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ISSUES IN RESOURCE MANAGEMENT*

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In this paper, we wish to explore four questions about environmental management and Australia's resources. First, what are the issues that we face in resource management over the next 10 years? Second, what have economists said and what tools do we have to handle those questions? Third, how good are we at selling our story? Fourth, what else needs to be done? In other words, how do we complement the tool kit we use as economists to deal with these issues?

Relative to its population, Australia is richly endowed with natural resources. We have a comparative advantage in the exploitation of our natural resources, with almost two-thirds of our export earnings coming from the natural resource industries. Because of this, because Australia is a wealthy society and because of the growing public interest in conservation, environmental management issues will be far more important in the 1990s than they have been to date.

The questions and issues involved are not simple. For example, should we lock up the mineral resources in Kakadu and forgo the future wealth that could be generated from investment of the proceeds of the mining activity in favour of the conservation values inherent in the site? Does it matter that the mining activities at Kalgoorlie have generated extensive tailings dumps? Is society better off if miners remove slightly radioactive mineral sands from Western Australian beaches and, after those mineral sands have been removed, how should we value that activity if the mining company can then improve on the original dune systems by repairing natural dune blow-outs? Are we better or worse off as a consequence of pasture improvement which has led to both high levels of production and also to the acidification of some of Australia's soils?

One of the major problems in finding solutions to the conflicts inherent in these types of questions is what Davis (1988) referred to as 'legitimisation'. This is the fundamental communication problem that arises between groups that have different assumptions, different decision frameworks and perhaps even different ideologies. In the case of conflicts over the use of forest resources, for example, conservationists may argue on the grounds of the 'sanctity of nature' and

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'heritage' while the forest industry may emphasise questions of employment and trade balance. Economists emphasise the importance of marginal conditions, and trade-offs that result in the maximisation of discounted service flows or utility from the use of resources. The role of an adjudicator (which may be the government or perhaps a government agency) is to 'legitimise' conflicting claims by incorporating them into an understandable framework that is, at least, partly acceptable to all interests. In practice, it seems that economists could do more to explain their approach, in language that is more understandable to other parties in the resource use debate.

Technological change has increased the scope for making economic trade-offs more transparent. Specifically, with the development of better computer software, coupled with the standard techniques of optimisation, models with multiple objectives over space and time can be solved, and their graphical solutions can be conveyed to all interested parties. Rapid turnaround enables a variety of trade-off scenarios to be considered, and this can give the interested parties in the debate an ability to interact and learn about the trade-offs faced. The scope for using integrated multidisciplinary analysis of natural resource uses is thus quite large [see Hafkamp and Nijkamp (1986) for practical examples of this type of analysis].

In discussing the types of questions raised above, this paper is divided into seven sections which deal with the following topics: property rights; dynamic efficiency; intergenerational equity; welfare criteria; unpriced values; technological change; and discounting. No attempt has been made to review exhaustively the literature in all these areas. Instead, only a sample of the available literature is quoted to illustrate some of the important points.

Property Rights

Some of the resource management problems facing Australia are fairly straightforward, even though their solution in a policy sense may be non-trivial. Problems where externalities are important constitute such cases. It is worth remembering that it is possible to have both positive and negative externalities. In either case, one individual has an unintended or incidental effect on the welfare of others that is not reflected in the marketplace.

Externalities may lead to inefficient allocation of resources because of the divergence of private and social costs and benefits. Typically, externalities persist because of the absence of property rights. The atmosphere is a common property resource on a global scale, and not one of us necessarily directly bears the cost of the air pollution we cause, not to mention the possible problem of intergenerational equity which may result from the emission of greenhouse gases (Haynes, Fisher and Jones 1990). (This is not to imply that a problem actually exists in the case of the greenhouse effect, because although there is no doubt that greenhouse gas emissions are rising, there is disagreement in the scientific community about what this actually means for future trends in the earth's climate.)

In some cases, it is possible to design penalty taxes to bring private and social costs more into line. An example is the case of irrigation salinity. Of course, in Australia many of the existing problems with irrigation salinity might well be solved if farmers paid the correct price for water. Removal of any implicit subsidies in water prices would encourage the adoption of better irrigation techniques and may result in a smaller area under irrigation on major river systems.

