Valuation of environmental improvements
in continuous time with mortality and morbidity effects

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Abstract

We present a simple theoretical framework for analysing values of environmental improvements in continuous time, for individuals that can be either healthy or ill, with constant transition between the states and constant mortality rates in each state, and when direct welfare, mortality and morbidity are all affected by environmental quality. We first show that the values of being in each of the two live states can be represented by two Bellman dynamic programming equations, and derive values of statistical life in good health (VSL(H)) and in illness (VSL(I)), and “values of statistical health” (VSH(H) and VSH(I)). We then find the individual’s valuation of (small) instantaneous environmental changes, and of permanent environmental changes (“environmental investments”), and show how these valuations are related to VSL(H) and VSL(I) respectively. VSL(I) is often greater than VSL(H), and the values of environmental improvements are often higher in the ill state than in the healthy state, in particular when a typical illness is short-lasting and when the marginal value of consumption is substantially lower in the ill state than in the healthy state.

Key words: Value of statistical life; value of statistical health; environmental quality, environmental investments, mortality risk.

JEL classification: I12, I18, D11.
1. Introduction

The purpose of this paper is to contribute to the analytical basis for studying how changes in environmental quality are valued by individuals, when these changes affect their direct welfare and at the same time their rates of mortality and morbidity (illness). We distinguish between the values of two, rather diametrically different, types of environmental changes in this context. The first is the valuation of an immediate environmental quality change, i.e., a change that only affects environmental quality “right now”, but not later. The second is to consider the value of what we call “environmental investments”, i.e., interventions that affect environmental quality for all future periods. The presentation is based on a much simplified but instructive continuous-time model with constant transition (or hazard) rates between three mutually exclusive states: healthy, ill and dead; corresponding to exponentially distributed remaining times in each of the two former states. Following the literature, we define the value of statistical life in good health (VSL(H)) as the rate of substitution between consumption and mortality risk when initially in a healthy state. We similarly define the value of statistical life in illness (VSL(I)) (a concept coined by Cameron and DeShazo (2003) as the value of statistical illness) as the rate of substitution between consumption and mortality risk, when initially in the state of illness. We also define values of statistical health in the two states (VSH(H) and VSH(I)), as trade-offs between money and frequency of illness (when healthy) and frequency of cure (when ill). We will assume that “illness” is well-defined, here formally, by concentrating on one type of illness only (or one degree of severity of illness).
Under a continuous-time approach, current valuation of current risk change always departs from the current state. I here first show that this acknowledgement enormously simplifies the notions and derivations of VSL(H) and VSL(I) relative to some presentations in the literature. In particular, issues such as comorbidities (Bleichrodt, Crainich and Eeckhoudt (2003)), background risk (Eeckhoudt and Hammitt (2001)), risk aversion (Eeckhoudt and Hammitt (2004), Bommier and Villeneuve (2004)), and “dead-anyway effects” (Pratt and Zeckhauser (1996), Breyer and Felder (2002)) then lose much of their particular roles for VSL valuation. The continuous-time approach seems as the natural one for both VSL valuation and for the valuation of immediate environmental effects, given that the environment has immediate effects on mortality and morbidity rates. Relevant examples are stricter road traffic or workplace safety regulations (which immediately affect accident rates), or cleaner drinking water (with immediate effects on rates of sickness due to water contamination). For such cases the model here is particularly relevant. It is also relevant for studying cases with “competing risks” of the types analysed e.g. by Dow, Phillipson and Sala-I-Martin (1999) and Chang (2002), given that hazard rates are constant. We however also consider cases where an environmental change is permanent, and has a permanent effects on mortality or morbidity rates. “Dead-anyway effects” are then seen to play a role, not for VSL(H) or VSL(I) directly, but for the value of the environmental improvements considered.

To make the model simple, intuitive and instructive I concentrate on a stripped-down case where an individual’s consumption is constant in a given state (healthy or ill), current welfare depends on only consumption and environmental quality, and

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1 See also the empirical study by Breyer and Grabka (2001) who find no empirical basis for a dead-anyway effect, on a large German data set.
2 See e.g. David and Moeschberger (1978) and Elandt-Johnson and Johnson (1980) for the theoretical arguments supporting the current model, under competing risks.
risks are time- and age-independent. I first consider general instantaneous rate changes in mortality and morbidity rates. VSL(H) and VSL(I) can then be expressed simply as ratios between the expected discounted future utility value of being in each of the current states (healthy or ill, with values V(H) and V(I) respectively), and the marginal utility of income in the respective states. One implication of this formulation is that the “value of full health” (the value of being in the healthy state instead of in the state of illness) is always greater when the initial state is the ill state, than when the initial state is the healthy state, provided that the marginal utility of income is lower in the ill state (as is considered reasonable).

