ABARE

ABARE CONFERENCE PAPER 95.5

Property rights, information and physical transformation

A perspective on environmental valuation

Stephen Beare and Brian S. Fisher
Australian Bureau of Agricultural and Resource Economics

39th Annual Conference of the Australian Agricultural Economics Society
University of Western Australia, Perth
14–16 February 1995

In attempting to integrate economics with the physical environment a number of economists have introduced the concept of entropy. This has generally been in the context of the second law of thermodynamics — and, in that context, has commonly been referred to as the entropy law — largely as a means to consider absolute scarcity.

But entropy is in fact a much more general concept; it is a measure of disorder or the level of disequilibrium or uncertainty within a system. In this paper, entropy is used in this broader context to examine some relationships between property rights, information and the physical environment. The purpose is not to impose the laws of thermodynamics on information or property rights systems but to examine the interrelationships between systems in terms of a common measure.

The main inferences to be drawn are that the entropy balance of the physical environment does impose limits on information and its application to technological improvements. Furthermore, the entropy of the physical environment, the information set and the property rights set all serve to limit the number of possible transition states of the world.

Introduction

One problem in resource economics is that neoclassical economic theory is not well embedded for the physical environment. This is not intended as a fundamental criticism of economics but more a question of perspective. There is a tendency in economic models to use constructs which are free of physical constraints. Prices, capital, labour and land are often disembodied from any well defined physical analogue. A great deal of economic analysis is static and when time is admitted it is generally without direction. That is, temporal change is often treated as reversible. This is not in accord with the general laws which appear to govern the evolution of our environment.

A number of economists have attempted to introduce physical laws within the context of economic theory. This has largely been in terms of preserving mass and energy conservation (see, for example, Ayres and Kneese 1969; Ayres 1978; and Georgescu-Roegen 1979). The laws of thermodynamics have been considered by a number of authors including Georgescu-Roegen (1973), Boulding (1980) and Young (1991). The concept of entropy plays a central role in this paper but the idea is expanded to consider the more general notions of order and disorder as they apply to both the physical and economic environment.

The purpose in this paper is to explore the potential for integrating economic and physical constructs into a more cohesive framework. Within such a framework we might hope to link production, consumption and technological change to the physical constraints of the environment and, in particular, the basic irreversibility of some temporal flow.

The view to be considered is very macroscopic in the sense that it does not address the range of interactions between economics and the environment. The approach is to simplify, with minimal loss, most economic constructs and to add a few borrowed ideas which bind economics to a generalised physical world.

A view of the macro system

A view of the world is often described as a system — for example, an ecosystem or an economic system. A system may be defined in terms of its component parts, which are generally aggregates of other systems that are hopefully useful ensembles, the potential interactions between these components and the boundaries of the system.

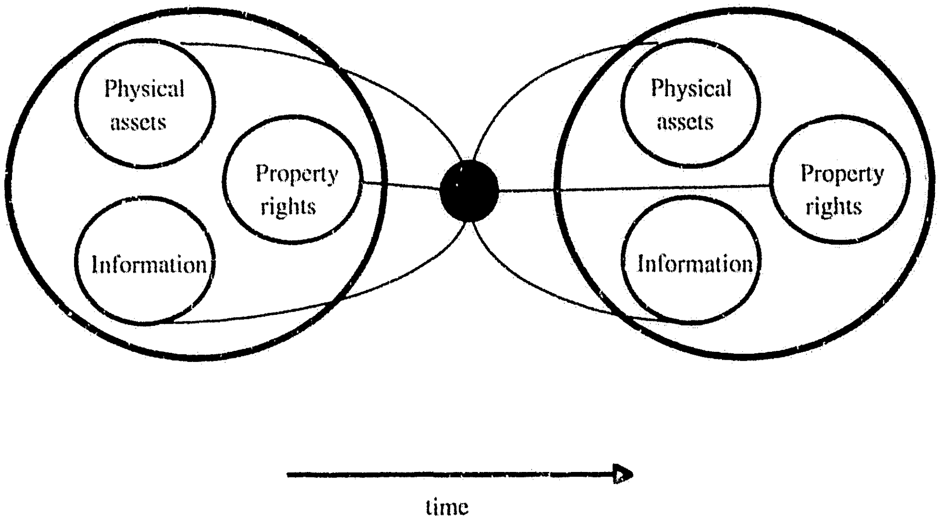
There are a number of global concepts which help define a system. A system may be isolated — that is, totally self-contained — or open where things may move across the boundaries. Systems may be static or dynamic which corresponds respectively to an equilibrium or a disequilibrium state.

