Environmental Option Values: a Survey

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SUMMARY

This paper surveys the literature on environmental option values taking into account the literature on financial option values. The existing measures of environmental option value may be classified according to a basic dichotomy between (plain) option values and intertemporal option values. The first concept is relevant when markets are complete and agents are risk averse; the second concept is relevant when markets are incomplete, the consequences of choices are (at least in part) irreversible, and learning before subsequent choices is not ruled out. The second concept is relevant when markets are incomplete, the consequences of choices are (at least in part) irreversible, and learning before subsequent choices is not ruled out. The second concept is the most general and crucial for the conservation of the environment although the measures suggested so far are not fully satisfactory.

SOMMARIO

Questo lavoro passa in rassegna i principali contributi sui valori d'opzione ambientali tenendo conto anche dei contributi sui valori d'opzione finanziari. Le misure esistenti dei valori d'opzione ambientali possono essere classificate secondo una dicotonia fondamentale tra (semplice) valore d'opzione e valori d'opzioneintertemporali. Il primo concetto si applica quando i mercati sono completi e gli agenti economici sono avversi al rischio; il secondo concetto si applica quando i mercati sono incompleti, le conseguenze delle scelte sono (almeno) irreversibili ed è possibile apprendere prima delle scelte successive. Il secondo concetto è più generale e risulta cruciale per fondare una politica di conservazione dell'ambiente, anche se le misure fin qui suggerite dei valori d'opzione intertemporali non sono del tutto soddisfacenti. si propone di valutare criticamente la proposta di introduzione sistematica delle cauzioni ambientali per controllare i rischi ambientali. Per chiarire i principali problemi sollevati dai lavori esistenti in argomento, risulta necessario introdurre la distinzione tra due tipi di cauzione ambientale i cui vantaggi, svantaggi ed ambito di applicazione risultano alquanto differenti.

CONTENTS

1. Introduction[1]

Environmental conservation is advocated for a host of reasons, many of which are extraeconomic: ethical, aesthetic, religious, and so forth. These motivations have an economic impact which should not be neglected since many people would be prepared to pay a sizeable amount of money in order to conserve certain environmental goods. However environmental conservation is also advocated for strictly economic reasons, some of which have often been neglected by mainstream economic theory. Whenever there is uncertainty and the choice of a decision-maker may have irreversible consequences, the conservation of an environmental good may be justified, irrespective of any extraeconomic consideration, by virtue of its implicit intertemporal option value (or quasi-option value), i. e. by virtue of the fact that by preserving the environmental good, one gains the possibility of exploiting subsequent information on the pros and cons of existing alternative choice strategies. In other words, the choice of preserving an environmental good gives time to learn and eventually discover a more profitable choice strategy.

The preference for intertemporal flexibility revealed by (quasi-)option values has been analyzed in monetary and financial theory at least since Keynes (1936), who called it (speculative) liquidity preference. The idea was subsequently developed by Hart (1942), Marschak (1938, 1949), Marschak-Nelson

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1 Though this paper was jointly written by the authors, Marcello Basili takes responsibility for section 3, and Alessandro Vercelli for the rest of the paper.

(1962) and others. Similar ideas have been introduced in environmental economics since the seminal contributions by Weisbrod (1964) and Krutilla (1967). Rigorous treatments were suggested by Arrow-Fisher (1974) and Henry (1974, a and b) which are the starting point for the recent debate.

This paper surveys a few crucial aspects of the literature on environmental option values (or quasi-option values), taking into account the parallel literature on liquidity preference and financial option values. In the second section the concept of quasi-option value is clarified with reference to other partially overlapping concepts, emphasizing its crucial role in measuring the preference for intertemporal flexibility. In the third section different measures of intertemporal option values are briefly presented and discussed. A few concluding remarks follow.

2. Option value and intertemporal flexibility

The recent environmental literature has stressed the importance of a family of values which depend, at least in part, on non-user benefits: existence value, bequest value, waiting value, option value, quasi-option value, flexibility preference, etc. A close affinity among these concepts is readily recognizable, but the exact nature of their mutual relationships has not yet been sufficiently clarified. In this section we will try to put some order in this conceptual web in order to orientate the ensuing discussion. The main thesis that will emerge from this short critical survey is the following: the basic concept for an economic analysis of environmental conservation is that of 'intertemporal' option value, or 'quasi-option value' whose existence and degree rests on intertemporal flexibility preference.

2.1 Non-use value and (quasi-)option value

Krutilla (1967) was the first to emphasize the importance of non-user benefits in order to efficiently allocate natural resources. He defined the existence value, which expresses the desire to preserve certain natural resources, and the bequest value, which measures the propensity to leave a certain amount of natural resources to future generations. Both these categories of value depend mainly on extra-economic motivations, such as aesthetic and ethical considerations, but they have potential economic impact as people are prepared to pay for them[2]. In other words, the environment appears in the utility function not only indirectly as use value (which depends directly on the consumption of different kinds of natural resources), but also directly as non-use value. Existence and bequest value also depend on economic considerations based on the prospective use value of certain natural resources due to possible future changes in the conditions of economic activity (change in tastes, in the choice set, in the consequences of actions, in the quality of goods, etc.).

The economic aspects of environmental conservation under uncertainty have recently been studied in terms of option values and quasi-option values[3]. In the recent debate[4], Weisbrod (1964) was the first, to relate environmental conservation to option value. Considering, for example, an action with irreversible consequences such as the closure of a national park, he argued that many people would be willing to pay something to preserve the option of visiting the park in the future. Under uncertainty and risk aversion, it is generally rational to keep open an option which could turn out to be useful in the future.

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2 Empirical work based on contingent valuation confirms a disposition to pay per adult per year for the conservation of environmental goods as in the following examples:

-$8 for the conservation of tropical forests (Markandya, 1991);

-$6 for the conservation of the European salmon (Salmo salar) in New England (Stevens et al., 1991);

-$28 for the conservation of a rare kind of eagle (Haliaetus leucocephalus) in New England (ibidem).

A general survey of this sort of empirical estimation may be found in Swanson-Barbier, 1992.

3 Option values and quasi-option values may also be related to possible future changes in extraeconomic values, but these topics have been neglected so far by the economic literature.