The use of value functions of the Bellman type (see Bellman and Kalaba (1965)) in continuous time is by now widespread in economics, in particular within theoretical and empirical labor market analysis, see e.g. Mortensen and Pissardies (1999), Pissarides (2000) and van den Berg (2003). This tool has turned out to be quite powerful and at the same time intuitively easy both to understand and to handle mathematically, at least in simple contexts similar to those considered here. Basic ideas behind its use are that decisions and evaluations are always made sequentially and based on the current state, and that one typically makes no current commitments to future actions. This framework has however so far had few applications in health economics settings. A main purpose of this note is then also to stimulate others to undertake research following related approaches.

3 One early exception is Hey and Patel (1983), who use a related two-state transition model to study effects of preventive measures to avoid illness, and care to improve the medical state the patient has become ill. No implications of their model for VSL valuation are however drawn.
2. The basic model framework

Consider an individual who can be in only one out of three mutually exclusive states: alive and healthy; alive and ill; and dead. When healthy current utility is $u(c_1, E)$, and when ill, utility is $v(c_2, E)$. $E$ denotes the level of an environmental quality variable that affects utility in all live states, where a higher $E$ denotes a better environment. Thus, reasonably, the derivatives of $u$ and $v$ with respect to $E$, $u'(E)$ and $v'(E)$, are both positive. The utility of being in the dead state is normalized to zero. $c_1$ and $c_2$ denote the consumption levels in the healthy and ill states; these are assumed constant over time for a given state, but generally differ between states, and typically such that $c_1 \geq c_2$, and assumption that we adopt in the following.\(^4\) Possibly, consumption may fall or increase directly as a consequence of changes in $E$. The current utility levels $u$ and $v$ are then assumed to be constant over time in a given state, as long as consumption and the environmental variable are constant. Assume that $u(c, E) > v(c, E)$, and $u'_c(c, E) > v'_c(c, E)$, implying that total and marginal utility of consumption are both higher in the healthy than the ill state, for given consumption and $E$. In fact we will make the stronger assumption that $u(c_1, E) > v(c_2, E)$ even in cases where $c_1 > c_2$ (where we also from the above clearly must have $u(c_1, E) > v(c_2, E)$).

Time is modelled as continuous. An individual who starts from an initial healthy state faces Poisson rates $\lambda_D(E)$ and $\lambda_I(E)$ at which death and illness occur respectively. After having fallen ill the individual faces a constant death rate $\mu_I(E)$ (> $\lambda_D(E)$).

\(^4\) I here do not discuss the sources of consumption possibilities. These will typically be labor income, initial financial wealth, pensions and possible insurance schemes. Labor income is likely to be systematically lower in the ill state than in the healthy state, while initial insurance contracts to insure the individual against illness may (partly or fully) counteract the reduction in labor income. Our formulation is obviously too simple, for several reasons. One is that a protracted illness during which the individual cannot work is likely to run down savings and ultimately lead to lower consumption. Another is the issue of optimal life insurance or insurance against income loss during illness. One particular complication then is that when life insurance contracts can be continuously renegotiated, changes in death and illness risk will in principle induce a renegotiation of the initial contract so as to ensure an actuarially fair return to the insurer; see Strand (2003). This is likely to induce a reduction in ill-state consumption when the probability of illness increases, and a reduction in general consumption when the probability of death increases.
thereafter, and a constant rate $\mu_H(E)$ at which health is restored.\(^5\) These rates are all functions of $E$, as environmental quality is assumed to affect the incidence of death, illness and recovery from illness. Reasonably, derivatives of $\lambda_D(E)$, $\lambda_I(E)$ and $\mu_D(E)$ with respect to $E$, denoted $\lambda_{DE}$, $\lambda_{IE}$ and $\mu_{DE}$, are all negative, i.e., death rates and the rate at which illness occurs are lower when environmental quality is higher, while the derivative of $\mu_H(E)$, the transition rate from the ill to the healthy state (the rate of recovery from illness), generally should increase in $E$. Our assumption of constant transition rates here clearly makes the model less general than otherwise.\(^6\) It is however useful for deriving and illustrating certain principal factors that are far more difficult to derive and interpret under more general formulations. It is also easily found that a number of the more important results do not depend on transition rates being constant over time.