In other cases, it is clearly possible to assign well defined and legally enforceable property rights, solving the common property problem. For example, more effective assignment of property rights in a number of Australian fisheries has gone some way towards improving the long-term profitability and sustainability of our fish resources (see Geen and Nayar 1989).

It is not impossible to imagine an internationally tradeable quota system for greenhouse gas emissions. Of course, the enforcement problems associated with such a system would be far more difficult than those associated with assignment systems for common property resources inside national borders (Haynes, Fisher and Jones 1990). However, such problems are not necessarily insurmountable, given for example that surveillance agreements on nuclear arms are in place.

One question that arises here is how property rights should be assigned. For most classes of utility functions, a random assignment of the property rights, for example by ballot, will result in an efficient outcome. However, for a common property resource which is already being exploited the random assignment of rights will have distributional consequences. This would clearly be so in the case of assigning quotas to emit greenhouse gases. From a practical point of view at the national level, assignment of transferable quotas to existing users of a resource, such as a fishery, may be the best approach.

In deciding to assign the rights to exploit a particular resource, the community, represented by the government, may wish to seek some payment in return for access to its resource. However, setting the payment (tax) to be made for access to the resource is not straightforward. For one thing, the existence of risk plays a big part in the outcome of any taxation policy. This is particularly a problem in the case of mineral deposits and fisheries, where even the extent of the resource is not known with certainty, let alone the pattern of future demand and technological change (see for example Hinchy, Fisher and Wallace 1989; Hogan and Thorpe 1990). At this stage, these issues are only raised. Some research which addresses these problems is outlined below.

There is a considerable volume of literature which shows that in a competitive economy without complete risk markets, the most efficient pattern of resource allocation cannot be achieved [see Newbery and Stiglitz (1981) for an introduction to the literature]. In the absence of risk, resources are allocated efficiently when all industries operate at a point where the additional cost from expanding each activity equals the additional revenue from doing so. When firms face risk, price will exceed marginal cost in all industries by the size of the risk premium demanded by firms for their role in bearing risk.

Achieving an allocation of resources equivalent to that possible with complete risk markets is taken to be an unattainable goal because not all the required markets and institutions exist. A more appropriate goal is to attempt to achieve the most efficient allocation of resources possible with the available set of markets and institutions.

The information and administrative cost incurred by a government in attempting to do anything to improve the efficiency of resource allocation may, however, far exceed the costs of the inefficiencies in the existing allocation. In many circumstances, although there may be a *prima facie* case for intervention, it does not follow that intervention is warranted. As Wonder, Morris and Wilks (1989) point out, government involvement by means of market-based financial incentives or taxes has distinct advantages compared with the use of more inflexible rationing approaches. Inflexible regulations will fail to achieve the desired outcome in circumstances where technology and society's preferences change over time more quickly than governments can respond.

Dynamic Efficiency

In deciding whether to use a non-renewable resource now, to save it for future use or to make a commitment never to use it, the community faces a fundamental trade-off: whether to use the resource now and put the proceeds towards generating different kinds of wealth (for example, investing in education or health), or whether to save the resource in its natural state. By adopting the alternative of saving the resource in its natural state, the community trades-in a stream of financial returns over time for an uncertain future income or for some intangible benefits that might be associated with an unchanged environment. In some instances, the current generation may wish to make a commitment never to deplete a particular resource or change some part of the environment. Of course, the current generation cannot make its commitment binding on those who follow.

Many insights in analysing the trade-off between current and future use are illustrated by Hotelling's *r*-percent rule and its subsequent extensions. In fact, the papers discussed in this section may all be viewed as part of the search for models which explain what is an efficient allocation of resources over time, that is, dynamic efficiency.

Hotelling's rule

Hotelling (1931) was concerned with determining whether the scarcity of non-renewable resources could lead to a need for government intervention to achieve an efficient resource allocation, and sought to develop a theory of natural resources which emphasised the dynamic nature of supply response. Hotelling examined various models of non-renewable resources using the calculus of variations, which, while then a sophisticated technique, has since been superseded by optimal control theory and dynamic programming as the standard methods for examining issues in dynamic efficiency.