4 A concept similar to that of option value may already be found in the concept of 'prospective utility' analyzed by Jevons, 1888 (see Moretti, 1993a).

Later on, Arrow-Fisher (1974) and Henry (1974, a and b) independently pointed out that under uncertainty, when a given decision may have irreversible effects (at least in part) and learning is possible before future decisions, it is generally valuable to keep open an option, even in the case of risk neutrality. Arrow and Fisher called 'quasi-option value' the extra value attached to the preservation of the reversible option in order to stress the crucial role played in their analysis by irreversibility and learning (neglected in the preceding analysis of option value), and stressed its independence of risk aversion. Notwithstanding the misleading name, we should consider the theory of environmental quasi-option values as the most general approach to intertemporal flexibility and environmental conservation under uncertainty, since it is relevant whenever there are at least two options the consequences of which have different degrees of irreversibility[5] (perfect temporal symmetry would obviously be an extreme case), and whenever learning is possible before future choices are made (the impossibility of learning would be a very extreme hypothesis)[6].

In order to avoid confusion, not absent in the literature even after the illuminating contributions by Arrow-Fisher (1974) and Henry (1974a and b), we have to distinguish sharply between two concepts of option value. Although both refer to rational behaviour under conditions of uncertainty and assume different degrees of reversibility of available choices, the conceptual differences are quite radical.

The (plain) option value is an expression of rational behaviour towards soft uncertainty ('risk'). The intertemporal option value ('quasi-option value') is an expression of rational behaviour towards hard uncertainty (Jones-Ostroy,

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5 Irreversibility is also sometimes considered in the literature on option value, but its role is not clearly spelled out.

6 Another magnitude conceptually close to (quasi-)option value is the 'value of waiting' which is analyzed mainly in order to choose the optimal starting time for a new project or investment. The value of waiting may be regarded as a special case of (quasi-)option value when a subset of two alternatives (to start the investment or to postpone it) is involved (see, e.g., McDonald-Siegel, 1986).

p.26). This second concept of option value is defined as intertemporal because the intertemporal decision problem cannot be reduced, even in principle, to the choice in the first period of the optimal contingent strategy, unlike in the first case. In this second case, learning before a subsequent choice is the crucial factor. In the first case, learning intervenes only in the very weak sense of prompt recognition of the contingencies to which to adapt the optimal strategy. In the case of intertemporal option value, learning plays a strategic role as new information may be used to detect systematic mistakes produced by the existing strategy so that it can be replaced with a better one. Option value is a sort of 'risk premium' the value of which is mainly precautionary and related to different adjustment costs (e.g. transaction costs). The value of an intertemporal option is mainly strategic and reveals a preference for intertemporal flexibility which is related to the reversal costs of a given strategy and is higher the larger the choice set available for the future[7].

The main results of the contributions of Arrow-Fisher (1974) and Henry (1974, a and b) were the following:

(a) the sign of the intertemporal option ('quasi-option') value is positive under quite general assumptions;

(b) an increase in uncertainty induces an increase in the intertemporal option value and therefore encourages environmental conservation.

Both these conclusions were challenged in the ensuing debate. The debate on the importance and the sign of quasi-option value clarified the dependence of the intertemporal option value on the shape of the benefit function, the relationship with different types of uncertainty, etc. Today there is a wide agreement that option value should be regarded not as the

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7 In monetary theory the distinction was already quite clear with Keynes (1936) who distinguished between precautionary liquidity related to probability ('risk' in the Knightian sense) and speculative liquidity related to the weight of evidence ('uncertainty' in the Knightian sense). In this view, precautionary liquidity plays the role of a risk-premium, while speculative liquidity is best interpreted in terms of preference for intertemporal flexibility (Hicks, 1974). A similar dichotomy was emphasised by Makower and Marschak (1938) who distinguished between two properties of liquidity: safety and plasticity.

"unrecognized son of that old goat, consumer surplus", as argued by Long (1967), but rather as an extra component of the benefits associated with preservation.

As for the sign of intertemporal option value, Schmalensee (1972) and Bohm (1975) claimed that the sign of option value is undetermined as it depends on the particular shape of utility functions. Plummer and Hartmann (1986) found an undetermined sign when uncertainty is related to a change of preference but were able to prove that when uncertainty is relative to the quality of an environmental good, the sign of option value is generally positive. As soon as we consider irreversibility, neglected by the preceding models, a positive quasi-option value becomes likely (Smith, 1983). However, also in this case, it has been maintained (notably by Freeman, 1985) that the sign of quasi-option value need not be positive. On the contrary, Fisher and Hanemann (1987, p.189) proved that if information about future benefits and costs of development is independent of the current development decisions, the quasi-option value of preservation must be positive. Assertions to the contrary are based on confusion of quasi-option value with the net benefit of preservation which need not be positive.

These results were recently confirmed by Hanemann (1989), but have been criticized by Olson (1990), who claimed that when the developed resource is utilized as an input to production, an unambiguous bias toward preservation does not exist. In his opinion, preservation, by reducing current production, may jeopardize future consumption opportunities. However, Moretti (1993b) has proved that Olson's conclusions depend on very restrictive assumptions and collapse in a more general model. At this stage of the ongoing debate, it may be concluded that the sign of a quasi-option value is likely to be positive under quite general circumstances.

As for the effects of an increase in uncertainty on the intertemporal option value, the results obtained by Arrow-Fisher (1974) and Henry (1974a and b) have been confirmed in a different analytical setting by Jones and Ostroy (1984). Generally speaking, an increase in uncertainty tends to increase the intertemporal option value, inducing a more conservationist environmental policy. However, this statement is quite sensitive to different assumptions on the nature of prospective information and viable learning processes. Generally speaking, the more it is possible to learn in subsequent periods, the more it is rational to increase intertemporal flexibility, which allows the exploitation of expected learning (Epstein, 1980). However, if prospective learning depends on the choice made in the first period, the above conclusions may be altered (Viscusi-Zeckauser, 1976; Miller-Lad, 1984). If uncertainty refers to the benefits of development, learning might depend on the effective implementation of the development project, so that the desirability of a policy of environmental conservation would be weakened. If uncertainty refers to the conservation benefits, learning is fostered by a conservaton policy. In addition, when information is dependent on development, a very slow and cautious process of development could be sufficient to make learning possible (Fisher-Hanemann, 1987, p.190).

