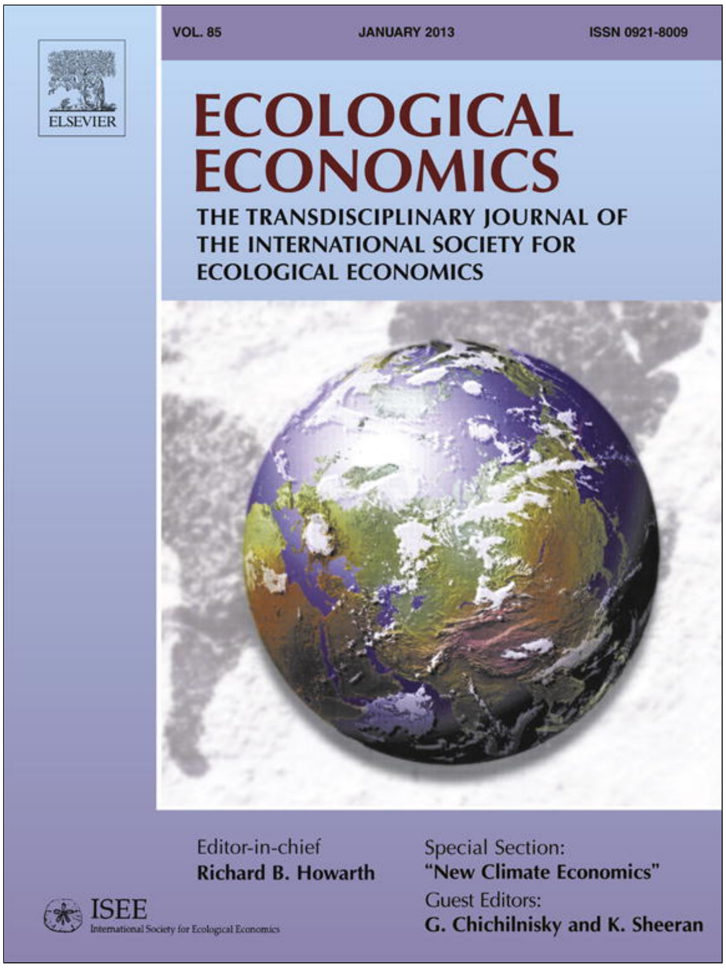
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Analysis

Revocability and reversibility in societal decision-making

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A R T I C L E I N F O

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A B S T R A C T

Reversibility and irreversibility are poorly defined in the decision-making literature. Defining reversibility as "the ability to maintain and to restore the functional performance of a system" is consistent with thermodynamics; specification of its crucial terms is case dependent. Reversibility is coming in degrees from flexibility, over rigidity to preclusion, with irreversibility as an absolute end. Further substantiating reversibility considers three variables: duration of impacts, revoking costs, and substitutability. Substitutability depends on weights assigned to the strict identity or to the functional performance of something valued. For given degrees of substitutability, revocability of an action is measurable in time-dependent revoking costs. Together with future time and doubt, reversibility sets a three-dimensional context for societal decision-making, revealing domes of expanding complexity. Cost–benefit analysis is a useful decision tool at lower complexity but falters at high complexity because there prevail non-monetary trade-offs. A revival and proper use of the concept reversibility are recommended for improved dialog on major societal issues, with climate change outstanding as the case where reversibility could turn into absolute irreversibility. Also shown is the correspondence between reversibility and ecological concepts like resilience, lock-in, tipping points, and others.

1. Introduction

In sciences like physics, cosmology, biology, ecology, and medicine, reversibility is a commonly used term, theoretically explored and practically applied (Denbigh, 1989; Reynolds and Perkins, 1977). Ecological economics uses reversibility concepts and metabolism laws for describing the thriving of economic systems within the natural environment (Ayres and Warr, 2009; Georgescu-Roegen, 1971), delivering a frame for arguing limits to growth (Daly, 1973; Krysiak, 2006). However, the framework is no breeding ground for operational models (Baumgärtner, 2004; Dasgupta and Heal, 1979). In ecology, reversibility is related to phenomena like resilience, hysteresis, collapse, and similar concepts (Ludwig et al., 1997; Scheffer et al., 2001).

Irreversible impacts on local or global environments are largely triggered or occasioned by inappropriate demands by human societies on the sources and sinks of the environment. This has been documented extensively in cases such as loss in biodiversity and climate change, not amenable to mitigation after they have occurred (Chapin et al., 2000; IPCC, 2007). In this article most examples and literature are related to climate change.

Human decision-making is recognized to be the main difference between the functioning of ecological-physical and of social-ecological systems (Perrings and Brock, 2009). "Humans are unique in having the capacity for foresight and deliberative action… Their capacity to manage resilience with intent determines whether they can successfully avoid crossing into an undesirable system regime or succeed in crossing into a desirable one" (Walker et al., 2006).

