. Equity and efficiency in environmental markets and in markets for knowledge

The most attractive feature of competitive markets is the efficiency with which they allocate resources, requiring minimal intervention once an appropriate legal infrastructure is in place. This was Adam Smith's vision of the "invisible hand," and was formalized in the neoclassical theory of competitive markets that has prevailed in the Anglo-Saxon world since the 1950's. The efficiency of markets is summarized in *the first welfare theorem of economics*. This theorem establishes that the prices and the allocation of goods and services that arise in a competitive market equilibrium are efficient, in the sense that there is no other allocation that can

make everyone better off. The first welfare theorem has practical importance. It had a major impact in the functioning of economies such as the US, which are market oriented. It underlies much of its *anti-trust legislation*, as well as its *insider trading laws* the laws that restrict *price discrimination*, and other forms of *market discrimination* including gender and age discrimination. The rationale is simple and compelling. Since, according to this theorem, competitive markets ensure an efficient allocation for society, it follows that competitive markets are a "public service." Economic actions that undermine the ability of the market to act competitively therefore detract from the public good.

The insight illustrated here is that the first welfare theorem is no longer valid in markets in which in addition to traditional goods (private goods such as apples or machinery) one trades public goods, such as the rights to use the planet's atmosphere, or knowledge. There is however a new first welfare theorem, reported below as the *first welfare theorem for privately produced public goods*, that establishes that the market reaches efficiency, but only for certain allocations of the rights to use knowledge, or licences. The results are quite general, and apply to any competitive market in which, in addition to private goods, trading involves privately produced public goods. Therefore they apply to environmental markets as well as markets with knowledge. In the case of environmental markets, in the special case considered in those works, the licences involved permits for the use of the atmosphere of the planet as a sink for the emission of greenhouse gases.

Theorem 21.1. *(Chichilnisky, Heal* and *Starrett). Given a total global level of emissions* $\bar{a}$, *there exist* a *finite number of ways to allocate property rights on emissions among the two regions, i.e. there is a finite way of distributing emissions rights (or permits to emit)* $\bar{a}_1, \bar{a}_2$, *with* $\sum_{i=1}^{2} \bar{a}_i = \bar{a}$, *so that at the resulting competitive equilibrium, the allocation of private and public resources in the world economy,* a_1, a_2, x_1, x_2, *is Pareto efficient. For distributions of permits other than these, the competitive market equilibrium is inefficient. When both traders have the same preferences, then the region with more private goods should be given fewer property rights on the public good.*[46]

This theorem is illustrated in diagram 1 provided in the text. The diagram shows a starting distribution of permits that gives proportionately more rights to emit to the North, and computes the corresponding competitive market equilibrium allocation. In a second step, by redistributing the permits in favor of the South and at the same time tightening the emission targets on the whole world, the competitive market achieves a new equilibrium allocation which increases the welfare of the North and the South. This means that the first distribution was not Pareto efficient, and illustrates the potential efficiency gains obtained by redistributing permits in favor of the poorer countries.

[46] For environmental markets rather than markets with knowledge see also Chichilnisky (1993a) Chichilnisky and Heal (1994) and Chichilnisky, Heal and Starrett (1993).

Theorem 21.2. *(Chichilnisky) By allowing total world emissions* $\bar{a}$ *to vary, one obtains a one-dimensional manifold of property rights from which the competitive market with permits trading achieves a Pareto efficient allocation of the world's resources. For allocations of property rights different from these, the competitive market does not achieve Pareto efficient solutions.*

Proof. See Chichilnisky (1996f and 1997c).

The following result applies to the model presented above, which is different from the model of environmental markets in that the privately produced public good is *knowledge.* The model with knowledge is different from the model of emission markets, because knowledge does not enter in the utility function (as the environmental asset does), but does enter into the production function to improve productivity (as the environmental asset does not).

Theorem 21.3. First welfare theorem of economics for markets with knowledge. *There exists a one-dimensional manifold of property rights allocations from where the market with knowledge achieves an efficient allocation of resources. For allocations of property rights other than these, the competitive market does not achieve Pareto efficient equilibria.*

Proof. See Chichilnisky (1996f, 1997c).

Theorems 21.2 and 21.3 identify the set of all "efficient" allocations of property rights on the use of knowledge, i.e. all allocations of licences to use the available knowledge products in society from which the competitive market achieves efficient allocations of resources as in the case of private goods. It turns out that the allocations that yield efficient solutions provide more property rights to those traders who have fewer property of private goods. As an example, this would involve proving for people to lower income free access to a number of software programs, a number that is larger than the corresponding number would be for someone with larger income.