Define Bellman (or value) functions $V(H)$ and $V(I)$, as expected discounted lifetime values of current health and current illness, as follows: \(^7\)

\(^5\) Apart from the introduction of environmental quality $E$, this formulation corresponds to that used in Strand (2004), and is similar to Cameron and DeShazo (2003) except for two main further differences: time is here continuous instead of being discrete; and hazard rates are constant instead of more general variable rates. Assuming constant hazard rates are of course unrealistic and has some objectionable implications, in particular that the values of remaining lifetimes and WTP for environmental improvements are independent of the individual’s age. Extending the model to increasing mortality and morbidity rates over time is an important topic for future research here.

\(^6\) Assuming that all hazard rates and their derivatives with respect to $E$ are independent of age is of course unrealistic and has some objectionable implications, in particular that the values of remaining lifetimes and WTP for environmental improvements are independent of age. Cases with increasing mortality rates with age (but where morbidity is ignored) are treated by Johansson (2001, 2002). Extending the current two-state model to increasing mortality and morbidity rates over time is an important topic for future research. Note that while mortality and morbidity rates ought to increase with age, it is less clear how their derivatives with respect to $E$ change with time. These derivatives may in some cases be greater in absolute value for the young and the old, signifying that younger persons’ health may in some circumstances be more responsive to environmental conditions than older persons’ health. In most cases we however probably have the opposite relation, in particular when environmental conditions are very adverse (during lapses of extremely poor air quality leading to substantial excess mortality among the ill and elderly).

\(^7\) The formulation of Bellman functions in continuous time follows from taking limits of the associated discrete-period functional equations, presented e.g. in Bellman and Kalaba (1965). Derivations are straightforward; for a standard application reference which has had great influence on the labor market literature, and where also a simple derivation is offered, see Shapiro and Stiglitz (1984).
\begin{align}
(1) \quad rV(H) &= u(c_1, E) - \lambda_D(E)V(H) + \lambda_I(E)[V(I) - V(H)] \\
(2) \quad rV(I) &= v(c_2, E) - \mu_D(E)V(I) + \mu_I(E)[V(H) - V(I)]
\end{align}

where $r$ is a (constant) subjective rate of interest. The left-hand sides of (1)-(2) can be interpreted as current returns to two different assets, namely the present discounted value of currently being healthy, and the present discounted value of currently being sick. These returns have three components. The first is the current utility of consumption (or “current well-being”) in each state. The second is a component representing the change in asset value when the state changes from the current to the dead state (which is here simply the loss of the whole initial asset value). The third is a component representing the change in asset value when the state changes, from the current to the alternative live state (from healthy to ill in (1), and from ill to healthy in (2)).

(1)-(2) can be solved with respect to $V(H)$ and $V(I)$ as follows:

\begin{align}
(3) \quad V(H) &= \frac{r + \mu_D + \mu_I}{D} u(c_1, E) + \frac{\lambda_I}{D} v(c_2, E) \\
(4) \quad V(I) &= \frac{\mu_I}{D} u(c_1, E) + \frac{r + \lambda_D + \lambda_I}{D} v(c_2, E)
\end{align}

where

\begin{align}
(5) \quad D &= (r + \mu_D + \mu_I)(r + \lambda_D + \lambda_I) - \mu_I \lambda_I.
\end{align}