To effectively consider economics in the context of the physical environment the system is open, in disequilibrium, and it boundaries may be very expansive. This is just another way of saying that the study of environmental economics presents some very difficult problems. The approach adopted here is to seek a great deal of simplification in defining the components of the system and the rules which govern the transformation between states of the system. The macroscopic view under consideration consists of only three components:

- The first is a complete set of physical assets which exist at any point in time. This set of assets includes mineral and biological resources, capital and consumption goods. In describing these assets both composition and location are important.
- The second component is an information set. Information has both a quantity dimension in that it generates a number of options or possible choices and a quality dimension which refers to the content of the signal. There is no reason not to extend the information set to things which are not necessarily completely accessible to human understanding, for example, the information contained in genetic material.
- The third is of set of property rights over these assets. This set is not the rules which govern property but the set of specific rights held by individuals over the set of assets at a point in time. We will assume that the set of rights is well defined in the sense that access or ownership, common or exclusive, is defined over the complete set of physical assets and the information set. Again there is more than one dimension to this set of rights as the rights correspond to both the assets and the individuals who hold them.

The interactions between these components is complex. Changes in the structure of the set of physical assets have an impact on the set of property rights and the way in which property rights are distributed can influence changes in the physical environment. Information is used to define the property rights and changes in both the physical environment and property rights structure can influence the evolution of the information set. Information can improve our understanding of the rules and thereby make new states of the world accessible. The rules which govern the potential future states of the system are not independent of the state of the system. While we cannot change physical laws we can

Figure 1: A schematic diagram of the macroscopic model



change the rules which govern the transaction of property rights. This, however, will be taken as one of the system boundaries.

Within this framework, according to the rules, the world is mapped into itself over time as illustrated in figure 1. For the moment it is assumed that the system is closed but this will be extended later. What is a more immediate requirement is a means to measure changes in the state of the system in an economic and physical context.

Market and non-market values

As a starting point it may be useful to try and place traditional economic concepts of value within the system. Clearly, they must be defined within the context of the set of property rights. The set of property rights can be divided into two components: transactable (tradable) property rights and non-transactable rights. The former might include the rights over the physical disposition of an apple, control over a mineral deposit or a set of information. The latter might include access to the atmosphere, environmental amenities, or gold extraction rights to a hill of pure sand.

For rights to be transactable, transactions costs must be less than the value of exchanging property rights. The question of what is meant by transactions costs or the value of exchange is open to question at this point. The fact that there are rates of exchange between different property rights admits the concept of relative prices. The summation of price times the volume of the transaction admits the notion of an aggregate value. The transactable property rights, as they are distributed, are in fact economic wealth which is measured in aggregate, at a point in time, by this transaction value.

Measures of market values are limited to the set of transactable property rights. That is, we cannot put a dollar measure on the economic equivalent of an aesthetic value of a landscape or an existence value unless these rights are placed into a transactable form which ultimately results in some transactions costs. However, this does not imply that non-transactable rights are without value nor does it imply that changes to the rules governing non-transactable rights will not affect market values. For example, a loss of a common non-transactable property right will likely lead to a change in the relative exchange rates between both inputs and outputs. The net result may be a gain or loss in total value of the set of transactable rights.

The fact that the set of transactable rights will change over time raises a question as to whether there exists an absolute set of economic values; a set of values which allows for intertemporal comparison. If the set of property rights changes due to a change in the set of physical assets or a change in the rules, a comparison of the relative values corresponding to these different sets of tradable rights (much less the non-tradable rights) has no real validity, or at least the validity is limited by the degree of similarity between the two sets of property rights. In summary, commodity prices, when compared over time, are an index value and subject to all the well known limitations of indexes in making value comparisons.

This inability to make intertemporal value comparisons is a very real problem in resource economics. In the development of neoclassical economics absolute labour or capital based value systems were replaced by relative factor shares. But this system of value is based on the assumption that the existing distribution of wealth is ideal. If one presumes that the existing distribution of wealth needs to be changed, as is the consequence of most economic policy, nothing substantive can be said about economic efficiency and economic value in the context of neoclassical economics. However, the point is not to dismiss the concept of economic value but rather to accept that a number of value systems might provide some insight in consequence of alternative public choice options. The fundamental problem is, should we consider a change in the rules which govern the definition and transaction of property rights to achieve some alternative state of the world. Within the system under consideration this represents the only policy option available.