The consequences of an increase in uncertainty on quasi-option values are ambiguous because we have assumed uncertainty neutrality[8] so far. As soon as we assume uncertainty aversion, an increase in uncertainty generally increases the intertemporal option values (Caballero, 1991). Whenever uncertainty neutrality is assumed, the option values are sensitive not to the degree of 'risk', but to the amount and characteristics of expected learning which depends not only on the amount of missing information, but also on the actual viability and timing of learning and its dependence on different categories of actions.

We cannot say much a priori about the degree of uncertainty aversion (as is usual with individual tastes), however, psychological considerations provide some insights. A few authors have observed that ignorance of relevant information that could be possessed by someone else is particularly upsetting. This may explain why hard uncertainty may restrain people from betting, particularly when they feel incompetent in the field to which the bet relates (Heath-Tversky, 1991; Frisch-Baron, 1988). Further insights come from experimental economics. Generally speaking, economic agents are uncertainty

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8 It is necessary to speak of uncertainty neutrality or aversion rather than of risk neutrality or aversion, since irreversibility implies hard uncertainty. An analysis of a few measures of uncertainty aversion may be found in Montesano (1993).

averse, though a limited degree of uncertainty preference may emerge for very low gain probability or for very high loss probability (Hogart-Einhorn, 1990, and Camerer-Weber, 1992). It is also confirmed that agents prefer to bet on events in which they feel fairly competent (Fellner, 1961, p.687; Keppe-Weber, 1991), or on events whose occurrence is affected by their ability rather than on purely random events (Langer, 1975). Similarly, they prefer to bet on future events rather than on past events which might be known to others (Brun-Teigen, 1990). These experimental results also depend on the fact that competence affects the social attitude towards the choices of an agent: competent people may be praised for having chosen the right bet, while incompetent people may be only blamed for having chosen the wrong bet (Heath-Tversky, 1991). Finally, uncertainty aversion increases when the bet is adjudicated in public (Curley-Yates-Abrams, 1986).

Summing up, the recent literature clarifies that the value of an intertemporal option under uncertainty and irreversibility depends on two basic factors: the value attributed by the decision-maker to prospective learning and the degree of uncertainty aversion which depends crucially on the stock of past learning or competence.

2.2. Quasi-option value and intertemporal flexibility

The analysis of quasi-option values is founded on the assumption of a preference for what we have called 'intertemporal flexibility', whenever the choice is characterized by uncertainty, irreversibility, and potential learning before subsequent decisions. The trouble is that intertemporal flexibility preference is itself in need of solid foundations as it is inconsistent with the mainstream decision theory under uncertainty based on the maximization of EU (Expected Utility; see e.g. Arrow, 1971, and Cohendet-Llerena, 1989), since one of its fundamental axioms, the axiom of independence, implies the dynamic coherence of choices (Strotz, 1956; Hammond, 1988). In this view, a rational agent makes the optimal choice in the initial period, taking into account all the final consequences of each possible choice profile. He then tries to avoid any change of choice profile since this would reduce its expected utility, even by adopting strategies of precommitment, as in the classic case of Ulysses and the Sirens (see, e. g., Elster, 1979), or of drug addiction (see, e. g., Hammond, 1976). According to Strotz (1956), a rational agent is prepared to pay in order to avoid intertemporal incoherence. In other words, the intertemporal coherence of choice implied by EU decision theory implies a preference for intertemporal rigidity, or a negative preference for flexibility, which would exclude the existence of positive quasi-option values.

However EU decision theory is not applicable in situations characterized by hard uncertainty[9] and irreversibility, as it requires that the decision-maker knows all the possible choices and states of nature at any date and all the possible consequences of actions, as well as their utility and probability. These hypotheses are acceptable only in cases of soft uncertainty, when the relevant probability distributions are known and stationary. This is clearly excluded by the joint assumptions of hard uncertainty and irreversibility which underlie intertemporal option values, for a host of reasons:

a) preferences may change, and we do not know when and how;

b) the set of possible actions may change as a consequence of irreversible actions, but we cannot forecast when and how;

c) the consequences of the choices are partly unknown and the probabilities of those which are known are unreliable;

d) a rational agent has a preference for the early resolution of uncertainty[10].

Strotz himself had a clear intuition of the limits of his suggested strategy of precommittment:

'What needs to be explained is not that people do precommit their future actions, but that the practice is not still more wide-spread. The reason it is not, I believe, is because of the presence of risk and uncertainty, both as to future tastes and future opportunities. Because of risk and uncertainty people are also willing to pay for options permitting them a greater range of choice

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9 Uncertainty may be defined 'hard' whenever it may not be expressed in terms of a unique, additive, fully reliable probability distribution (for a short survey of the recent literature on hard uncertainty orientated towards environmental problems, see Vercelli, 1993).

10 This is excluded by EU decision theory which implies indifference to the timing of resolution of uncertainty; otherwise, the axiom of independence would be contradicted (see Willinger, 1990).

at future dates and this is of overwhelming importance, especially as it affects the detailed aspects of future behaviour'.

It should be emphasized that the concepts of rationality underlying mainstream decision theory and that underlying the existence of positive quasi-option values are quite different. EU theory rests on substantive rationality, as the decision-maker is able to choose the optimal choice profile which, by definition, will never be regretted in the future; intertemporal coherence is nothing but a corollary of such a conception of rationality. However, as soon as we assume hard uncertainty and irreversibility, substantial rationality does not apply; we may only adopt a conception of procedural rationality, since the optimal decision strategy may change as a consequence of learning and can only be approximated by periodically revising the sequence of choices according to a rational rule (Favereau, 1989).