Reversibility is not seen as a foundational concept in economics or in other social sciences (Manson, 2007), although implicitly marginal analysis, which is the foundation of neo-classical economics, assumes smooth reversibility. The term reversibility acquired some explicit popularity in for example ecological economics (Georgescu-Roegen, 1971), environmental economics (Arrow and Fisher, 1974), and investment theory (Dixit and Pindyck, 1994). These strands were joined in debating optimal timing of climate policy but without establishing terminological clarity during that debate (Caron and Ohndorf, 2010; Kolstad, 1996; Manne and Richels, 1991; Nordhaus, 1994). The social sciences lack clarity in defining and using the term irreversibility (Manson, 2007; Perrings and Brock, 2009). The practice of citing irreversibility as coming in degrees is widespread, although proper vocabulary preserves the term for the absolute impossibility of reversal.[1]

The principal goals of this inquiry are a workable definition and a substantiated description of reversibility for policy-making processes. The search does not start at the kaleidoscope of reversibility and irreversibility terms scattered in the literature, but by outlining a framework of societal decision-making (Section 2). A stylized description of

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[1] One reviewer pointed this out. Aligning the article on standard vocabulary for terms beginning with "im-" and "ir-" prefixes assigning absoluteness, I avoided describing the actual confusion in the literature that quotes irreversibility as coming in degrees or uses the concept as such. At some occasions (e.g., Section 4), literal quotes from the literature do not align with standard vocabulary.

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decision components and decision context is provided. The literature relates irreversibility on the one hand to irrevocable spending of resources by undertaking actions, and on the other hand, to undesirable evolutions in the environment. In societal decisions actions generally affect environmental evolutions but mechanisms and ultimate impacts are susceptible to high degrees of uncertainty. This reflects the multiple interactions between system (where the own actions belong to) and environment (impacts on third parties, society at large, nature). Societal decision-making aims at balancing attention for both sides, but proper distinction and separate terminology are helpful. Revocability puts the focus on revoking costs when one would like to recall an action and it is limited to economics. Reversibility relates to impacts governed by laws of physical sciences with economics in a secondary role. Reversibility is – or should be – one of the three main dimensions of a societal decision context, next to (future) time and doubt (used here as a more encompassing term than the commonly used "uncertainty", in Section 2.2 described as one of the phases of doubt). Section 3 offers a definition of reversibility, with necessary guidance on its interpretation. It is compatible with the thermodynamic reversibility concept widely applied in the life sciences. Section 4 develops a substantiated description of reversibility based on three variables: duration of impacts, revoking costs, and substitutability. With duration and revoking costs, revocability is defined; by adding substitutability revocability is enriched to reversibility, or seen from the other side: substitutability is extended with duration and revoking costs to obtain reversibility. The constituent variables and their interactions are illustrated with diagrams. The conclusion (Section 5) recaps the main results for societal decision-making. The performance of cost–benefit analysis is dubious when a decision and its context are unwieldy complex with a high likelihood of stranding in irreversibility.

2. Policy Decision-making: Components and Context

One property that made mankind the dominant species on earth is its capacity to explore the future for taking considered decisions (Walker et al., 2006). That capacity has developed over time; it is not perfect and never will be. Since World War II scientific methods for supporting decision-making made the human planning capacity more consistent and robust. Wartime operational challenges were tackled with scientific methods, giving birth to an extensive field of research and applications, today known as operations research, decision science or management science. For strategic decision-making by large corporations, organizations and governments, the sub-discipline decision analysis emerged (Raiffa, 1970; SRI, 1977). Cost–benefit analysis added a public (also called: welfare) economics perspective when large-scale infrastructure projects were investigated in the USA, in Europe and in developing countries (Harberger, 1972; Layard, 1972; Lesourne, 1975).

Decisions are made for a future characterized by doubt. Scientifically proven methods are warranted for long-term, complex, unique actions with persistent effects and impacts (Lempert and Collins, 2007). Climate governance deals with issues stretching into the far future with aspects of doubt being immense, being complex and unique, and mattering to entire societies (IPCC, 2007). Emphasis on comprehensiveness and integration does not thwart that "it is critical to distinguish between the governance of the *ecosystems* that may be harmed by negative Earth system interactions and governance of the *drivers* behind those negative interactions" (Nilsson and Persson, 2012). For clarifying the differences between revocability and reversibility, decisions and their components are discussed separately from their context.

2.1. Decision Components

Decision-making is interplaying three sets of variables: possible events, alternative actions, and expected outcomes conditional on previous actions and on events that happened (Matheson and Howard, 1968). Events occur beyond the control of decision-makers, but affect outcomes and generally also future action opportunities. Actions (also named alternatives, options, or elaborated strategies) are the objects of decision-making. Decision analysis aims at finding actions with outcomes optimal according to encoded preferences, and by systematically processing information. Encoded risk and time preferences are a reduced way of considering decision-makers' values about doubt and about future time. Iterative and time-sequential processing weights the net value of additional information. Outcomes (effects, impacts, consequences, results) can be measured as distances to targets. Decision-makers react on the course of events to avoid or minimize negative outcomes and to obtain and maximize positive outcomes, subject to constraints faced.

Three comments on the components and their interplay in societal decision-making are due. First, coverage of events, actions and outcomes has to be comprehensive, complete (sufficient detail about diverse components within the comprehensive scope), and consistent (recognize interdependencies, mutually exclusive or contradictory options, etc.). If not, the dangers of too narrow scopes and biased decisions lurk, wasting analytical and political resources on local or false optima far from real overall optima. Especially a good catalog of outcomes is important, because disruptive decisions bring winners and losers. Losers are generally the poorer people without influential voice or unborn people without direct voice by definition, climate change being an example in case (UNDP, 2007).