The measure to be considered is one of disorder or randomness, a measure of disequilibrium. The measure is entropy which is derived from the Greek and means 'transformation'. Quite logically it is an inverse measure of order. As mentioned, entropy is a concept that has been introduced into economics previously. One problem to date is that entropy has been confused with the second law of thermodynamics which in summary states that systems decay. This is not the case. Entropy is a measure of disorder and as such may be useful in a context which is quite independent of any particular physical law.

In considering entropy as a measure of order, the notion has been applied to more than mass and energy. Shannon extended the concept to information, Eddington to time, Kolmogorv to the dynamic evolution of systems and Renyi to fractal dimensions. The measurement of disorder would appear to be relevant in a wide range of systems. The underlying challenge is not so much about how disorder can be used to describe and measure the state of the system but rather how this measure can be related to both physical and economic phenomena in a meaningful way. However, first the system must be subject to measurement.

Randomness

Entropy is not an observable physical quantity, it is an accountancy system. Fynman et al. (1963) state that disorder can be measured as the number of ways in which the internal components of a system can be arranged without changing the way it looks from the outside — that is, the system functions identically to an outside observer. Entropy is simply the logarithm of that number. The lower the number, the more ordered the system.

What is meant by the way the system looks, or invariance of function, serves to define what is being measured or accounted for and any number of entropy measures can be defined. This requires some form of macroscopic measure of equivalence for the system as a whole. The arrangements are then accessible microstates of the system's component parts. Whether such quantities are useful or comparable is not yet at issue. However, it is not simply the case that order is good or valued or that the tendency for a system to become disordered is bad and implies a loss of value. Cambel (1993) provides an interesting discussion of the many forms of entropy.

The number of possible microstates of a system, denoted W, can be related to a probabilistic definition referred to as statistical entropy, denoted S:

$$S = \sum p_i \ln(p_i)$$

where p_i is the probability that the system will exist in an accessible microstate. The two entropies are related by Boltzmann's constant, k, in the form $S = k\ln(W)$. When comparing the entropy levels of two systems the entropies are additive: $S = S_1 + S_2$ as the probabilities are multiplicative: $W = W_1 W_2$.

The classical notion of entropy is a fundamental aspect of the laws of thermodynamics which for an isolated system are, first, the energy in the system is constant and, second, entropy is only increasing. In the classical thermodynamic model, a system evolves to an equilibrium state in which disorder is maximised, a state referred to as thermal death. The thermodynamic concept of entropy can be directly related to the configuration of mass through statistical mechanics. It is not correct to infer that the laws of thermodynamics apply to all forms of entropy. However, if an equilibrium state can be defined in terms of maximum entropy and the system tends toward a state of equilibrium then the classical second law, in effect, applies.

The initial application of thermodynamic laws to open systems was made by Prigogine (1947). The laws can be extended to an open system in which entropy can be gained or lost — that is, order can be produced or destroyed. The accounts are maintained though an entropy balance stating that the rate of change in entropy within the system is equal to the entropy produced within the system less any net entropy flux across the boundary of the system.

Energy

Generally what flows across physical system boundaries is energy. Not all energy from a source is available to do work. Some energy, by the second law of thermodynamics, is lost or unavailable. This loss is in addition to any losses due to the inefficient transfer of energy into work, through for example friction. The proportion of available energy is a property of the energy source, quite independent of the technology used and represents an ideal level of efficiency, referred to as Gibbs energy. The loss component is the entropy contribution of the energy source.

Different energy sources have different levels of available or free energy — that is, energy in different forms has different qualities. A high quality energy source has a high proportion of free energy and a low entropy. These proportions have been measured by Dyson (1971).

Gravitational energy has an entropy value of zero per unit of energy, nuclear energy is of the order of 10^{-6} per unit of energy and chemical energy in the range of 1–10 units of entropy per unit of energy. This according to Cambel (1993) serves to explain why hydroelectric generation of power (and to a lesser extent nuclear power) are so much more efficient than chemical power generation.