In the simplest model considered, the problem was how a social planner would choose to extract a known finite homogeneous stock of a natural resource when extraction was costless. The solution to this problem is known as Hotelling's *r*-percent rule. Hotelling showed, for a given set of conditions, that along an efficient extraction path the price of a resource would grow at the rate of interest. The rule is a condition for asset market equilibrium. There is no net gain in shifting extraction between periods when the present value of each unit extracted, the resource rent or the opportunity cost of depletion, is the same in all periods. This means that the net price of the resource (in a competitive industry, the market price less the marginal extraction cost) must rise with the return on all other comparable assets, that is, the interest rate. As Hartwick and Olewiler (1986) explain, if the growth in rent exceeded the interest rate it would pay to keep the resource in the ground, that is, to minimise the extraction rate (and vice versa); such an outcome would be inconsistent with asset market equilibrium.

Hartwick and Olewiler (1986) also discuss the tendency for extraction to occur in the predicted sequence, from low to high cost deposits (given uniform quality). With constant marginal extraction costs, two deposits, and physical exhaustion assumed, it follows that both deposits cannot be mined simultaneously as this would violate Hotelling's efficiency criterion. Rent must rise at a slower rate on the high cost deposit, so that the net present value of profits is maximised by exploiting the low cost deposit first. However, it can be shown that the existence of set-up or capital costs can reverse this tendency, basically because it will then pay producers to wait to expand capacity and so achieve a form of increasing returns (Hartwick, Kemp and Long 1986; Olsen 1989).

While Hotelling's rule has a good deal of intuitive appeal, the assumptions used to derive it are very restrictive. They include: homogeneous output; no exploration; perfect foresight and certainty of future demand (no uncertainty or technological change); and no common property problems. Under these conditions the r-percent rule must hold for a competitive resource industry provided the private discount rate equals the social discount rate. Clearly some, if not all, of these conditions do not hold in practice.

Exploration

Producers of exhaustible resources are often engaged in exploration and development as well as extraction activities. Discovery not only adds to new reserves but provides information about potential future reserves and associated exploratory risk. Pindyck (1978) provides one of the simplest models of exploration and extraction, which is based on optimal control theory. In this model, the optimal price path turns out to be contrary to Hotelling's rule.

Barrett (1986) extended Pindyck's model to include increase in recovery effort and assumed that cumulative discoveries have an initial positive effect on the rate of discovery due to knowledge acquisition. Livernois and Uhler (1987) also extended Pindyck's model by including output in the extraction cost function and allowing for multiple deposits. In all cases, ordinary least squares, applied to aggregate time series data, was used to estimate the relevant functions for costs and state variables. Optimal paths for the endogenous variables were then simulated and graphically compared with history. Such casual forms of model validation produced rather mixed results, and form a very loose check on the dynamic efficiency criterion underlying such models.

Just as static duality theory has proved a most useful vehicle for empirical analysis of static firm and consumer behaviour, dynamic duality theory offers the applied researcher a tractable means of analysing and estimating dynamic demand and supply responses. Larson (1989) provides a fairly comprehensive description of the problems for which dynamic duality theory is relevant and also outlines the corresponding dynamic versions of Hotelling's lemma. His bibliography contains a range of empirical applications of this technique, including the analysis of uncertainty and technological change.

Given the importance of obtaining accurate measurements of long- and short-run own- and cross-price elasticities and the need to measure resource rents accurately, research using and extending dynamic duality theory could well be pursued. Halvorsen and Smith (1984) and Turner (1988) provide examples of applied research in this direction, but they stop short of obtaining long-run results. However, it is worth bearing in mind that as real world complexities are added data requirements tend to become severe. The benefits of dynamic programming analysis then come into play. For complex problems, computational tractability and data needs are less severe in dynamic programming provided the problems are carefully structured. The virtues of dynamic programming are extolled and examples of the technique and its underlying principles illustrated in Kennedy (1988).