Rigorous foundations for a theory of intertemporal option values and of their measurement require a theory of decision under hard uncertainty based on axioms different from those of EU decision theory. The first to suggest a new set of axioms for decision theory under hard uncertainty, incorporating the hypothesis of (intertemporal) flexibility preference, was T. Koopmans (1964). The fundamental axiom suggested by Koopmans establishes a correlation between the relation of inclusion among sets and preference relation: a set of choices is always preferred to any of its subsets, unless their complement is characterized by 'redundant flexibility'. Kreps (1979) generalized Koopmans' set of axioms obtaining a representation theorem for flexibility preference based on the idea that more flexibility is preferred only if the extra choices are associated with a larger set of non-redundant information. Further generalizations have been provided by Freixas-Laffont (1984), Freixas (1986), and Suppes (1987). All these contributions still suffer from a few restrictive assumptions. In particular, it is assumed that uncertainty is fully resolved before future choices. The next step is that of generalizing this sort of decision theory in order to model learning in a satisfactory way[11]. This is particularly important because learning may be properly modeled only in the

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11 A first attempt is that of Willinger (1988), who defines preferences directly on the modalities of revelation of information.

framework of a decision theory incorporating preference for intertemporal flexibility. In a decision framework characterized by full irreversibility or precommittment, information, and consequently learning, is deprived of any strategic value. In the meantime, the existing measures of intertemporal flexibility must be further refined and better founded.

3. Measures of option value

In the preceding section we identified a wide variety of definitions of option value, with or without modifiers. Sometimes these concepts appear to be close relatives, but sometimes we cannot detect more than a vague kinship. In order to create some order in this tangled matter we distinguished two 'ideal-types' at the extremes of the spectrum: the plain option value and the intertemporal option value.

The (plain) option value is the expression of a rational valuation under soft uncertainty ('risk') and depends on the attitude towards (soft) risk, while intertemporal option value (often called 'quasi-option value' in the environmental literature) is the expression of a rational valuation under hard uncertainty and is independent of the attitude towards (soft) risk, although it is sensitive to the attitude towards hard risk (or 'uncertainty' in the Knightian sense). The option value so defined is basically a static concept although its use may be extended to dynamic problems whenever markets are complete and the decision problem is not a genuinely intertemporal one. The intertemporal option value is an intrinsically dynamic concept as it presupposes incomplete markets and a sequential decision problem which cannot be reduced to an equivalent non-sequential problem. Most definitions of option value suggested so far may be classified in a grey zone between these two ideal-types. We shall examine some of them in more detail in order to assess the robustness of the measures of option value suggested so far.

3.1. Marschak and Nelson's measures of flexibility

The seminal contribution of Marschak and Nelson (1962) is the first to suggest a rigorous measure of intertemporal option value and to identify the main problems raised by this attempt. They formulated three alternative measures of flexibility which are at the root of much of the subsequent literature on option value measures. Flexibility is seen as 'that characteristic of early decisions in a sequential chain which permits the decision-maker to adjust and take advantage of the information he perceives as time elapses' (p. 56). Therefore the measures of flexibility analyzed by Marschak and Nelson may be interpreted as measures of option value.

The first measure explored is connected with the size of the second-stage choice set (Λ_2) feasible in (t+1), when a choice a_1 is made in t. Given this $\Lambda_2(a_1)$ subset, they define "an initial action a_1' as more flexible than another action a_1'' if $\Lambda_2(a_1'') \subset \Lambda_2(a_1')$" (ibidem, p.45). In this case, the measure of flexibility depends exclusively on the size of the second-stage choice set: the wider the second-stage set of feasible choices, the more flexible the initial choice. This is fully consistent with intuition. Unfortunately, this measure is not fully satisfactory, since it does not permit a univocal ranking of the initial actions according to the degree of flexibility so defined. In fact, although $\Lambda_2(a_1') \subset \Lambda_2(a_1)$, many actions in $\Lambda_2(a_1')$ may be "more expensive if a_1' is taken initially than if a_1 is taken" (ibidem).

The second measure is based on the payoff of a given initial action a_1 and on second-stage actions. In this case, the payoff π is given by the difference between the revenue, depending on the state of the world w and the second-stage action a_2, and the cost of switching from a_1 to a_2: $\pi=R(w, a_2)-C(a_2, a_1)$.

Then, given two initial actions, a_1'' is more flexible than a_1' if

(i) given any number $\alpha>0$, there exists an action a_2 such that

$$C_2(a_2,a_1'')-C_2(a_2,a_1')>\alpha$$

(ii) there exists a number $\alpha^*\geq 0$ such that for all a_2

$$C_2(a_2,a_1')-C_2(a_2,a_1'')\leq\alpha^*.$$

From these inequalities "the amount by which the more flexible action can turn out to have the lower cost is unbounded; the amount by which the less flexible action can turn out to have the lower cost is bounded" (ibidem, p.46).

The third measure extends the logic of the second measure to situations in which the payoff function cannot be expressed as a difference between a revenue and a cost. An initial action a_1' is more flexible than a_2'' if

(i) given any number $\beta>0$, there exists a signal z_2 such that

$$\pi^*(z_2,a_1')-\pi^*(z_2,a_1'')>\beta$$

(ii) there exists a number $\beta^*>0$ such that for all z_2

$$\pi^*(z_2,a_1'')-\pi^*(z_2,a_1')\leq\beta^*$$

Therefore "the amount by which a_1' can turn out to be better is bounded from below but not from above" (ibidem, p.46).

All these measures are ordinal and they have partial applicability, since "they permit ranking of some pairs of initial actions with respect to flexibility but not all pairs" (Marschak-Nelson, 1962, p.45). According to Marschak and Nelson, the second and third measures never contradict the intuitive notion, best captured by the first measure, 'that an action which permits all the alternatives that another permits, and more besides, is the more flexible of the two' (p.57). However there is a possible tension between the first definition, based on the size of option sets, and the other two, based on the amount of reversal costs, as clearly emerges from the definition of Jones and Ostroy (1984) which combines the two (see, infra, section 3.4.1). The criterion of the size of option sets must be made relative to a certain maximum reversal cost, but the ranking of options may change with different thresholds. As will become clear in the rest of the paper, none of the existing measures seems able to overcome this problem.

3.2. Environmental measures

A further step towards a clear distinction between option value and intertemporal option value comes from environmental economics.

Arrow and Fisher (1974). Arrow and Fisher proved that whenever uncertainty is assumed, 'even where it is not appropriate to postulate risk aversion in evaluating an activity, something of the feel of risk-aversion is produced by a restriction on reversibility of decision' (Arrow and Fisher, 1974, p.318). Therefore, assuming risk-neutrality, they were able to identify 'a quasi-option value having an effect in the same direction as risk aversion, namely, a reduction in net benefits from development' (ibidem, p.315).