The main conclusion from this is that to maintain or increase the level of physical entropy within an open system comes at a physical cost. Technological improvements in production processes may reduce this cost but there are well defined limits. This cost, whether a matter of economic choice or not, may be met by an additional loss from a larger encompassing system.

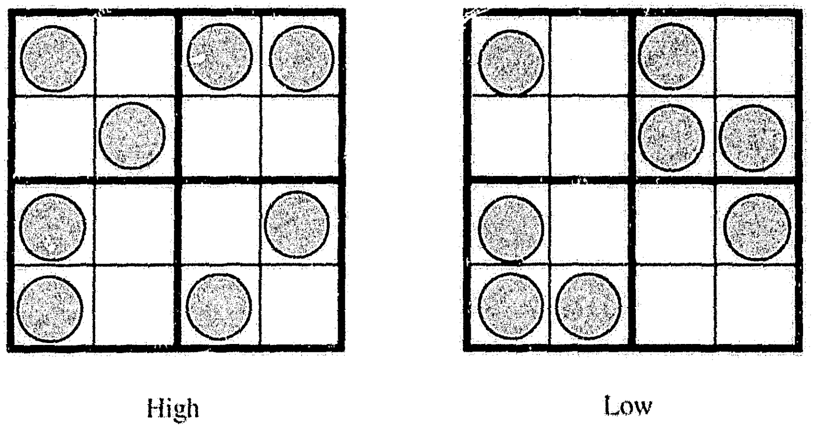
This brings us back to a consideration of an open system. Light energy has a greater amount of free energy than heat. That is, it is less entropic. The sun is an external low entropy source. Some of this light is reflected from the earth but the balance is either temporarily fixed in a higher entropy form as chemical energy (carbon based molecules) or potential energy (wind and waves) and then ultimately radiated from the system in a high entropy state as heat from the atmosphere. While it would be difficult to argue that we are near any state of static or declining system entropy, both are possible in an open system.

Configuration

An interesting question is the extent to which order can be related to value or wealth associated with physical objects or mass. A very stylised example of mineral extraction can be used to illustrate the problem. Consider a finite area divided into four minable blocks. It is assumed that each block must be mined discretely and cannot be subdivided. Within each block the mineral is randomly distributed between four locations. The concentration of the mineral in the ore is assumed to be 50 per cent. If the ore is distributed randomly across the area the expected concentration in any block is again 50 per cent as in the high entropy form shown in figure 2. Alternatively, due to the process of ore generation we might consider an alternative expectation in which minable blocks contain either a mineral concentration of 25 per cent or 75 per cent. The average concentration for the area as a whole will remain at 50 per cent, as illustrated by the low entropy form in figure 2.

The entropy calculations for these two systems are somewhat complex but there are approximately 52 million ways in which to arrange the high entropy blocks and about 10

Figure 2: **High and low entropy configurations of a mineral resource**



million ways to arrange the low entropy blocks. These correspond to entropy values of 17.8 and 16.1 respectively. From an economic perspective it is reasonable to conclude that the cost of extracting and processing a mineral concentrate from a highly concentrated block is less than for an average block and less again than for a low concentration block. Less waste material has to be taken up and separated from the ore the higher the mineral concentrate of the substrate. In entropy terms, it takes less energy to transform a more ordered base material into a more highly ordered product.

However, a higher level of entropy cannot be equated with a higher level of mineral wealth, if one views wealth as total mass of the extractable ore. Consider three cases. In the first case, the return to extraction and processing is sufficiently high to mine the entire area whether the ore be of high or low concentration. The potential difference between a low and high entropy state may be small as the saving from extracting a high concentration block are offset by the costs of extracting the low concentration blocks. In the second case, it may be profitable to extract only the high concentration blocks. In this case only the low entropy state yields a usable resource and can generate any subsequent wealth. In the final case, it may be profitable to extract and process both high and average grade concentrations. The low entropy state yields a lower quantity of the resource at a lower unit cost relative to the high entropy state.

In a manner similar to free energy, it may be useful to think of the quality of a physical asset such as a mineral deposit in the context of entropy. For a given product, say a certain purity of gold bullion, the net entropy increase associated with transforming the ore will tend to be higher the lower the base concentration of the ore, independent of any inefficiencies in the transformation process. The physical value or quality of a given energy source is defined in terms of the maximum work which can be accomplished per unit of total energy or inversely to the ratio of its entropy to the total. This presumes that there are no other external costs associated with the use of a particular energy source such as the perceived risk associated with nuclear energy. Here we are limited to a comparison between the minimum value of entropy loss associated with transforming two alternative base states into a common final state. When we attempt to compare alternative final states we run into a problem in terms of any absolute question of value in that a higher entropy final state may be preferred to a low entropy state. One need only consider the relative value of a hot versus a cold cup of coffee.