Second, dynamic and complex interplaying between components is a spiraling time-sequential process of conditional deployments of actions, events, outcomes, actions, events, outcomes, and so on. Modeling this reality of interlaced facts and policies is an intellectually challenging effort. It differs from single vantage point scenario projections delivered by most integrated assessment and economic models that in one bow cover time spans of 30, 40 or 100 years (Nordhaus, 2007). One-bow projections stifle crucial conditionality among the components, with constant-rate discounting reducing the weight of values according their rank on the bow. Complexity theory recommends time-sequential modeling that "concentrates on the significant issues which need to be handled in the short-term, and ensure that the debate about their long-term consequences is lively and engaged." It does "not justify short-termism, but points towards a more practicable way of taking the future into account" (Rosenhead, 1998). Time-sequential cycles match adaptation management in allowing flexible and reversible policy designs, learning, knowledge integration and experimentation (Voss and Bornemann, 2011).

Third, distinguishing between actions and outcomes in a time-sequential process helps in anchoring reversibility terminology used in the literature. Irreversibility is named as an inherent attribute of spending resources by taking actions (Dixit and Pindyck, 1994; Kolstad, 1996), but also of outcome impacts that one cannot undo (Arrow and Fisher, 1974; Pindyck, 2000). While expenses of actions are well inventoried, outcomes considered are mostly limited to the ones falling within the decision-makers' accountability. Important external effects are rolled off to the environment and to the distant future. Climate change is beset by external effects some with low degrees of reversibility, such as melt of the Greenland ice sheet, dieback of the Amazon rainforest and shift of the West African monsoon (Lenton, 2011; Schneider, 2003; Solomon et al., 2009). Next to the dichotomy internalized/externalized, the distinction between desirable and undesirable outcomes is important. In principle concerns about reversibility only apply to undesirable outcomes, with the understanding that preferences shift over time regarding what is desirable or undesirable.

2.2. Decision Context

With higher complexity, drawing boundaries between systems and their environments is very difficult and largely arbitrary (Homer-Dixon, 2011). Yet it remains helpful to see actions, events, and outcomes as constituting the decision system in a decision-making context, made up by three dimensions: future time, doubt, and reversibility.

Future time is a major contextual factor because decisions are made for a future over years, decades, and centuries, up to perpetuity. For societal decisions with important persistent impacts decision-makers should consider eternity (Chakravarty, 1969). But mostly a finite time horizon is adopted. Additionally, natural myopia of people is reinforced by the technique of discounting. Economists observe time preference: people prefer to obtain, own, and enjoy valuable things rather earlier than later. It explains why money is borrowed at a positive rate, arguing discounting future values is appropriate. While properly reflecting daily economic behavior of contemporary people, discounting vaporizes the distant future by a mathematical trick juggling away the infinite horizon challenge. Discounting at positive rates over very long time periods is problematic, what adds to the unsolved issue of fixing an appropriate discount rate for societal decision-making (Arrow et al., 1995; Portney and Weyant, 1999; Weitzman, 1998).

Climate change urges care for the future beyond a few decades (Arrow et al., 1995). But economics Nobel prize winners could not answer how to properly weight the distant future (Portney and Weyant, 1999). There are proposals of declining discount rates over time and of zero discounting for the distant future, but a consensual answer is not available (Hof et al., 2010; Weitzman, 1998).

Doubt is pervasive when the long-term future is poorly known. Three "depths" of doubt are distinguished: risk, uncertainty, and ignorance (Harremoës et al., 2002; Neumayer, 1998; Stirling, 1999). Risk is shallow doubt with an overview of the possible events/outcomes and an experimental or scientific basis to assess the probabilities of the occurrences. Uncertainty reflects more doubt: one can obtain an overview of possible events/outcomes, mostly fuzzier and less complete than in the case of risk. Very little is known about the likelihood of various events to happen, because for example, some predicted possible future events never happened before. There is no empirical or logical basis to assess probabilities and one is thrown back on subjective assessments to elicit probabilities. Ignorance is the abyss of doubt: one has no description of the eventual events/outcomes, but "black holes" are assumed to exist because of peripheral evidence. The constitution of black holes is unknown and there is no firm ground to assess the likelihood of falling in such holes. Ignorance is now receiving more attention because of predicted threats for future sustainability triggered by human interventions in natural and social systems (Harremoës et al., 2002; Stirling, 2010). Decision analysis can process risk information, to some degree addresses uncertainty by eliciting subjective probabilities, but is rather powerless when ignorance and unpredictability prevail. Doubt is used as an overarching term in this article. Ambiguity describes the state of doubt when uncertainty prevails (Asano, 2010).

Surprise has become common to refer to situations of ignorance (Funtowicz and Ravetz, 2003). Surprises are also classified into "known unknowns" and "unknown unknowns" (Taleb, 2007). Surprises are seen as "unexpected destructive shocks, rapid and discrete events such as technological failure, hurricanes, and violent attack" in a communicative planning perspective, and from a social-ecological resilience perspective as "a range from sudden, rapid, discrete, and irreversible disasters to more gradual and insidious events, such as climate change" (Goldstein, 2009).