The rationale behind the proof of these results is simple. Competitive markets in which public goods are traded have more stringent criteria for efficiency than markets for private goods. In addition to the standard marginal conditions (i.e. marginal rates of substitution must equal the marginal rates of transformation) the allocations must also satisfy the Lindahl-Bowen-Samuelson conditions for efficient levels of the public good, requiring that the sum of the marginal rates of substitution equals the (common) marginal rate of transformation between the private and the public good. Since more conditions are needed, the standard competitive allocations are not generally "first best", i.e. they are not generally Pareto efficient. In addition it can be shown that they are not "second best" efficient as well, where second best means that they are Pareto efficient conditional on a total level of world emissions which does not exceed the given target. Generally the total amount of the public good is lower in competitive markets than the "first best" or Pareto efficient level.

21.6. When trade liberalization is helpful to the environment

The following results show how and when trade liberalization fosters efficient use of resources and knowledge, and when it does not. The starting point is Chichilnisky (1993a) where it was shown for the first time how differences in property rights regimes between two regions explain trade, and how the international market amplifies the "tragedy of the commons". In Chichilnisky (1994a) resources are an input of production. This section enlarges the scope of the earlier results showing that there is much more to them than a repetition of the tragedy of the commons; indeed when the ill-defined property rights occur in outputs rather than inputs (e.g. in the case of knowledge goods) the tragedy of the commons is shown to reverse itself. It seems useful to remind the reader of the 1994a methodology in order to facilitate the understanding of the new results presented here.

The methodology used in my 1994a article generalizes 'comparative statics' to more complex and dynamic situations involving property rights.[47] In a nutshell, it consists of comparing the solutions to two sets of simultaneous non-linear equations, each of which represents a North-South economy: one describes a standard competitive market with a unique equilibrium, and the other the same market modified to reflect a historic characteristic of the South, the fact that resources are common property. In some cases they also compare welfare before and after trade.

The 1994a article introduced a mathematical formulation of property rights within the set of equations describing equilibrium and showed how one function, representing resource supplies in the South, varies with the property rights regimes.[48] I showed that at each price more resources are supplied with common property than under private property regimes. This simplified a larger and more diffuse problem by showing that the impact of property rights regimes on the economy can be formalized by the solutions to two sets of non-linear equations describing the North-South economy, differing only in one function: the supply of resources in the South. The first set of equations describes a perfect market equilibrium so that its solutions are Pareto optimal;[49] in addition it has a unique equilibrium. The prices and resource consumptions corresponding to this solution are a benchmark which we use to represent 'optimal prices' and 'optimal consumption' levels in the North and the South. The second set of equations describes an economy where the South has common property rights; it has also a unique equilibrium.

Comparing the prices and the consumption of resources that arise from resolving the first and the second set of equations, the second set has lower resource prices, and higher consumption of resources than the first. From this one deduces that common property of resources leads to lower resource prices, and to more consumption of resources than is optimal. In addition, after trade the welfare of the South is shown to be lower. This is the nature of the results.

[47] A dynamic version of my 1994 results appeared in Chichilnisky (1996d).

[48] It uses a Nash equilibrium solution to a game theoretical model (similar to that in Dasgupta and Heal (1979)) to derive the supply function of resources in terms of prices when the resource pool is common property.

[49] A.k.a. first best optimality.

It is somewhat surprising that the impact of changes in property rights on the solutions to a system of several non-linear equations can be determined simply by examining the slope of one function, the supply function for resources in the South. By revisiting this methodology I show below how it extends to a number of other interesting cases.

The reality is that when recommending resource exports economists have in mind the standard model with private property rights, and my point is that such a model could be misleading. They could be computing apparent gains from trade, not real ones. It is the second model, with common property resources, that is more relevant. In the second model, specializing in resource exports can lead to welfare losses. This is what Chichilnisky (1994a) shows.

21.7. Common property of software

The 1994a methodology can also be used to distinguish the results from the so-called 'tragedy of the commons,' namely the tendency of societies to overuse their common property resources. There is an interesting analogy here, but I show below that with common property regimes international trade can lead either to overconsumption or to underconsumption of resources. The former case confirms the tragedy of the commons, but the latter goes in the opposite direction. Matters are more complex and subtle than a mere extension of the tragedy of the commons to the international arena. The following result explains what makes the difference.