The relationship between energy and the configuration of mass is complex but well established in principle. Measuring the exchange is for the most part a technical problem though the scale of the calculations is ultimately prohibitive. A point to be made here about physical measures of entropy is that they can be used to make cost comparisons in terms of a singular scarce commodity, order. As with any cost based approach these comparisons cannot be equated with relative economic or social values. However, unlike relative economic or social values, entropy based cost comparisons are valid as the system changes through time. The extent to which a value system may be derived depends on the relationship between physical entropy, information and individual rights.

Information and uncertainty

Consider the mining problem in which the base concentrations are known but the location of any high or low concentrate deposits is unknown. In the high entropy state, information about the local concentration of deposits makes no net contribution if both the overall concentration and the entropy state are known. In fact, all we need to know is the average concentration of the mineral and that the entropy state is at a maximum. This is because all possible arrangements of the minable blocks are identical from a rational miner's perspective. However, in the case of the low entropy state, location is important and in fact there are six additional possible states of the world which have the same overall prospectivity. The uncertainty associated with the more ordered state is in fact greater than the unordered state given that the location of the blocks is unknown. In the example, we can measure the reduction in entropy value associated with fixing the relative location of the high and low concentration blocks at about 1.8 (the natural logarithm of the six additional possibilities). It is a quantity which is greater than the difference in the low and high physical entropy states.

Physical equilibrium is characterised by a high level of entropy and in such states there would appear to be little need for information about the system. Alternatively, and perhaps more precisely, less information is required to characterise the number of macroscopic states that can exist within the system. Opportunities exist in low entropy or disequilibrium systems. Here the potential value of information is high.

Suppose we had a message about the state of the system. The longer the message the greater the potential complexity of the information. For an equilibrium system many of the messages would have the same content (for example, the temperature t at the location x, t_{x1}, t_{x2} ..., are all equal). That is, a large percentage of the possible messages can be interchanged to give the same information about the state of the system, and therefore entropy is high. Conversely, in a disequilibrium system a smaller percentage of the messages can be interchanged to yield an equivalent statement about the state of the system (t_{x1}, t_{x2} ... are unequal and an interchange of the values gives a different description of the system). We can expect that the complexity of the message required to describe the compete state of the system increases exponentially with the complexity or the low entropy state of the system. This seems backwards — the more ordered a system is, the more predictable it should be. The resolution to this paradox has to do with irreversible processes when viewed from outside the system. A disordered state will remain disordered but an ordered state can move into a wide range of states which are detectable from outside the system. If the state of the system remains constant we can suspect that somebody or something is putting a great deal of effort into it.

Shannon (1948) formalised the notion of information entropy from an engineering perspective in so far as he quantified a relationship between the possible states of a system and the level of uncertainty which is associated with that system. Information in this context is simply a sequence of binary code which describes the system. The information entropy of the code is measured by how many ways the code can be arranged to give the same message. As the number of possible messages increases and the probability that some messages are more likely to get through than others declines, uncertainty increases.

What is asserted here, without formal proof, is that if the entropy of the physical system is low, the entropy of the information set that would describe the system is also low. Conversely, a highly entropic system can be described by a more entropic code. If we view this set of information about the physical system as what could be known, then in a physical system with increasing entropy the corresponding information set is becoming more entropic. What can be inferred from this is that the potential for technological innovation is declining as the world becomes more entropic. The potential for technological change to generate new states of the world is not independent of the physical state of the world; it increases and declines inversely with entropy.

Shannon stated that information does not imply meaning. Meaning is critical in attempting to consider the value of the information which is presently available about the state of the world. Despite the obvious problem of defining meaning in any absolute context, we can approach the question from a relativistic perspective — that is, the potential contribution of new information from within the current view of the world. This presumes that new information does not yield a radical shift in our understanding, a phenomenon which is known to occur from time to time.