Reversibility is not a foundational concept in economics (Manson, 2007), and no unified definition is available. A definition is proposed in Section 3 and substantiated in Section 4. In common language reversibility is linked to the capability of going through a series of changes either backward or forward, including the possibility to return to a previous or normal condition. This capability and possibility are grading down from flexibility, over rigidity to preclusion, ending in absolute irreversibility where all return is excluded. Related to flexibility or ample reversibility are foundational concepts from ecology like resilience and adaptability, as the following quotes from the literature confirm. "Resilience is the ability to absorb perturbations without flipping to some alternate state, or to recover from or adjust to misfortune or change" (Ludwig et al., 1997; Perrings and Brock, 2009). "Resilience is the potential of a particular configuration of a system to maintain its structure/function in the face of disturbance, and the ability of the system to re-organize following disturbance driven change. Adaptive capacity is a component of this resilience that reflects a learning aspect of system behavior in response to disturbance" (Holling and Walker, 2003). "Resilience is the capacity of a system to experience shocks while retaining essentially the same function, structure, feedbacks, and therefore identity. Adaptability is the capacity of the actors in a system to manage resilience" (Walker et al., 2006).

Preclusion and absolute irreversibility are described in the literature by crossing of tipping points or thresholds, and by experiencing catastrophe (IPCC, 2007; Lempert and Collins, 2007; Lenton, 2011; Mäler et al., 2003). "Social-ecological systems exhibit thresholds that, when exceeded, result in changed system feedbacks that lead to changes in function and structure. The system is said to have undergone a regime shift that may be reversible, irreversible, or effectively irreversible, i.e., not reversible on time scales of interest to society" (Walker et al., 2006).

Fig. 1 shows a three-dimensional decision space with domes of expanding complexity when the outer range of the space is entered (Funtowicz and Ravetz, 2003). The complexity of a decision process grows with higher values of the context variables.

3. Defining Reversibility

Defining reversibility as the "possibility to return to a previous or initial state" runs the danger of trivializing reversibility as always impossible and irreversibility as ubiquitous, because the arrow of time points only to the future. First, purely time depending adjectives like "previous" or "initial" are better replaced by an adjective describing which accessible state is strived for. Examples are "normal", "desirable" or "functional" state. Most of such adjectives require a circumstantial description for explicating the full meaning assigned by the decision-makers on duty. Even the more neutral "functional" requires a selection and prioritizing of the relevant functions and of criteria for monitoring degrees of functional performance (Section 3.1).

Second, "state" of something (being an object, subject, person, social group, or more generally a system) can be identified by its identity on the one hand, and by the functions it fulfills on the other hand (Section 4.1). When all weight is on identity, loss of a system is irreversible because every identity is unique. This view again paralyzes reversibility as a useful concept. A societal perspective puts the focus on the functions that systems and persons offer.

Based upon these considerations, the following new definition for reversibility is proposed: "*the ability to maintain and to restore the functional performance of a system*." This short sentence needs several footnotes. First, "ability" has to be qualified by something like "at affordable costs within an overlookable period", raising questions about the meanings of affordable and overlookable, being both case specific. Second, by inserting "maintain" next to "restore", the literal link to the word "reverse" in reversibility is left and a bridge to the concept "resilience" is made. Third, "functional performance" is considered sufficient omitting the requirement of preserving identity for avoiding the pitfall of trivial irreversibility (Manson, 2007). Irreversibility then only occurs when the functional performance of an absolute unique identity breaks down. Fourth, the generic term "system" covers subjects and isolated objects or phenomena too, and facilitates the link to applied thermodynamics (Reynolds and Perkins, 1977). Applied studies must specify what "functional performance" and "system" cover. Doing this well is a prerequisite for further steps, but value-laden dependant on the mental perspective, preferences and beliefs of dominant decision-makers.

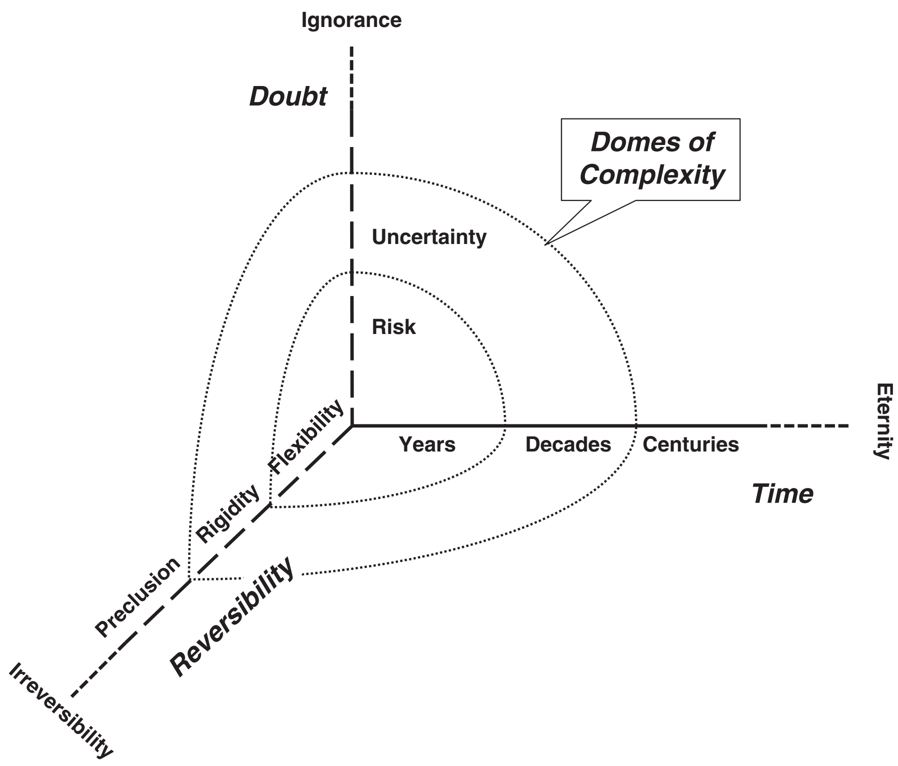

Fig. 1. Decision context space made up by time, doubt and reversibility.