As pointed out above, a crucial factor emerging from my 1994a results is the form of the supply function for resources under two different property rights regimes. Recall the simplest case analyzed in my Chichilnisky (1994a) article. A number of harvesters in the South extract a resource (such as fish or trees) from a pool that is owned as *common property* (such as a lake or a forest), using their labor, x. I showed that at any market price p the harvesters apply an amount of effort x which optimizes the difference between average revenues and marginal cost (Chichilnisky (1994a), see also Dasgupta and Heal (1979)), so that x satisfies the expression.

$$pf(x)/x = c'(x).$$

Matters are different under private property regimes; here, instead, the harvesters optimize profits:

$$Max_x[\, pf(x) - c(x)],$$

and the optimal amount of effort x therefore satisfies the expression

$$pf'(x) = c'(x).$$

Since the production function $f(x)$ is concave, it follows that for all x, average productivity exceeds marginal productivity $f(x)/x > f'(x)$, so that the rewards appear to be larger than they are and the optimal amount of effort x applied in the former case is larger than in the second. Therefore more resources are extracted with

common property than with private property at any price p, and the supply function for resources has a higher slope[50] with common property than it does with private property. In a nutshell: the problem of overextraction of resources arises because the pool from which the resource is extracted, namely the *input* used to 'produce' fish or wood, is common property,

Matters are quite different when an *output* of production is common property. Software can provide a good example. An economy produces software using labor x and (privately owned) capital. Software is an output that is sold to a number of commercial clients who pay a market price p; it is however treated as common property by non-commercial users. A proportion k, $0 < k < 1$, of the users are commercial, the others are not. Once the software is produced there is no cost for duplicating the software, and no restrictions or penalties for non-commercial users in doing so. Using the 1994 method of analysis, we focus on the shape of the supply function for software in one region under two regimes: private property and common property.

Under private property rights, all users pay for the software, so the workers maximize the profits function:

$$Max_x\,[\,pf(x) - c(x)],$$

choosing therefore their input x so it satisfies the standard conditions:

$$pf'(x) = c'(x).$$

However, with common property regimes for non-commercial users, the worker's benefits are instead

$$\frac{1}{k}pf(x) - c(x),$$

so that workers choose effort levels x that maximize benefits, i.e. those satisfying

$$\frac{1}{k}pf'(x) = c'(x).$$

Since $pf'(x) > \frac{1}{k}pf'(x)$, and f' is a decreasing function because f is concave, when software is common property among non-commercial users, less effort x is applied to production than under private property regimes. The supply function for software as a function of p has a *lower* slope with common property than with private property. In a general equilibrium *less* software is produced at any price. By contrast, in the case of resources the common property supply function has a *higher* slope in the case of common property rights, and *more* resources are produced at each price.

Furthermore, if there were no penalties associated with duplicating software by any user ($k \sim \infty$), as it is in countries with weak intellectual property legislation such

[50] As a function of prices.

as Japan or China, there would be no effort applied to producing software except for that which the producer itself can benefit from. The supply function would be nearly zero. Software is a labor-intensive commodity that uses skilled labor, which is a comparative advantage in a nation such as China or Japan. These countries would therefore be expected to export software under standard assumptions. Nevertheless the results given above would predict that these countries would not specialize in software, importing more software than is optimal, namely more software than what they would import under a private property rights regime. The facts agree with this observation: neither Japan nor China have developed a software industry despite their comparative advantages in abundant skilled labor. Applying the rest of the methodology developed in my 1994 paper to this newly derived supply function for software, one can deduce that China and Japan would be better off if they were to develop a better regime to protect intellectual property rights, running counter to their current policies.

For the purposes of this paper the main observation emerging from this analysis is that common property can lead to *overproduction* or to *underproduction*. Using the same methodology I introduced in 1994 one can deal with a variety of different examples. The results presented then are more than an extension of the tragedy of the commons.

The following subsection explains when taxes or tariffs may not be adequate policies.

21.8. Tariffs

Tariffs or taxes could depress the price of resources or agricultural output, and therefore may induce a reallocation of labor away from extracting or deforesting activities. This is the rationale for introducing barriers to trade. However, as I showed in 1994, tariffs that depress the price of resources may have the opposite effect to that desired when there is a binding subsistence constraint, and therefore they are not reliable policy. Margolis (1997) discusses trade barriers and comes to a similar conclusion. Cruz and Repetto (1992) have reported interesting empirical work supporting this conclusion as well, on the effects of structural adjustment polices in the Philippines. They discuss the 'income effects' of adjustment, which have precisely the effect I predicted theoretically on exploitation of forests and coastal fisheries. Repetto[51] points out, however, that where there are still substantial resource rents, as in commercial logging of tropical timbers, the rent capture through resource taxes can have the opposite effect of reducing the rate of extraction.

[51] Private communication, October 1994.

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