In order to define the notion of 'quasi-option value', Arrow and Fisher work out a very simple two-period model where the decision-maker is uncertain about the future state of nature and faces two feasible choices, one of which is irreversible while the other is reversible. Then they calculate the net expected benefits of the irreversible and reversible choices, whether a given event, favourable to the irreversible decision, occurs or not. The difference in conditional expected benefits between the irreversible and reversible choice gives the net benefit of the irreversible choice; whenever this measure is positive, it is optimal to choose the irreversible choice (development of the area) in the first period. They repeat the same sort of evaluation procedure assuming that the decision-maker replaces the uncertain variables with their expected values and find that 'the expected value of benefits under uncertainty is seen to be less than the value of benefits under certainty' (ibidem, p.317). The value of this difference is named 'quasi-option value' and is related to the possibility, permitted by the reversible choice and not by the irreversible choice, of acquiring and exploiting further information before the second-period decision. This 'irreversibility effect' clearly identifies what we have called a 'intertemporal option value' although in the Arrow and Fisher model soft uncertainty is assumed. This precludes the analysis of further factors which may influence the intertemporal option value, as for example the subjective attitude towards hard uncertainty, which should be sharply distinguished by the attitude towards 'risk'.

Henry (1974). The same year, independently of Arrow and Fisher, Henry published two seminal articles which further clarify what Arrow and Fisher had called 'quasi-option value', although from a slightly different perspective. He proved (1974a) that the coexistence of uncertainty and irreversibility prevents the use of the standard certainty-equivalence methods to solve decision problems, even when the payoff function is quadratic. He also clarified that, given an uncertain future, available indivisible decisions and a sequential decision process in which uncertainty may be reduced by incremental information, the 'existence of a positive option value is a very general property, true whatever the number of periods, the way of coming to fuller information, the intertemporal shape of utility function and the lesser or greater the uncertainty of the benefits and costs' (Henry, 1974b, p.94).

The contributions of Henry are an important step in the direction of a clarification of the concept of intertemporal option value. However, the measure suggested suffers from a few shortcomings. In particular, even in this case, the influence of different modalities of uncertainty is not explored. This is unfortunate because the coexistence of irreversibility and learning is hardly consistent with soft uncertainty and, in any case, learning may have different features and a diffent value with different modalities of uncertainty. Therefore, only the case of independent learning can be considered.

As we have saw in section 2, the subsequent literature on environmental option values has somewhat further developed the seminal ideas of Arrow-Fisher and Henry, but the measures of sequential option value suggested so far are still quite unsatisfactory. In the remaining part of this section, we shall explore whether some useful suggestions may come from the monetary and financial literature which, in its turn, has tried to develop a measure of sequential option value related to liquidity preference and negotiable financial options.

3.3 Monetary and financial measures

As mentioned in section 2, monetary and financial theory tried to define measures of option values even before the environmental literature. The monetary and financial measures suggested so far may be classified in two broad categories: objective and subjective measures. The objective measures try to work out an 'operational' measure independent of the individual characteristics of the decision-maker. This is appealing because it would greatly simplify the application of the theory to actual choices. However, according to a few authors, this target is utopistic, if not misleading. In their opinion, less ambitious but more robust subjective measures should be worked out. We will now consider in some detail a selected sample of these two categories of measure.

3.4.1. Objective measures

The idea of a measure independent of the subjective characteristics of the decision-maker is certainly appealing, because it would avoid ambiguities while improving the robustness of option value theory. It is therefore worthwhile to evaluate the success of the efforts made in this direction.

Jones and Ostroy (1984). Jones and Ostroy's important contribution is a very comprehensive and illuminating synthesis of the preceding literature on option values and also takes the environmental literature into account. In particular, they establish a connection between an ordering based on the variability of beliefs, and an ordering of current actions, or positions, based on flexibility. In a sequential decision problem, a clear behavioral principle emerges: "the more variable are a decision-maker's beliefs, the more flexible is the position he will choose. This principle potentially applies whenever (i) there will be opportunities to act after further information is received, and (ii) current actions influence either the attractiveness or availability of different future actions" (Jones and Ostroy, 1984, p.13).

Jones and Ostroy assume a set of states of the world (S) and a set of messages (Y), each element $s \in S$ and $y \in Y$ having a probability measure. Given the sets of possible probability vectors on states (Ω_S) and messages (Ω_Y), naming $(\Omega_S)^Y$ the set of conditional distributions of s given y, Jones and Ostroy denote a belief conditional on the message y with $\pi(y) \in \Omega_S$. The set of conditional beliefs is termed 'information structure' (Γ,q) as in Marschak-Miyasawa (1968). On this basis, Jones and Ostroy compare two information structures and define a partial ordering based on the variability of beliefs. In order to define a belief more variable than another, they propose using the (gross) value of the information structure or regarding (Γ,q) as an «experiment» in Blackwell's sense (1951 and 1953). The gross value of the information structure is the maximum expected utility, and a structure is more informative than another if its gross value is not inferior to that of the other structure. In the second case, the structure is defined by its likelihood matrix (Bohnenblust-Shapley-Sherman, 1949): an information structure Y is more informative than another structure Y' if the convex hull $K(W_Y{}^W)$ of the set $W_Y{}^W$, contains $W_{Y'}{}^W$ for all w[12]. Jones and Ostroy assume the following switching cost function $G(a,s,\alpha) \equiv \{b: c(a,b,s) \leq \alpha\}$, $a \in A$, $b \in B$, $s \in S$, $\alpha \geq 0$, such that:

(i) $G(a,s,\alpha)=0$ if $\alpha<0$ for $(a,s) \in A_x S$
(non-negative switching costs);

(ii) there exists a $g: A \to B$ such that $g(a) \in G(a,s,0)$ for all $(a,s) \in A_x S$
(zero switching cost alternative).