The problems with using time series data for supply response analysis led Miller and Upton (1985) to consider a cross-sectional investigation of Hotelling's rule. One of the implications of this rule is that 'the value of the resources in any currently operating, optimally managed mineral deposit depends mainly on current period prices and extraction costs, regardless of when the reserves are extracted' (Miller and Upton 1985, p. 3). This has been called the Hotelling valuation principle. Miller and Upton found some support for this proposition in the case of the US petroleum industry when market values of reserves per unit were regressed on variables including the current output price net of extraction costs. However, it is clear that this alone is only a weak test of the rule, because other theories can easily be thought of which are also consistent with this principle.

Uncertainty

A rather vexing question is how to incorporate uncertainty into Hotelling-type models. Hotelling's r-percent efficiency criterion, as was stated earlier, assumes that economic agents have perfect foresight; the expected price is assumed to rise with the interest rate and expectations are held with certainty. However, it is more likely that economic agents have different levels of information regarding future supplies and demands for natural resources. In the absence of complete risk markets, this information problem will lead to allocative inefficiency. Consequently, uncertainty imposes costs or risks which must be included in models that are concerned with analysing issues of dynamic efficiency.

Uncertainty regarding supply and demand prospects pervades natural resource issues. Fisher (1981) describes some of the simpler theories of how uncertainty affects optimal extraction paths for a non-renewable resource. If uncertainty is reflected in a risk premium on the interest rate structure, then this could well raise the producer's optimal production rate. However, as Fisher (1981, p. 46) notes, 'The effect on the rate of depletion is not always captured simply by an increase in the discount rate. Further, the effect of a change in the discount rate is not clear-cut, once we take into account the possibility of expanding the resource stock through exploration and development of new deposits.'

Building a model that takes account of risk, the possibility of exploration and the effects of technological change is by no means simple. It is necessary to decide what form uncertainty about the future takes. For example, how does demand for a particular mineral change over time in the face of the discovery of substitutes?

If there is uncertain demand for a resource and the degree of uncertainty increases with the time to depletion, a rise in the depletion rate is expected, all else constant. It is also intuitively clear that whether agents are risk neutral or risk averse, provided competition prevails, uncertainty regarding the time of introduction of a backstop technology (see Nordhaus 1973) will shift extraction toward the present with, again, all else constant. However, where there is an uncertain level of reserves, intuition tells us that the depletion rate will decline. Risk-averse firms simply want to avoid running out of the resource.

Quyen (1988) presents a model with uncertainty regarding the size of mineral reserves, where there is a chance of discovery and a probability distribution for size which is related to cumulative exploratory effort. Quyen shows that, under risk neutrality, the tendency for a monopolist to be excessively conservationist is even more pronounced than under certainty. In addition, the monopolist will also underexplore compared with the social optimum. These results have parallels in storage theory, where it can be shown that a monopolist will store a deficit amount.

The earlier approach used by Pindyck (1980) to model uncertainty is also a reasonable one. He asserts that it is more common to see gradual changes in technologies than to see rapid commercialisation of a new process or product. For example, there has not been a complete replacement of copper wires with optical fibre cables in all feasible applications. A more gradual change has occurred.

Pindyck (1980) models demand and reserve uncertainty by shifting the demand curve and reserves level according to a (continuous) stochastic process. In particular, the present is known exactly but the future is not. Stochastic dynamic programming is used to examine the impact of these forms of uncertainty on competitive, monopolistic and a social planner's decisions. However, for risk-neutral firms with constant extraction costs, both forms of uncertainty do not change Hotelling's *r*-percent rule (in expected values) under competitive and monopolistic conditions. Also, with constant extraction costs, exploratory effort is shown to be valueless to producers as a means of reducing stochastic fluctuations.

Two papers which together cover important related territory on uncertainty in non-renewable resource markets are Devarajan and Fisher (1982*a*, *b*). In both papers the authors are interested in measuring resource rents and in explaining how these rents are influenced by uncertainty, which enters via a stochastic production function for exploration. In the first article the authors investigate the effect of uncertainty on both risk-averse and risk-neutral firm behaviour. The risk-averse firm maximises the expected utility of the net present value of profits over two periods subject to a state equation for reserves. They find that the effect of uncertainty on exploratory effort depends critically on key parameters of the exploration and extraction cost functions and the firm's degree of risk aversion.