\textsuperscript{8} Note the overly simplified structure where mortality and morbidity rates are constant through time. By construction, VSL and VSI will then also be invariant through an individuals’ life. This is counterfactual; see e.g. Johansson (2002), Aldy and Viscusi (2003), Viscusi (2004) and Viscusi and Aldy (2004), for recent discussions of models where individuals’ VSL values vary over their lifetimes, and the empirical evidence in this regard.
(3)-(5) define the coefficients $D(H;H)$, $D(I;H)$, $D(H;I)$ and $D(I;I)$. $V(H)$ can here naturally be interpreted as the “present value of current health”, and $V(I)$ in (4) as the “present value of current illness”, given constant transition rates between states. Under our formulation the transition rates from healthy to ill state, and from ill back to healthy state, are both generally positive, implying that $V(H)$ and $V(I)$ are both functions of $u$ and $v$. $D(H;H)$ and $D(I;H)$ are here weights attached to future benefits from healthy and ill states when currently healthy, while $D(H;I)$ and $D(I;I)$ are similar weights when currently ill. Note that $V(H) > V(I)$, as $u > v$ and $D(H;H) + D(I;H) > D(H;I) + D(I;I)$ (since $\mu_D > \lambda_D$ : expected remaining lifetime is shorter when ill than when healthy).

We will now derive measures of individual willingness to pay (WTP) for small changes (reductions) in the probability of dying in each of the two states, healthy and ill. These measures will correspond to the value of statistical life in the healthy and the ill state, denoted $VSL(H)$ and $VSL(I)$ respectively. Holding $V(H)$ respectively $V(I)$ constant and differentiating with respect to death rates and consumption levels, we find the following simple expressions (5)-(6):

\begin{align}
VSL(H) &= \frac{dc_1}{d\lambda_D} = \frac{V(H)}{u_i} \\
VSL(I) &= \frac{dc_2}{d\mu_D} = \frac{V(I)}{v_i}.
\end{align}

$VSL(H)$ and $VSL(I)$ are defined and derived in standard fashion as the value of remaining lifetime evaluated at the current marginal value of consumption (see e.g. Rosen (1988), and the more specific applications by Cameron and DeShazo (2003) and Strand (2004a)). $VSL(H)$ may be either greater or smaller than $VSL(I)$. Since
$V(H) > V(I)$, a sufficient condition for $VSL(H) > VSL(I)$ is $u_1 \leq v_1$. The latter is likely to hold when the functions describing utility of income in the two states are not too dissimilar (as income is likely to be at least as high in the healthy state when the individual can work, as compared to the ill state where he possibly cannot). On the other hand, when $u_1$ is substantially greater than $v_1$ for given consumption (i.e., consumption is much more valuable at the margin in the healthy state than in the ill state), and the healthy-state income is close to being retained in the ill state, $u_1 > v_1$, in which case we may have $VSL(H) < VSL(I)$. Intuitively, $VSL(H)$ and $VSL(I)$ express tradeoffs between the overall values of longevity, and current consumption. When current consumption is less attractive in the ill state, longevity is correspondingly more attractive in that state. This is perhaps illustrated most easily in the case where illness is very short-lasting, i.e. $\mu_H$ is very high relative to other parameters, in which case we have approximately $V(H) = V(I) = u/(r+\lambda D)$ (the value of current illness is “almost” fully determined by what happens in the healthy state). Then unambiguously $VSL(I) > VSL(H)$ only given that $u_1 > v_1$. An opposite polar case (when the ratio of $VSL(H)$ to $VSL(I)$ is at its greatest) is $\lambda I = \mu_H = 0$, i.e., no transition between states. Then $VSL(H) = u/[(r+\lambda_D)u_1]$, and $VSL(I) = v/[(r+\mu_D)v_1]$.

Consider next the “value of statistical health” as the corresponding trade-offs between money and the risk of illness in each of the states (the WTP to avoid such risks), which we denote by $VSH(H)$ and $VSH(I)$. We find

$$VSH(H) = \frac{dc}{d\lambda} = \frac{V(H) - V(I)}{u_1} \quad \text{(7)}$$
$$VSH(I) = -\frac{dc}{d\mu} = \frac{V(H) - V(I)}{v_1} \quad \text{(8)}$$
Here obviously, an increase in $\mu_H$ is valued positively (and an increase in $\lambda_I$ is valued negatively). We find that the two VSH concepts are completely equivalent except for the difference in marginal consumption values in the states. Thus $VSH(I) > (<) VSH(H)$ unambiguously, whenever $v_1 < (>) u_1$.