Using G, they define a partial ordering on A, such that position a is more flexible than a' if, given $\alpha \geq 0$ and $s \in S$, $G(a',s,\alpha) \cup g(a') \subset G(a,s,\alpha)$; that is "the set of

12 Given an information structure Y and a payoff function w, we can find the set $W_Y{}^W$.

positions attainable from a always contains the set attainable from a', excluding its zero cost option g(a')" (ibidem, p. 17).

Combining the two partial orderings, they derive a net payoff function, additive in both costs and returns, that represents the result of a sequential decision process. From the strategy that maximizes the expected total payoff $J(\Gamma,q)=\max_{a\in A}[\hat{r}(a)+V(a;\Gamma,q)]$, Jones and Ostroy derive the following order-preserving relation[13]: if $(\Gamma,q)\geq(\Gamma',q')$ and $a\geq a'$ then

$$V(a;\Gamma,q)-V(a;\Gamma',q')\geq V(a';\Gamma,q)-V(a';\Gamma'q').$$

Crucial assumption for the validity of this order-preserving relationship between variability and flexibility, is that the difference of two convex functions $v(a;\pi)-v(a';\pi)$ is also convex. Therefore "when all positions are perfectly flexible, the optimal initial position is that which offers the highest expected first period return ... when all positions are economically irreversible, the optimal position depends only on prior beliefs $\hat{\pi}$ ... an increase in the variability of beliefs raises the value of any position relative to any economically irreversible position" (ibidem, p. 20).

The approach of Jones and Ostroy engenders a few technical perplexities. The first doubt regards the possibility of deriving a net payoff function. In fact, the function that distinguishes between the monetary profit of a decision and the monetary cost associated with a message not only presupposes a linear utility function for money, but may also reverse the preference ordering. In fact, whenever the net payoff w_y is decomposed into gross payoff w and information cost $\mu(y)$, then:

(i) $w_y(z,d,y)=w(z,d)-\mu(y)$ such that for any $k\in R_+$

(ii) $k>U_y(Y;w_y)-U_{y'}(Y';w_{y'})\geq 0$

and "it is always possible to imagine information cost functions k(y), k'(y') that would reverse the second inequality in (ii)" (Marschak-Miyasawa 1968, p.149). That is, another pair of net payoff functions $\hat{w}_y$ and $\hat{w}_{y'}$ exists such that $U_y(Y;\hat{w}_y)-U_{y'}(Y';w_{y'})<0$. In this way, the preference ordering cannot be preserved. Since the structure of the net payoff function is fundamental in

13 An increase in the variability of beliefs never leads to the choice of a less flexible position.

the definition of ordering of alternatives, its rebuttal would have a devastating effect on the model.

The second technical doubt is connected with the role of switching costs to determine the objective measure of flexibility. If "an agent is interested in the costs of a change in asset position only for states at which he will find it optimal to change [then] the agent may regard a chosen *a* as more flexible than another without satisfying the Jones-Ostroy criterion" (Hahn, 1990, p.72). In addition, as it was rightly observed by Hahn (1990), the assumption of convexity of the difference between the variability of belief function and the flexibility function looks arbitrary[14].

Jones and Ostroy show a clear understanding of the need to distinguish between two different concepts of option value (or 'liquidity preference'): one expresses behaviour towards 'risk' (as in the famous paper by Tobin, 1958), the other (which corresponds to what was called here 'intertemporal option value') expresses behaviour toward 'uncertainty' (as stressed by Hart, 1942, and Hicks, 1974):

'One individual might value flexibility because, by appropriately adapting choices to the information received, it permits a more nearly certain pecuniary reward; but another might value it because it allows the making of informed higher risk bets at the last moment. The way flexibility is used to exploit forthcoming information may be dictated by attitudes toward risk; but flexible positions are attractive not because they are safe stores of value, but because they are good stores of options'(Jones-Ostroy, 1984, p.14)

Therefore Jones and Ostroy correctly emphasize that the second meaning of option value, intertemporal option value, is 'basically unconnected with risk aversion' (ibidem). Unfortunately, in Jones and Ostroy's paper the analysis of the role of hard uncertainty is quite rudimentary. In particular, the degree of

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14 On the contrary, it is possible to defend the contribution of Jones and Ostroy from another charge of arbitrariness raised by Hahn (1990). The assumption of linearity of the utility function is justified by the assumption of risk neutrality which is meant to distinguish the sequential option value, unrelated to risk aversion, from plain option value which crucially depends on risk aversion.

hard uncertainty is measured by an index of dispersion of second-order probability distributions, interpreted as an index of variability of beliefs. Even neglecting the criticism raised against this sort of measure of uncertainty (see Vercelli, 1994, and the literature there cited), its application requires the assumption of identical prior beliefs of decision makers, which is a very controversial assumption in the case of soft uncertainty (Kurz, 1993) and appears altogether unacceptable in the case of hard uncertainty.

Lippman and McCall 1986 Lippman and McCall explicitly look for an operational measure of liquidity, or financial flexibility (interpreted as the expected time to convert an asset into cash), in the framework of a search model. In fact, "in a simple search model (with timeless search), a set of initially available assets with exponential offer distributions and a subsequently available golden asset, the risk-neutral investor improves his expected return by selecting a more liquid asset for his initial investment" (Lippman-McCall, 1986, p.54). In this approach, an agent maximizes the expected discount value of the net proceeds associated with the sale of the asset. The liquidity of the asset is the "expected time until the asset is sold when following the optimal policy" (Lippman-McCall, 1986, p.44).

If $R(\delta)$ are the discounted net receipts associated with a stopping time δ of the search, the agent chooses a stopping rule δ^* in the set T of all stopping rules such that: $ER(\delta^*)=\max\{ER(\delta):\delta\in T\}$. $V^*=ER(\delta)$ is the value of the asset, and the random variable δ^* is the length of time to convert the asset into money. The variable δ^* determines the liquidity of the asset. Lippman and McCall suggest employing $E\delta^*$ as "the measure of an asset's liquidity with an increase in $E\delta^*$ corresponding to a decrease in liquidity" (ibidem, p.45); therefore, if $E\delta^* = 0$ liquidity is perfect, while if $E\delta^* = \infty$ illiquidity is perfect.

The model shows that:

(i) an increase in the market interest rate and the asset holder's time preference (lowest value of the discount rate) leads to an increase in asset liquidity;

(ii) the market thickness for an asset directly influences the liquidity;

(iii) the asset's liquidity is a growing function of its predictability.