The results for the risk-neutral firm are re-emphasised in Devarajan and Fisher (1982*b*). They argue that, under risk neutrality, the firm may be induced to explore beyond the point at which expected marginal discovery cost exceeds rent. Further, it is noted that where uncertainty is faced by an entire industry, a competitive equilibrium will not be socially efficient. That is, 'If . . . there is an industry risk, though producers will continue to overlook the effect of their actions on prices, a planner ideally will not' (Devarajan and Fisher 1982*b*, p. 1287). The latest sequel to this research is Lassere (1985) which extends Devarajan and Fisher (1982*b*) to a general multi-period framework.

One of the loudest rumblings in the natural resource literature on uncertainty remains to be heard. Is it reasonable to assume that, faced with information deficiencies, economic agents will still behave as complete rather than myopic dynamic optimisers? Graham-Tomasi, Runge and Hyde (1986) consider this question at length but there are two issues worth highlighting. First, the framework of rational expectations fits rather neatly with optimal control theory. Rational dynamic efficiency involves modelling a sequence of temporary rational asset market equilibria. It would seem that a good empirical test of such a model would tell us whether we should put more research effort into analysing myopic optimisation scenarios.

Second, to the extent that there are going to be examples where myopic behaviour is apparent, some research effort could go into developing recursive programming models of natural resource behaviour under uncertainty. Recursive programming is promising because as Labys and Pollak (1988, p. 68) observe, 'The rationale behind this approach is that it emulates a decision maker who proceeds according to a succession of behaviourally conditioned, suboptimising decisions. The decision maker in protecting himself from errors of estimation and forecasting reviews his maximisation plans each period based on current information'. In this context, a Bayesian updating procedure could be used to process new information and help resolve uncertainty, as in Bjorstad, Hefting and Stensland (1989).

The case of risk and mineral taxation

Having discussed property rights and uncertainty, some of these concepts can now be brought together. A specific example worth considering is the effect of risk in determining an optimal mineral taxation scheme (see Hinchy *et al.* 1989 for further details).

In the area of mineral taxation the government makes decisions that influence the distribution of risk and the efficiency of resource allocation. The terms on which the government assigns property rights to mineral sites will determine how the risks that can be transferred under the terms of the contract are shared between the government and the recipient firms. If a firm makes a lump sum payment for the rights to a site, then the firm bears all the risk. The government receives a certain (that is, a riskless) payment, while the firm bears the entire risk of an uncertain income stream from the site, including the possibility that zero or negative net income may be derived (in the event that exploration expenditure was undertaken without a commercial find being made).

If, instead, the exchange takes place in return for the firm undertaking to pay some type of tax that is dependent on the outcome of the project, then the government bears all the risk associated with the transfer. The government bears the risk of an uncertain income stream, including the possibility of no income (or even negative income, if the government undertook to pay the firm a rebate on unsuccessful exploration expenditure). Furthermore, if exploration proves unsuccessful, the amount the government would receive from re-auctioning the site is likely to be less (possibly zero) than the amount it would have received by auctioning the site before exploration.

Of course, this is not to deny that after the transfer is made particular firms face exploration, production and demand risks. If the contract specifies both an initial lump sum payment and a tax dependent on the outcome of the project, then risks will be shared between the parties. Of course, sovereign risk will always remain and will have a significant effect on the attitudes adopted by private firms. Two questions that remain unresolved is just how risk averse the government is compared with individuals or firms and how the question of intergenerational equity should be dealt with.

Intergenerational Equity

How does society determine the trade-off between exploiting a resource now and saving it for the future? This question comes down to one of intergenerational equity. What does the current generation owe those generations as yet unborn?