3.1. Functional Performance

Identifying the functions expected from economic systems of limited size seems feasible. However, clearly defining the functions of complex large-scale economic systems is rather impossible (Dasgupta and Heal, 1979). A similar observation is valid for technical systems. Engineering thermodynamics can define and monitor the functional state of matter, systems and cycles quite easily for a given machine, but not for large industrial complexes or sectors. Hueting (1980) and De Groot (1992) suggest function catalog to value environmental goods and services in cost–benefit analysis. IPCC (2007) assesses the functional performance of the climate for various scenarios of future greenhouse gas concentrations.

3.2. Identifying "The System"

Thermodynamics defines the degree of functional reversibility of systems by the net amount of low-entropy energy the systems import from their environment (Reynolds and Perkins, 1977). The extent and durability of the reversibility status of a system depends on system–environment proportionality and on qualitative degradation caused by their interactions. The distance to irreversibility depends on the quantitative and qualitative proportions of the system to its environment as metaphorically described by Boulding (1966). What is designated as system and as environment depends on the analyst's perspective. Economists see complexes of human activities as systems and nature as the environment; the opposite vision holds when preservation of ecosystems is studied. Spash (2012) finds "a primary concern for a physical reality and how the mix of natural and social sciences should be addressed" a foundational issue for ecological economics. Revocability (Section 4) suffices for the study of economic systems. The extension to reversibility is due when functional performance is a concern for the environment that human society is embedded in.

The borders between system and environment and the flows across the borders need clear identification and continuous monitoring. In exporting entropy to the broader environment one maintains the proper homeostasis within the limited system for the time being, but entropy accumulated outside the system may backfire causing faster and wider loss in reversibility. For example emissions of greenhouse gases may destroy the proper functioning of the atmosphere and climate dependent functions for centuries to millennia (Solomon et al., 2009). This is a case of absolute irreversibility because of the unique strict identity of the earth's atmosphere. Its pre-industrial composition was affected by major natural phenomena and by some land-use changes with modest variability being the foundation of a stable climate. Since growing anthropogenic greenhouse gas emissions are leading to yearly higher concentrations of long-living gases, the stability of the global climate is eroding. This affects the environmental conditions of all life on earth.

4. Substitutability and Revocability

Irrevocability and irreversibility are used interchangeably in the literature on decision-making and investment under uncertainty. Matheson and Howard (1968) define a decision as "an irrevocable allocation of resources, in the sense that it would take additional resources, perhaps prohibitive in amount, to change the allocation." They distinguish between "inherently irrevocable, such as whether or not to amputate a pianist's hand" and "essentially irrevocable, such as the decision by a major company to enter a new field of endeavor." The "inherently irrevocable" refers to irreversible because it enters the idea of substitutability (Section 4.1). Decision theory applied on (often contentious) development projects with high impacts on unique environmental or cultural values (Arrow and Fisher, 1974; Fisher and Krutilla, 1985; Henry, 1974) added "real option", "irreversibility effect", and "quasi option value" to the vocabulary. An explicit definition of "irreversibility" was not settled, and the social sciences literature (economics, decision-making, environmental policy) offers a kaleidoscope of terms. Authors emphasize various aspects of the concept differently, creating slightly different meanings, for example: the difficulty or impossibility to return to an initial state, (often) including: to maintain an equilibrium state (Fisher and Krutilla, 1985; Perrings and Brock, 2009); the difficulty or impossibility to undo the impact of decisions or developments (Fisher, 2001; Perrings and Brock, 2009); the limitation of the set of choices in the future by earlier decisions, or the restriction of tomorrow's possibilities (choices) by today's actions (Dixit and Pindyck, 1994; Henry, 1974; Kolstad, 1996; Ulph and Ulph, 1997). Such descriptions flag the phenomenon but disparities remain.

A substantiated description of reversibility considers three attributes each measuring a degree of difficulty to undo the effects of an earlier action. First: substitutability; second: duration of the impact or time to recover or restore; third: revoking costs for undoing actions and their impacts. Temporal irreversibility is generally acknowledged (Baumgärtner, 2005). Henry (1974) considers a decision "irreversible if it significantly reduces for a long time the variety of choices that would be possible in the future." Arrow and Fisher (1974) describe irreversibility as "a loss in perpetuity", referring to the extreme end of the time axis. Impacts on the functional performance of systems may be ephemeral, transient, lasting, or perpetual. The cardinal variables duration of impacts and revoking costs define two-dimensional revocability spaces (Section 4.2) for every degree of substitutability, being the third dimension of reversibility (Fig. 2). Substitutability is an ordinal variable, discussed more in depth in Section 4.1.