When future opportunities differ from current opportunities, the agent avoids investments with high $E\delta^*$ (illiquidity), and prefers to have more flexible assets in his portfolio. Therefore, this model leads to a portfolio behaviour similar to that of Jones and Ostroy.

However, neither is the approach of Lippman and McCall fully convincing. First, because the saving decisions are analyzed independently of investment decisions so that it is restricted to considering the effect of uncertainty on a portfolio's composition, given the saving decisions. Second, they arbitrarily neglect the subjective factors, such as the attitude towards risk and uncertainty. As correctly observed by F.Hahn, it "...is the frequent abstraction from risk aversion by (implicitly) assuming that utility functions are linear [that] leads Lippman-McCall to claim that they have found an operational measure of liquidity, i.e. one that is independent of the agent" (Hahn, 1990, p.64). Third, the statement that all agents face similar costs of search and distribution of offers seems very dubious when we consider that the discount rate of each agent affects $E\delta^*$, and consequently also the measure of liquidity, through the effect on the reservation price and thus on the decision rule.

Pindyck (1991) According to Pindyck an irreversible investment opportunity can be seen as a financial call option which "gives us the right (which we need not exercise) to make an investment expenditure (the exercise price of the option) and receive a project (a share of stock) the value of which fluctuates stochastically" (Pindyck, 1991, p.1114). The exercise of this opportunity (investment) is irreversible because it 'kills' the option. The comparison between an irreversible investment opportunity and a call option on common stock allows, in some cases, the extension of standard pricing methods to the estimate of the option value of a decision. But, before extending this methodology to the investment decisions, we have to know whether the markets are complete (the decision to invest doesn't affect the opportunity set that is available to investors) or if there are missing markets.

Assuming complete markets, we can obtain an estimate of option value independent of the agent's preferences and of the expected return of decision by risk arbitrage, given Black-Scholes conditions (1973). Let us assume that C is the sunk cost of irreversible investment, and F=F(S,C) the project worth, where S (competitive spot price of the single commodity produced) is assumed to follow the exogenously given continuous stochastic process: $dS/S=\mu dt+\sigma dz$[15]. Since in this case the stochastic changes in S are spanned by existing assets, that is "it is possible to find an asset or construct a dynamic portfolio of assets (i.e. a portfolio whose holdings are adjusted continuously as asset prices change), the price of which is perfectly correlated with S" (Pindyck, 1991, p.1119), the agent can estimate the value of investment and the option value by applying the method of contingent claims. In fact, by constructing a replicant risk-free portfolio of the investment project, the agent can estimate the option value and find the rule for optimum investment[16].

The analogy between an irreversible investment opportunity and a call option on common stock, suggests the extension of financial option pricing methods to the estimate of environmental option values. However, although the use of these measures may be partially extended to problems typically analyzed by intertemporal option values (problems involving irreversibility and learning) this possibility is very limited because a correct application of Pyndick's stochastic methods requires the assumption of complete markets and soft uncertainty.

3.4.2 Subjective measures

The shortcomings of the 'objective' measures of option value has led a few authors to regard the search for an 'operational' measure of option value as utopistic and misleading. They tried instead to define 'subjective' measures of option values and work out statements concerning option values as robust as possible, i.e. valid under wide subjective assumptions.

Goldman (1974, 1978) Goldman's analysis focuses on variable consumer preferences which depend upon the observation of a random event describing the 'state of the world'. Goldman (1974) aims to clarify why an agent holds money (without return) when other assets yield higher rates of return. He works out a simple theoretical model in which an agent (consumer) has to

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15 dz is the increment of a standard Gauss-Wiener process, σ is the instantaneous standard deviation of the spot price and μ is the trend in price.

16 Applying Ito's lemma, we derive a partial differential equation of F(S,C) which together with the constraint conditions gives the solution to the choice problem.

decide the allocation of wealth across different assets to maximize expected utility. This model of portfolio selection involves a sequential decision process with learning, uncertainty (since the consumer faces the prospect of stochastic bargains) and switching costs. The consumer has to select a particular allocation of his wealth, between money and interest-bearing assets, before gaining precise knowledge of his preferences.

Goldman analyzes a model with two periods where the consumer's preferences depend on the state of the world. The consumer has to allocate his given wealth between money and other assets before learning his exact preferences. Once a choice is made in the first period, the possibility of modifying the allocation depends on the flexibility of his portfolio, as the consumer can revise his consumption flow only "by selling assets subject to transaction costs or by carrying his unspent balances" (ibidem). Given an a-priori feasible consumption (choice) set, Goldman describes the upper and lower bounds of this flexibility measure by defining total flexibility, a situation in which a coincidence exists between ex-ante and ex-post choice sets, "no opportunities have been lost by initial allocation", and complete inflexibility when the ex-post choice set coincides with the particular choice initially selected (ibidem, p.214). The desire for portfolio flexibility, ceteris paribus, induces the individual "to raise (lower) his holdings of money where the interest rate is low (high) ... further, on the average, the desire to maintain flexibility renders the demand for money more sensitive to the interest rate than would be expected from time preferences alone" (ibidem, p. 213). Goldman shows that flexibility is not the property of a particular asset (such as money), but relates to the 'opportunities' (or options) for consumption flow revision.

In 1978, Goldman extended its approach to the case of a multiplicity of assets having different expected returns and transaction costs (for sale prior to maturity). The agent, whose utility function is assumed to have zero elasticity of substitution, has to compromise between immediate return and liquidity. The measure of option value suggested by Goldman suffers from many limitations. First, it cannot be applied to entire portfolios since in this case 'the ordering cannot be complete as there will always be noncomparable portfolios' (p.271). Second, it applies only to soft uncertainty, since the random variable is characterized by a known probability distribution. Third, learning is limited to the observation of the realization of the random variable. Since uncertainty is soft, the sequential nature of the decision problem is not essential. We may conclude that Goldman's measure may be interpreted as a measure of (plain) option value examined in its intertemporal implications.

Hahn 1990 While Goldman's model is developed in a partial equilibrium framework, Hahn (1990) works out a subjective measure of option value in a general equilibrium framework.