Expected remaining lifetimes starting from state H and I, which respectively are here given by

\begin{align*}
EL(H) &= \frac{\mu_D + \mu_H + \lambda_I}{(\lambda_D + \lambda_I)(\mu_D + \mu_H) - \lambda_I \mu_H} \\
EL(I) &= \frac{\lambda_D + \hat{\lambda}_I + \mu_H}{(\lambda_D + \lambda_I)(\mu_D + \mu_H) - \lambda_I \mu_H}.
\end{align*}

$EL(H) > EL(I)$ given that $\lambda_D < \mu_D$ (expected lifetime is longer when healthy than when ill). We see that the ratio of $EL(H)$ to $EL(I)$ is given by $(\mu_D + \mu_H + \lambda_I)/(\lambda_D + \lambda_I + \mu_H)$. $EL(H)$ can be split up into the time that a healthy individual expects to stay healthy, $L(H)$, and the expected time to remain in future illness, $L(I;H)$ (when currently in the healthy state), and the same can be done for $EL(I)$, as follows:

\begin{align*}
L(H) &= \frac{\mu_D + \mu_H}{(\lambda_D + \lambda_I)(\mu_D + \mu_H) - \lambda_I \mu_H} \\
L(I;H) &= \frac{\lambda_I}{(\lambda_D + \lambda_I)(\mu_D + \mu_H) - \lambda_I \mu_H} \\
L(I) &= \frac{\lambda_D + \hat{\lambda}_I}{(\lambda_D + \lambda_I)(\mu_D + \mu_H) - \lambda_I \mu_H} \\
L(H;I) &= \frac{\mu_H}{(\lambda_D + \lambda_I)(\mu_D + \mu_H) - \lambda_I \mu_H}.
\end{align*}
Expected remaining lifetime spent in either of the two current states is here proportional to the sum of the transition rates out of the opposite state, which is a special property of the constant-transition-rate model.

3. Values of environmental improvements

This section derives expressions for the instantaneous value of an improved environment in each of the two states. We here in effect ask what income loss makes the individual exactly indifferent with respect to a given instantaneous (small) improvement in the environmental level \( E \), when currently in the healthy or ill state respectively; or put otherwise, what is the individual’s maximum willingness to pay (WTP) for such an improvement in each of the states.

These WTP values are found differentiating (1) and (2) with respect to \( E \), and \( c_1 \) and \( c_2 \), respectively. The instantaneous transition rates \( \lambda_D \) and \( \lambda_I \) (starting from the healthy state) and \( \mu_D \) and \( \mu_I \) (starting from the ill state) are all affected by this change in \( E \), the three first negatively and the last positively. The expressions containing \( V(H) \) and \( V(I) \) on the right-hand sides of (1) and (2) express future and not instantaneous values, and are thus not affected. This leads to the following expressions:

\[
\frac{dV(H)}{dE} = u_{1E} - \lambda_{DE} V(H) - \lambda_{IE} (V(H) - V(I)) + u_1 \frac{dc_1}{dE} = 0
\]

\[
\frac{dV(I)}{dE} = u_{2E} - \mu_{DE} V(I) + \mu_{IE} (V(H) - V(I)) + v_1 \frac{dc_2}{dE} = 0.
\]
Define now WTP in response to marginal increases in E, in the healthy and ill state respectively, as follows:

\[
WTP(H) = -\frac{d_1}{dE} = \frac{1}{u_1} (u_E - \lambda_{1E} V(H) - \lambda_{1E} (V(H) - V(I)))
\]

\[
WTP(I) = -\frac{d_2}{dE} = \frac{1}{v_1} (v_E - \mu_{1E} V(I) + \mu_{1E} (V(H) - V(I))).
\]

In interpreting first WTP(H), we separate between the three main terms on the right-hand side of (17), corresponding to three principal effects of changes in E. The first is the immediate welfare (or utility) effect of an improved environment for healthy persons, the most traditional effect in this context. The second and third terms express WTP for reductions in immediate mortality and morbidity risks respectively, when one currently is in the healthy state. All three effects are evaluated at the marginal utility of income in the current (healthy) state. The second (mortality) terms can be expressed using the VSL expressions derived above, and the third (morbidity) terms using the VSH expressions. In (17), the consumption value in the initial H state is traded off against the increase in E affecting the frequency with which the I state occurs (and a smaller probability that this state will occur), which entails a lower utility level than the H state. Note then also that the willingness to pay for such a reduction in illness incidence is smaller in the H state than the I state whenever the marginal value of consumption is higher in the H state.