Spash and d'Arge (1989) point out that much of the literature that addresses the question of intergenerational equity in relation to non-renewable resources focuses on the maintenance of future productive capacity as a means of compensating the future for 'bad' decisions made in the present. For example, Solow (1986) considers one possible intergenerational choice criterion to be the one that maximises the current generation's needs from the common intertemporal resource pool subject to the constraint that it leaves each successive generation as well off as the present one. This seems reasonable as it amounts to saying that the level of consumption possible for any future generation should be at least as high as that available to any past generation. The question becomes one of efficiency: how best to transmit productive capacity to the future. To put it in Solow's (1986, p. 142) words: 'Whether productive capacity should be transmitted across generations in the form of mineral deposits or capital equipment or technological knowledge is more a matter of efficiency than of equity'. Note that Solow's criterion does not imply that all present and future generations' consumption patterns need be identical. For example, use of some resource now in order to build up capital stock and to contribute to new knowledge and technology might be a more effective way of passing on wealth to the next generation than leaving a resource in the ground.

What strategy will lead to the maintenance of a constant stream of consumption over time? One answer, for a particular set of assumptions, is encapsulated in Hartwick's rule (Hartwick 1977; Solow

1986), which is a specific investment policy: in every time period, society must invest in reproducible capital goods the full competitive rents from its current use of non-renewable resources. Some of the assumptions underlying this rule are that there are constant returns to scale, no technological progress and a constant supply of labour. Solow (1986) considers the extensions required to take into account technological change and exogenous population growth. Positive technological change opens up the possibility that, if resource rents are invested in reproducible capital, consumption per person can grow over time. Once allowance is made for the possibility that population growth is endogenous, no simple results are available. But Hartwick's rule does alert us to the question of how resource rents are used and points towards one possible policy. [It also raises a question, addressed by Eliasson (1984), about the implications of investing rents in paper assets rather than investments which improve the capital base of an economy.]

The arguments just presented sidestep two key points raised by Spash and d'Arge (1989). There may be direct consumption transfers for which intertemporal comparisons of utility enter the decision calculus: the preservation of natural beauty is an example. Second, the literature avoids the issue of how to distinguish or separate productive capacity from consumption activities.

Spash and d'Arge consider a simple two-period model in which productive capacity (capital and technological knowledge) and bequests of final goods are passed to the future. They assume expected utility maximisation in order to examine the compensation required for (uncertain) environmental damage, and assume a zero discount rate. Not surprisingly, they find that the marginal utility from each form of transfer must be equal across periods. They point out that care is needed in determining what are suitable items for intertemporal transfer, given the potential inconsistency of preferences over time.

The case of risk and hazardous waste

The issue of intertemporal efficiency in hazardous waste cleanup in the presence of risk is obviously closely allied with intergenerational equity. Segerson (1989) provides a useful summary and analysis of optimal financing of hazardous waste cleanup based on the principal-agent framework. Because future cleanup costs are uncertain, it is apparent that the choice of financing scheme will depend on the polluter's and government's attitudes toward risk. Segerson analyses both retroactive and prospective waste cleanup problems. The results for the prospective case are highlighted below.

Segerson (1989, p. 4) notes that '. . . a financing policy that is applied prospectively generally will have an incentive as well as a risk-sharing effect'. Her results suggest that the optimal financing scheme in which to trade off risk sharing and distortions to incentives is in general a combination of an *ex ante* fixed fee, which could be, say, an environment insurance fund, and an *ex post* liability rule. That is, the government or environment fund bears some of the risk under the fixed-fee arrangement, which could create moral hazard for the polluter. To counterbalance the resulting disincentive to avoid pollution, some amount of *ex post* liability is needed. Full liability would be sub-optimal as it would transfer all the risk to the polluter.

Welfare Criteria

A major problem resource use managers face is the choice of welfare criterion to use in the analysis of various trade-offs. Fisher (1989) claims that where one is considering a catastrophic or irreversible event the Rawls worst-off or maximin criterion may be appropriate, irrespective of discounting and adjustments for uncertainty. Most of the models and results already discussed are derived using objective functions based on discounted streams of consumption or expected producer and consumer surpluses. Although it is more appropriate to deal with these types of problems in a utility framework it is also more difficult. In addition, the results from the traditional approaches will not necessarily carry over.