Hahn postulates a perfect market economy in which, for every state and date, all assets have well-defined prices; these prices are functions of the state and date. The decision-maker is assumed to have a three-period time horizon: in t=1, the agent receives a money income $y(s_1)$ and zero assets, he can trade but he sells all assets in t=3, $a(s_3)=0$. The agent is uncertain about the true future state of the world and he has a separable von Neuman utility function with discount factor δ, $(0<\delta<1)$. Let $k(b,a,s)$ be the switching cost from a to b $(a,b \in R^m)$ in state s, $k(a',a,s)=0$ for all s if a' differs from a only in money,

$q(s_t) \in R^m{}_t$ the price vector of assets at s_t,

$c(s_t) \in R^l{}_t$ the agent's consumption (l goods) vector at s_t,

$p(s_t)$ the money vector,

$\alpha(s_t)=(c(s_t),a(s_t))$.

The agent makes his choice by solving a problem of constrained maximum (see, ibidem, pp.66-69). Since the idea of liquidity is related to the cost of reversing a position, "in the present context this suggests that the cost of selling an asset in a second period which was bought in the first should play a [crucial] role" (ibidem, p.71). Then Hahn defines an index T of the illiquidity of a portfolio that measures "the maximum an agent would be prepared to pay to escape reversal costs" (ibidem). The value of T will be smaller when the variability of beliefs of the agent is higher. In any case, the value of T depends on the subjective characteristics of the agent.

Hahn shows that, in this model, money commands a liquidity premium σ over any asset. This premium "is due to the possibility that an asset bought at one date and state is optimally sold at a future date and state and so incurs the cost of selling" (ibidem, p.77). It is possible to achieve another ordering of assets "by utilizing the premium σ an asset must earn over money if that asset is to be bought in an optimum plan" (ibidem, p.74). Using this premium, an asset j is more liquid than an asset k if, and only if $\sigma_j<\sigma_k$.

Hahn rightly observes that the recognition of the importance of transaction costs, implied by liquidity considerations 'leads us to conclude that agents will maximize, subject to a number of, rather than a single, budget constraints'(p.65), and this may be used to account for missing markets (ibidem). However, it is questionable whether this correct observation is consistent with the kind of soft uncertainty assumed in the model (as an event tree characterized by known probability distributions: see p.66). Climbing this event tree, uncertainty resolves independently of the will of the learning decisions of the agent. This assumption prevents a deeper analysis of the nexus between the value of liquidity (option value) and the modalities of learning. We may conclude by observing that also Hahn's measure should be interpreted as a measure of option value rather than of intertemporal option value.

3.5 Financial and environmental measures of option value

The study of monetary and financial concepts of option values may be of some interest for the analysis of environmental option values, taking into account the profound conceptual analogies. In particular, the effort of producing an 'operational measure' of different varieties of option value is more developed in the monetary and financial field than in the environmental field. Any advance in this direction would also be precious for environmental applications. Unfortunately the recent attempts surveyed in this paper do not seemcompletely successful. The measures suggested so far are only ordinal and are based on a few arbitrary technical assumptions. In addition, the illusion of an operational measure is obtained only by abstracting from subjective factors which crucially influence option values according to theoretical and experimental considerations. However the approach in terms of stochastic processes surveyed and developed by Pindyck is a potentially fertile research programme as far as (plain) option values are concerned. Unfortunately, the assumption of complete markets and soft uncertainty precludes an application to genuine intertemporal option values which are crucially important in environmental economics. The only financial measure which clearly assumes hard uncertainty is that of Jones and Ostroy which unfortunately is spoiled by a few technical shortcomings and by a rudimentary analysis of hard uncertainty which could not take into account advances made after the publication of their paper.

The subjective measures of financial option values are more robust than the objective financial measures from the theoretical point of view, but this application is so far limited to soft uncertainty and exogenous learning. Thus, the insights which may be drawn from these measures are not easily transferred to the analysis of intertemporal option values which are particularly relevant to environmental problems.

4. Concluding remarks

Environmental option values play an important role in any assessment of environmental values for both theoretical and practical purposes, and provide the ultimate foundations for a rational policy directed towards the conservation of environmental resources.

We have surveyed a variety of definitions and measures of option values which may be classified according to a basic dichotomy between (plain) option values and intertemporal option values. The first concept is relevant when uncertainty is soft and markets complete, as it essentially reflects risk aversion. In this case a more flexible option commands a sort of risk premium because it is a safer store of values. The second concept is relevant when markets are incomplete, uncertainty is hard, and the decisional problem is intertemporal. In this second case, a more flexible option, even under risk neutrality, commands a reversibility premium to the extent that it allows the exploitation of prospective learning before subsequent decisions. In the environmental field, intertemporal option values are particularly important because the uncertainty faced is typically hard, and irreversibility is very serious, involving very delicate intertemporal decision problems. Unfortunately, while to (plain) environmental option values fairly precise measures may be assigned, particularly through the methods developed in financial theory for financial options, intertemporal option values cannot be easily measured. All the measures suggested so far are only ordinal and, what is worse, the ordering of choices according to intertemporal flexibility, which gives the ordering of intertemporal option values, is very sensitive to the specification of the model.

Notwithstanding all the shortcomings underlined in this paper, the theory of intertemporal option values has obtained a few qualitative results which are quite important for environmental conservation. First, it was established that whenever intertemporal options have a positive value, the traditional techniques for selecting the optimum choice and for analyzing problems characterized by uncertainty on the basis of the certainty equivalence approach cannot be safely used because they underestimate the value of environmental resources. Second, it was proved that intertemporal option values are positive under quite general conditions, whenever hard uncertainty and irreversibility coexist, and learning is possible before future choices. Third, the value of an intertemporal option, given a certain degree of hard uncertainty and of irreversibility of choice, depends basically on the characteristics of prospective learning, on past learning (competence) and on the attitude towards (hard) uncertainty. In addition, ceteris paribus, it depends on the degree of irreversibility (irreversibility effect). Finally, the intertemporal option value increases, under quite general conditions, with the degree of uncertainty. Therefore, the growing awareness of our deep ignorance about the long-term effects of the interaction between economic development and environment, as well as of their irreversibility, should induce a more cautious environmental policy.

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