4.1. Substitutability

Fisher (2001) quotes academic economists' reactions on his work as: "Nothing is irreversible, in that the consequences of any decision, for example, to develop a natural environment, can be reversed given sufficient inputs of conventional resources." This is the "anything is substitutable" argument, reducing reversibility to revocability (Section 4.2). In practice it is precarious to designate degrees of substitutability, as the lasting debate on the substitution between natural and human-made capital reveals (Ekins et al., 2003; Neumayer, 1999; Stern, 1997). The adoption of weak or strong sustainability as a guideline, and the actual distinction between both are already sources of fuss.

Substitutability is not a cardinal variable, but it can be ordered from easy, over difficult and problematic, to impossible. Fisher and Krutilla (1985) see as "basic" irreversibility what attends the modification of unique scenic or biological environments, with effects that cannot be remedied to any degree at all. Uniqueness is a synonym for impossibility of substitution. Uniqueness however is mostly not qualified as absolute but as circumstantial (Krutilla, 1967).

The degree of substitutability assigned to a subject, object or system depends on the valuation of respectively its identity and its function(s). When strict identity is assigned to a subject, object or system, no substitution is acceptable. Every intervention that destroys the strict identity is irreversible. When adopting "merely functional state descriptions" (Manson, 2007), a system is preserved or restored when it can perform the function(s) it is intended for. Most occurrences of strict identity and uniqueness are person related (familiar neighborhoods, the fortune of relatives, a person's own life), influenced by cultural, ethnic, historic, geographic, and other factors. Some identity cases are more global (e.g. UNESCO recognized heritages). A few are really unique in an absolute sense, for example global climate stability, the global hydrological cycle, and global biodiversity. All three systems are known for high variability, always in flux for natural and now anthropogenic-driven reasons. But their stability and resilience are strict identities because globally they are unique in an absolute sense without an environment they can tap from.

The allocation of weight to respectively identity and functional performance of subjects, objects or systems, is heavily dependent on the position of the analyst, decision-maker. Human life is a point in case: from the individual position one's life is unique and non-substitutable; from a societal perspective there are aspects of individuals that are replaceable, but not all aspects of any specific individual; life-cycle turnover of individuals keeps societies dynamic. This example may remind us that the position of decision-makers matters and that they are not value free in judging substitutability opportunities or ultimate uniqueness.

Standard economic analysis assumes that substitution among goods, services, factors of production, and technologies is generally feasible. When a price can reflect anything's value, anything is tradable, exchangeable and in this sense substitutable. Physical objects, technologies, assets, etc. are less substitutable than the extent implied by markets. But markets accommodate limits on physical substitutability by higher prices expressing greater scarcity of non-substitutable goods. The economics vision accords with the concept revocability; only when substitutability issues are considered and weighed separately as a non-monetary category, one faces issues of reversibility. It may be seen as a watershed between conventional economics (limited to revocability and

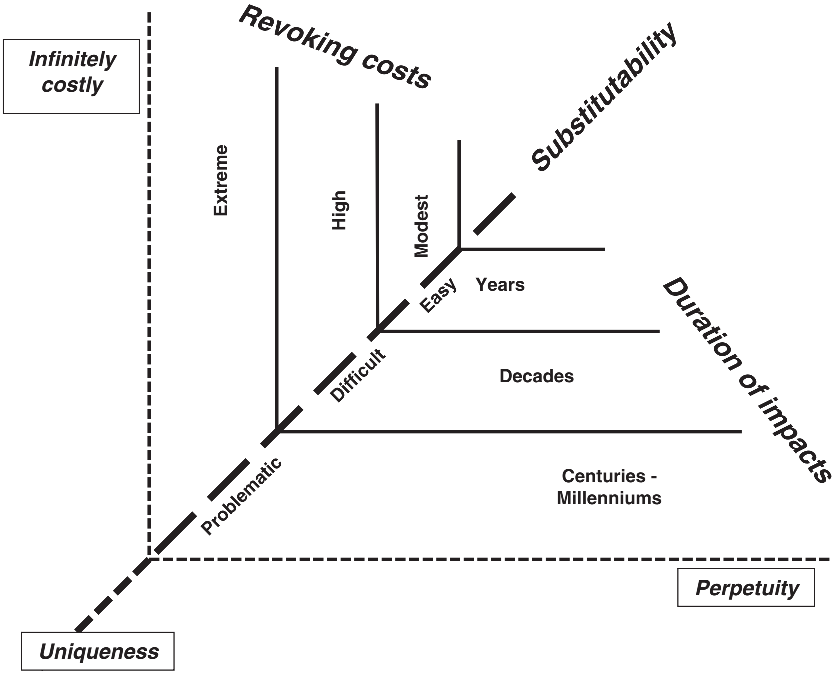

Fig. 2. Reversibility space described by duration of impacts, revoking costs, and substitutability.

monetary trade-offs) and ecological economics (adding non-monetary substitutability issues to face reversibility and irreversibility).