If a utility framework is needed what utility theory do you adopt? Empirical observations show that the choices of individuals are not always consistent with those predicted by expected utility theory. Because of this, those theories that have been grouped together as generalised utility theories (GUTs) are of relevance in this context. Perhaps the main point of relevance to empirical applications that can be drawn from generalised utility theory is that if preferences are expressed in terms of the moments of probability distributions, the third moment, that is skewness, should not be ignored (Quiggin and Fisher 1989). In many cases where observed preferences are inconsistent with expected utility theory, a significant change in the skewness of the relevant distribution occurs. A preference for positively skewed distributions is a central feature of the generalised utility theories. Such a preference can be used to explain the fact that a given individual may display both risk-averse behaviour, by taking out insurance, and risk-preferring behaviour, by gambling.

Bromley (1989) emphasises the importance of attitudes to risk in relation to the problem of intertemporal externalities. He cites empirical evidence to suggest that agents are risk averse in the positive domain and risk seeking in the negative domain, a feature which is explained by GUTs but obviously not by expected utility theory. He argues that this tendency helps explain why minmax criteria functions are used by governments in the design of environmental damage policy. It can be convincingly argued that, in many problems in resource management, the main conflict and discussion revolves around the effects of low probability event with severe consequences. Problems of this type are the ones where generalised utility theory has something to contribute. More needs to be done in this area.

Unpriced Values

In discussing Hartwick's rule the question of how to value natural beauty was sidestepped because, to quote Solow (1986, p. 142), 'The preservation of natural beauty is a different matter since that is more a question of direct consumption than of instrumental productive capacity'. However, it is possible to use dynamic duality theory and mathematical programming techniques as methods to impute the user costs of resources.

Practical and conceptual problems cloud some particular aspects of most of the indirect and direct methods which essentially attempt to measure the social costs and benefits of unpriced resources. In cost effectiveness studies, the emphasis is placed on measuring the maximum commercial net benefits from a project. The opportunity cost approach is obviously a useful starting point for obtaining information on the costs of using an unpriced resource but raises the issue of how to determine what is a reasonable choice set of potential projects over time and space and ignores the problem of multiple objectives and interdependences. In addition, the decision maker still requires an implicit reference price for the unpriced good.

The main pros and cons of techniques used to measure unpriced values are well known (Hanley 1988). Simple problems with the travel cost method include how to deal with congestion and multiple stops. Hedonic pricing rests on there being a strong correlation between the demand for the unpriced and priced goods. Both of these indirect methods ignore the values of non-use or existence value and the value of goods not yet supplied (Frederick 1990). These two shortcomings are dealt with by the contingent valuation method, which involves using a sample survey of unpriced values.

As to the design of contingent valuation games, there appears to be a growing consensus that sampling biases, due to such factors as strategic behaviour, inadequate information and starting point problems, can be minimised. For example, discrete choices rather than continuous choices could be elicited. However, in this approach, the problem of how to aggregate individual results, that is, what is a reasonable form of social welfare function, is directly confronted, and only some of the rules governing the appropriate welfare measurement are clear.

The promise of the contingent valuation approach is that it could be used to explore which utility theories are most relevant in the context of public goods and externalities, and to test the hypotheses of rational or myopic expectations in natural resource markets. It could also provide insights into issues of intergenerational equity.

Technology

The second last point we want to touch on is the question of how technology might be modelled. It seems that we have not devoted enough time to studying the process of technological change in view of its underlying importance. What is the best way to model what is effectively a stochastic process? What is the nature of technological change? Those issues are important because they have a direct bearing on how quickly substitutes might appear for mineral products that we currently rely on, and how mining and mine restoration technology might develop.

Metcalfe (1987) notes that the standard breakdown of technical change into three phases, invention, innovation and diffusion, has tended to promote a fragmented analysis of this dynamic process, overlooking interdependence and feedback relationships.