We might ask the question as to the number of ways in which we can rearrange the available information set, the message we have, and not change our understanding of the state of the system (or the way the system changes). If this number was large, this would correspond to a high entropy information set. A good example can be drawn from statistics when we regress a variable against a set of highly collinear explanatory variables. The exclusion of any one variable can change the interpretation (regression coefficients) with no significant change in the explanatory power of the regression. Conversely, with an orthogonal data set the contribution of each variable is unique. Deleting a variable does not change the remainder of the story but the overall explanation is reduced. Orthogonal data have a low entropy value. From a statistical perspective on value, the maximal contribution of new information is limited to its independent or orthogonal variation, though, if uncorrelated to the independent variable, it adds nothing to the explanation. We once again have the notion of quality; information has an orthogonal content contribution and a collinear content. The latter contributes to the entropy of the information set.

We may compare the uncertainty associated with the state of the physical system with the entropy content of available information (disregarding the problems associated with incorrect or misinformation). The level of uncertainty is a decreasing function of the entropy of the physical system while the entropy of the available information declines with new orthogonal information. However, it can be inferred that a given set of available information becomes more entropic as the system it describes becomes more entropic. This is because as the system approaches equilibrium, more and more of the messages become redundant.

The notion of information entropy can be applied to economic systems. To consider only a simple example, if a commodity market is in equilibrium then we can describe the relative value of a commodity by a single price. The record of transactions contains a great deal of redundant information. This of course would not be the case for a market in disequilibrium, as prices would vary between transactions and information would lead to the potential to generate rents through arbitrage.

Relative prices are information about the set of property rights, the relative rates of exchange between tradable rights. Rents are also related to property rights. In fact, in the system under consideration, rents can only be defined as a redistribution of property rights. A property right confers to an individual the ability to choose between accessible states of the world. What states are accessible depends on what is physically possible, the nature of the right and other property rights such as access to information on what physical states are possible and their relative rates of exchange.

Property rights and order

Is it possible to relate entropy to an economic state of the system? The answer to this question can be considered in the context of property rights. Consider the case of 10 individuals and a single exclusive property right — for example, the right to market a given product. Suppose that this right is given as a monopoly. There are only 10 ways in which this right can be distributed among the population to maintain the monopoly. For a duopoly the are 90 ways in which to confer these rights. In a perfectly competitive situation without any exclusionary rights to market there are 10! ways in which these rights can be distributed.

The first implication is that levels of imperfect competition correspond to lower levels of entropy in the distribution of property rights. From this a number of assertions are possible. First, the generation of economic rents are associated with low levels of entropy within the distribution of property rights. The association is loose in that available rents within the range of monopoly to perfect competition are not certain. A second assertion is that a perfectly competitive economic equilibrium is, in a property rights context, a state of maximum entropy.

In moving from a property rights system which is competitive to a monopoly, the economic implications appear to move from predictable to uncertain and, in the final state of monopoly, predictable. The notion of 'predictable' here refers to a clear implication of economic theory. But this conclusion is reached only from a static view of competition. When we consider the temporal evolution of an economic system, competitive behaviour remains predictable in this sense over time so long as the rules governing property rights remain unchanged. The nearer the property rights system is to a competitive allocation, the more likely it will evolve into a competitive state (an empirical rather than a theoretical conclusion). In fact, a monopolistic state is the most uncertain, as it may be difficult to break and there is the most substantial economic incentive among potential competitors to break it. Its future state is highly uncertain.

It is not really clear, however, that an economic system will approach a competitive allocation of property rights. This is because rents imply a redistribution of rights and if there are sufficient rents it is possible that segments of the set of rights may become monopolised. This is a notion of a self-organising dissipative system, which appears to occur only under conditions far from equilibrium. A discussion of such systems is well beyond the scope of this paper but are outlined in detail by Nicolis and Prigogine (1989).

The set of property rights is, in a way, an image of the physical and information components of the system and there are a number of other ways in which to view property rights in terms of entropy. It was noted that a property right conveyed a choice between alternative states of the system. If property rights are highly substitutable then there is likely to be a large number of possible combinations of rights from which a given microstate can be accessed. The rights are highly entropic. Alternatively, if substitution is limited some microstate may be accessible with only a limited combination of rights. The entropy is low and there is a greater potential to generate rents. Clearly, the degree to which rights can be substituted may be influenced by the way in which rights are defined.