4.2. Revocability

Revocability relates to a decision or action undertaken at a given moment, with the arrow of time only pointing forward. Undoing decisions or actions requires economic resources, from negligible to exorbitantly high. Arriving too late at the airport means that one's plane is irrevocably gone, but at some cost the next plane can be boarded or the trip canceled. When a country invested billions in the wrong energy supply systems, lots of capital is depleted, but it can develop the proper energy systems when bearing significant revoking costs. Revoking costs range from low, over high, extremely high, to "infinitely costly." Costs may be expected to be low when substitutability is high, but there is no linear relation as showcased by standard capital investments (Dixit and Pindyck, 1994; Verbruggen et al., 2011).

Fig. 3 shows five degrees of revocability based upon the evolution of revoking costs over time. Time plays an important role. Depreciation of invested capital reduces the costs of an action with time passing. The possibility to return to initial states may be limited by decay and aging in mechanical and in biological systems (Boulding, 1966). Inertia and hysteresis refer to retardation of effects when acting driving forces are changed (reverted). In ecology hysteresis expresses that "even after a long time, the state of a system may be partly determined by its history" (Ludwig et al., 1997).

The reference for categorizing revocability is the initial costs of an action at time point 0. Visual inspection of Fig. 3 shows that "adverse" refers to revoking costs that increase over time, for example when resources of increasing scarcity will be needed to undo the initial action and its impacts. "Costly and Slow" is when revoking costs in the future stay above the reference of the initial costs but decay over time. This may be the case when non-unique natural landscapes are converted to building areas, requiring more resources to restore than was needed to develop for use, but with technological progress decreasing the expenses over time. "Medium" refers to undoing costs higher than initial costs at moment zero and for some years, but falling below the initial costs later. An example is a building: when a brand-new construction has to be removed (undone) the value lost is not only the full price of erection but also the costs of demolishing and removal of the materials to recycling or dumping facilities. With time passing, the initial construction project is depreciated and its sunk costs decline. "Ready" revocability is when the investment could be undone without extra removal costs, with as revoking costs mainly the non-depreciated part of the initial investment. With time passing depreciation reduces costs incurred by the undoing (scrapping) before end of life. After a reference decision is phased out (passing its end of life at horizon H), revocability is no longer relevant. When a decision can be revoked at any time without costs (the abscissa in Fig. 3), "perfect" revocability holds. This is the case when a private party can, at any time, sell an asset at its value because there exists a liquid market (Verbruggen, 2012).

The value added by applying sophisticated decision analysis science grows with stiffer revocability. Rigidity is often connected to costly and slow revocability of actions due to sunk costs, path dependency, lock-in (Arthur, 1989; Perkins, 2003; Unruh, 2000). From a theoretical marginal cost viewpoint sunk costs are irrelevant for future decisions, but in practice they are a source of lock-in and apparently affect the future economic feasibility sets and agents' behavior. Socio-ecological resilience decreases in "rigidity traps" (Goldstein, 2009).

Linking Figs. 2 and 3 reveals that with decreasing substitutability conditions shift from ample to low revocability and that time horizon H in Fig. 3 shifts to the right. When at a given level of substitutability all impacts can be undone by economic spending, irrevocability sufficiently covers the problem.

Dixit and Pindyck (1994) use the word irreversibility for what is named here irrevocability. Dasgupta and Heal (1979) apply the term irrevocability on contents that arguably cover irreversibility. Terminology of most literature does not distinguish between irrevocable economic allocations and irreversible developments in the environment. Using a single term for different realities is rather confusing as Caron and Ohndorf (2010) observe but continue to practice by lack of alternative

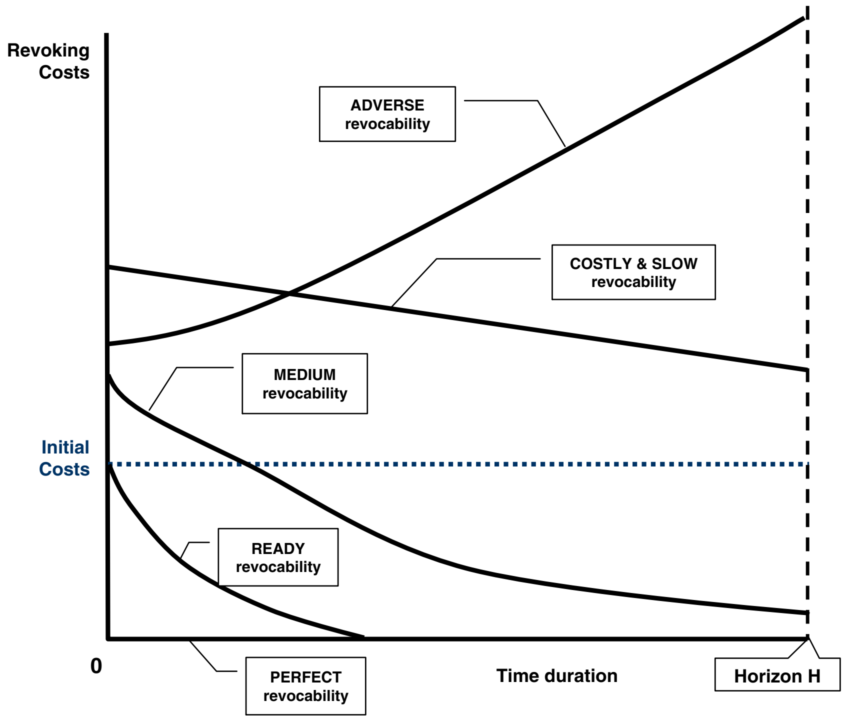

Fig. 3. Revoking costs in the future for undoing an action and its impacts.

proposition. By adopting a more precise delineation many publications would be less confusing, and assumptions about substitution feasibilities would have to be stated more explicitly.