There is growing evidence that modelling technical change using time trends is unsatisfactory. For example, Larson (1989) notes that all too often *ad hoc* time trends are appended to otherwise autonomous optimal control problems. If the aim is to proxy technical change with a time trend, then for consistency the analyst is forced to solve a non-autonomous optimal control problem. Alternatively, there is plenty of scope for using continuous stochastic processes as a means of analysing technical change. One such study (Pindyck 1980) has already been mentioned. Another more recent example is research by Stefanou (1987) which focuses on the effects of uncertainties about technical change on capital accumulation.

The concept of endogenous transition to new technologies can be taken a long way. For example, Kim, Moore, Hanchar and Nieswiadomy (1989) consider substitution responses to the rising scarcity of groundwater. The authors develop a general multistage optimal control technique which would appear to have considerable promise in analysing various facets of technical change. The authors consider the use of both planning and common property equilibria to analyse the intertemporal allocation of scarce groundwater among crops. They find that farm operators, in response to a rising shadow price for groundwater, tend to switch to less-water-intensive crops at a much faster rate than is economically efficient.

Simpler analytical techniques also have their place in providing insights into the effects of technical change. For example, Milliman and Prince (1989) illustrate some of the effects of various regulatory regimes on a firm's incentives to promote technological change in pollution control. They use standard scissor graph measurements of producer welfare gains to rank firms' incentives in technical innovation, diffusion and 'optimal agency responses' (adjustments to ensure an allocatively efficient adoption of the technology) in the presence of different pollution regulations. The regulations considered are direct controls, emission subsidies, emission taxes, free marketable permits and auctioned marketable permits. Milliman and Prince (1989, p. 260) find that '... once implementation has occurred, emission taxes and auctioned permits are better facilitators of technological change. This conclusion is based on the potential for significant firm gains beyond the initial step of innovation under these regimes.'

It is also worth mentioning a simple technique for comparing total factor productivities in extractive and non-extractive sectors (Lassere and Ouellette 1985). All too often, when constructing Divisia indexes of total factor productivity, the fact is ignored that one of the inputs to the extractive firm is a natural resource with special features. A meaningful intersectoral comparison requires comparison of like with like. Consequently, for the extractive sector the productivity index is the standard KLEM measure adjusted to exclude the negative contribution of (proxied) changes in resource quality and availability.

Last, consider those tailings dumps at Kalgoorlie mentioned earlier. When dumped, those tailings were considered wastes. Some would consider those dumps unsightly and damaging to the environment in the immediate vicinity. But those dumps still contain gold and have been sited, probably by accident, in such a way as to make recovery of the tailings relatively easy. Gold recovery technology and the price of gold have now improved enough to make it economic to flush the tailings into drains, collect the slurry and process it in a modern plant to recover about half the available gold. The tailings are then collected in a new holding area. The simple point here is that new knowledge has offered opportunities for further mineral recovery and for restoration of the original dump sites that were probably never contemplated by the original miners.

Discounting

Before concluding, the final question worth touching on in this short paper is the possibility of a divergence between the private discount rate and the social time preference rate. There is a substantial literature on this subject. Of course, the retort to the premise that a low social discount rate will stop projects with high environment costs is simply to state conditions under which the converse holds. Nevertheless, there are two good reasons to think that the social discount rate could be below the private rate. Samuelson (1964) and Arrow and Lind (1970) first argued that agents acting collectively, say through a public agency, may reduce risk by risk pooling and risk spreading, respectively. This means that the extent to which private risk markets are incomplete needs to be empirically investigated (Fisher 1989). Second, according to Marglin (1963), if the current generation views the welfare of future ones as a public rather than a private good then the current generation will collectively want more investment now.

Clearly then, one of the harder questions we face as economists is deciding on what interest rate to use in applying a cost–benefit framework to the solution of resource-use problems. The general public is likely to be suspicious of a profession that produces an estimate of the net present value of world gross national product in 100 years time of say $10b. It is not that the estimate is wrong as such but that the general public do not understand the concept and therefore find the proposition unsustainable. Our plea is that we try to explain ourselves a little better. In addition, if only for the two reasons mentioned above, sensitivity analysis with respect to the choice of social discount rate should be a prerequisite in cost–benefit appraisals.

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