This leads to a somewhat more unified view of entropy in terms of property rights, information and the physical environment. Consider the number of states of the world which are accessible from a given set of physical assets, given the state of the property rights set. Here is the closest we come to the notion of entropy as an environmental value. This number will tend to be larger, the lower is the level of physical and information entropy. Does this number decrease with a higher level of entropy within the set of property rights? The answer would appear to be yes as a lower level of entropy does not preclude access but a higher level may. For example, a monopolist may choose between outcomes which are not available to a competitive producer, including an outcome which is equivalent to what would occur in a competitive industry.

This does not imply that an increase in the options available will increase social welfare as some of the additional options may not be desirable. However, it does place a limit on potential. Nor should we infer that the second law implies that this potential is ever declining. The physical and information components are both open systems, the latter is open because we can discover new information. However, the concept of entropy balance in an open system does apply and as these entropies increase the potential does decline.

Conclusions

Entropy is a measure of disorder and as a general construct obeys no innate laws. It is a measure of the level of disequilibrium present in a system at any point in time. Entropy is a very general measure which can be applied to a system. There is no reason to accept that a common measure implies that laws or behavioural tendencies are transferable between systems that interact. However, where such commonality exists a useful synthesis may be possible. While no such synthesis has been attempted here, some degree of commonality does exist between entropy flows in economic and physical systems and they may be useful in attempting to describe the interactions between the two.

A value system based on entropy is a Ricardian construct and subject to all its limitations. Nevertheless, such an approach may be important in considering the more general question of environmental value. The reason for this is that entropy can be used to measure changes in time which are both reversible and irreversible.

As no measurements of system order have been made, it is not possible to draw any real conclusions on any sort of entropy flows. If we assert that current entropy balance implies that in a physical sense entropy is increasing (based perhaps on our current rate of consumption of non-renewable fuels) this does not imply that information entropy is in fact declining as we may be discovering information fast enough to offset the increase in information entropy imposed by the increase in entropy of the physical environment. If we assert that the set of tradable assets is becoming increasingly ordered (goods have become increasing complex due to technological innovations) and the entropy of the world is increasing, the balance equation implies that the entropy of the subset of non-tradable assets is increasing. One cannot infer directly from this that the non-market values associated with these assets is declining. We can only infer that the potential number of future states of the world that might be accessible is declining.

There are certainly other avenues to consider. The notion of preferences has been excluded from the global system considered in this paper. Preferences are no doubt another component of a more complete world view. The theory of preference in economics is based on order and the notion of indifference would clearly give rise to a consideration of entropy in the context of substitution in the consumption set.

References

Ayres, R. 1978, *Resource, Environment and Economics: Applications of the Material/ Energy Balance Principle*, Wiley and Sons, New York.

Ayres, R. and Kneese, A. 1969, 'Production, consumption and externalities', *American Economic Review*, vol. 59, pp. 282–97.

Boulding, K. 1980, 'Equilibrium, entropy, development and autopoises: towards a disequilibrium economics', *Eastern Economic Journal*, vol. VI, pp. 179–87.

Cambel, A. 1993, *Applied Chaos Theory: A Paradigm for Complexity*, Academic Press, Boston.

Dyson, F.J. 1971, 'Energy in the Universe', *Scientific American*, vol. 224, no. 3, p. 50–60.

Feynman, R., Leighton, R. and Sands, M. 1963, *The Feynman Lectures on Physics*, vol. I, Addison-Wesley Publishing, Reading, Massachusetts.

Georgescue-Roegen, N. 1973, 'The entropy law and the economic problem', in *Toward a Steady State Economy*, Daly, H. (ed.), Freemand, San Francisco.

Georgescue-Roegen, N. 1979, 'Energy analysis and economic valuation', *Southern Journal of Economics*, vol. 45, pp. 1023–58.

Nicolis, G. and Prigogine. I. 1989, *Exploring Complexity*, Freeman and Company, New York.

Prigogine, I. 1947, *Etude Thermodynamique des Phenomenes Irreversibles* (Introduction to Thermodynamics of Irreversible Processes), Duno, Paris.

Shannon, C.E. 1948, 'A mathematicl theory of communication', *Bell System Technical Journal*, vol. 27 no. 3, pp. 379–423 and vol. 27, no. 4, pp. 623–56.

Young, J. 1991, 'Is the entropy law relevant to the economics of natural resource scarcity', *Journal of Environmental Economics and Management*, vol. 21, no. 2, pp. 169–79.