Fig. 2 also shows that reversibility comes in degrees. Authors tend to focus on a particular point or small area in the reversibility space, obscuring the gradual and multi-variable characteristics of reversibility.

Economists consider substitutability as a given, and study only revoking costs, i.e. they limit attention to the reduced reality of revocability. Embedding tipping points (expressing non-substitutability) in the economic models that include precautionary behavior flips recommended policies from "learn before act" to "act before learn" (Caron and Ohndorf, 2010). Climate scientists focus on the longevity of atmospheric greenhouse gas concentration and on the duration of impacts like global warming and sea levels (Schneider, 2003; Solomon et al., 2009). They actually exclude substitutability, which is arguably right for unique global systems, and referring here to irreversibility is appropriate.

4.3. The Limits of Cost–benefit Analysis

The analysis also hints to a critical stance on cost–benefit analysis (CBA). Methods, tools, assumptions, and other aspects that are valid and useful for analysis of decisions for systems of limited complexity become dysfunctional and lead to wrong decisions when applied to complex cases. CBA is one standard framing for economists to analyze and inform societal decision-making, for example: Nordhaus (1994, 2007) on the economics of climate change and climate policy, and Costanza et al. (2011) on the acceptability of nuclear power. Monetizing all or as much as possible uses of economic resources in production and consumption activities is the goal of CBA. Assuming all values can be monetized makes substitutability a minor concern or none at all. Reversibility, if at all considered, is reduced to revoking costs. Discounting is the applied mathematical operator to process future time.

When complexity is low CBA may provide satisfactory answers. In the context of time shifting beyond decades, doubt fanned out in uncertainty, and flexibility stiffened to rigidity, implementing CBA is no longer a technical task because many subjective choices are due. Beyond the medium complexity dome and in the outer realm of the decision context space, CBA falters. Weighing values across centuries, prospecting the abyss of ignorance and imagining suitable responses, irreversibility precluding important options in the future, requires analytical tools and architectures for agreement of a different nature than available and applied by cost–benefit schemes (Lempert and Collins, 2007; Munasinghe et al., 1995; Söderbaum, 2007).

Jacobs (1997) argued that all institutions for articulating public opinion and for recommending or making decisions are normative in character. He proposed to search for agreement through deliberative and practical judgment in the public sphere. Public decision makers should arm society to face unpredictability by giving preference to flexibility, robustness and resilience above preclusion and direct financial gains. Harremoës et al. (2002) provide interesting late lessons from early warnings, in the conviction that "complex reality demands better science, characterized by more humility and less hubris, with a focus on 'what we don't know' as well as on 'what we do know'". Stirling (1997, 2010) supports more plural and conditional methods, such as multi-criteria mapping. Socio-ecological resilience provides a "conceptual framework to embrace surprise when it offers opportunities for structural change to avoid greater catastrophes or to change conditions that are neither desirable nor tenable" (Goldstein, 2009).

Reacting on the Fukushima catastrophe in the nuclear sector where early warning is overdue since decades, Costanza et al. (2011) however confirm their belief in the standard cost–benefit approach: "Faced with these grave issues, it is time to change our approach to evaluating nuclear power. It is time to make sure the full costs and benefits are clear and that enough information is available to society to make informed decisions." The latter would assume that humans master perpetuity, ignorance, and irreversibility, what seems illusory and likely a symptom of hubris.

5. Conclusions

Irreversibility is seen as "a buzzword in discourse on looming issues such as global climate change… The term is being thrown around a lot without much precision as to its meaning" (Ruhl, 2007). Also Manson (2007) and Perrings and Brock (2009) observe that the concept is poorly defined. This contribution clarifies the concepts reversibility and revocability for improved societal decision-making of graduating complexity (Fig. 1). First is distinguished the decision-maker's scope on actions–events–outcomes sequences from its context of future time, doubt and reversibility. This crucial distinction (Nilsson and Persson, 2012) helps in dissolving the confusion between revocability and reversibility. For monitoring the costs and time for undoing human actions, revocability is the recommended term (Fig. 3). By adding the ordinal dimension substitutability, the ordinal concept reversibility is obtained (Fig. 2). Reversibility is the appropriate term for monitoring impacts on the environment, nature, climate, and other life-support complexes. Irreversibility of investments in simple machinery is no proper vocabulary, with the term revocability available as a substitute (Matheson and Howard, 1968). Conventional economics is limited to revocability and monetary trade-offs, with ecological economics adding issues of non-monetary substitutability facing problems of reversibility and irreversibility.

Users of the term should respect a clear definition. The essence of the reversibility concept in thermodynamics (life sciences) is applicable to socio-economic systems. As workable definition is proposed: "*Reversibility is the ability to maintain and to restore the functional performance of a system*", with the substantive words (ability, functional performance, system) needing specification in practical applications, where the values and perspectives of decision-makers matter. Highly deployed concepts in ecological sciences (resilience, adaptability) are related to reversibility. Hopefully this article contributes to the revival of the concepts reversibility and irreversibility in the ecological economics discussion.

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