Can we say which is the greater of WTP(H) and WTP(I)? First, in the (more traditional) case where neither mortality nor morbidity is affected, we have the rather obvious relation that WTP(I) > WTP(H) unambiguously whenever \( v_E/v_1 > u_E/u_1 \) (an
ill person is annoyed more than a healthy person by worsened environmental quality, where annoyance is evaluated in terms of the utility of current consumption loss), which may seem like a typical case. When E in addition affects mortality and/or morbidity, the situation is more complex. To study such cases, assume first that E affects survival only ($\lambda_{IE}$, $\mu_{HE}$, $v_E$ and $u_E$ are all zero). Then $WTP(H) = -\lambda_{DE}VSL(H)$, and $WTP(I) = -\mu_{DE}VSL(I)$. Considering a further special case of $VSL(H) = VSL(I)$, $WTP(H) > (<) WTP(I)$ whenever $|\lambda_{DE}| > (<) |\mu_{DE}|$. Reasonably $|\lambda_{DE}| > |\mu_{DE}|$ in most cases, i.e. higher environmental quality affects death rates more for sick than for healthy individuals, and thus $WTP(I) > WTP(H)$. Such a difference will be further magnified whenever there are current consumption effects of environmental quality and $v_E/v_1 > u_E/u_1$, as was deemed reasonable above.

In contrast, when $VSL(H)$ substantially exceeds $VSL(I)$, and $|\lambda_{IE}|$ is substantially greater than $\mu_{HE}$ (environmental improvements reduce the frequency of illness, and by more than the increase in frequency of recovery from illness), $WTP(H)$ could easily exceed $WTP(I)$. The second factor implies an additional effect of environmental quality in the healthy state versus the ill state; in the first case the incidence of both death and illness are affected negatively; in the second case the death rate is affected in similar fashion, but the recovery rate from illness is affected much less.  

4. Environmental investments

We now wish to study effects of “environmental investments”, and the valuation of such investments. Environmental investments are here defined as interventions that increase E to a new, and permanently higher, level. They are thus rather diametrically different from the types of interventions considered in section 3, where the

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9 A similar second effect would have been obtained in the ill state, if a transition back to the healthy state had been possible and this transition affected by the environment.
interventions were assumed to only have an immediate effect (and thus no effect whatsoever beyond the immediate one).

Assume now an intervention that increases E permanently, by a small amount dE, and that this increase is to take place in the “near future”, i.e. from time $t + \Delta t$ where $t$ is the present time. For $\Delta t$ small, $V(H)$ and $V(I)$ can now be written approximately as follows:

\begin{align}
V(H) &= u(c_1, E)\Delta t + D(H; H)u + D(I; H)v \\
V(I) &= v(c_2, E)\Delta t + D(H; I)u + D(I; I)v.
\end{align}

We seek the trade-off between changes in immediate income, represented by $c_1$ and $c_2$ in (19)-(20), and changes in E (the permanent increase in environmental quality), that leave $V(H)$ and $V(I)$ constant. Assume also that, while both dE and $\Delta t$ are small, dE is small relative to $\Delta t$. Define $dR_i = dc_1(i)\Delta t$ as a small change in income that affects current consumption only, in state $i = H, I$, and consider the individual’s WTP for a small permanent change dE in E, departing from state $i= H,I$. This can be defined as the changes $dR(H)$ and $dR(I)$, that in each case make the individual indifferent about the change in E. We find in the two cases:

\begin{align}
Q(H) &= -\frac{dc_1 \Delta t}{dE} = \frac{1}{u_i} \left[ \frac{dD(H; H)}{dE} u + \frac{dD(I; H)}{dE} v + D(H; H)u_E + D(I; H)v_E \right] \\
Q(I) &= -\frac{dc_1 \Delta t}{dE} = \frac{1}{v_i} \left[ \frac{dD(H; I)}{dE} u + \frac{dD(I; I)}{dE} v + D(H; I)u_E + D(I; I)v_E \right].
\end{align}

We here consider $\Delta t$ to be sufficiently short that the current level of $u$ is not affected noticeably by the change in E. We are also assuming that the permanent change in E does not directly affect future income nor consumption.
Each of the expressions on the right-hand sides consists of two principal types of benefits resulting from permanent increases in E. The two first terms represent utility effects due to changes in mortality and morbidity rates over the individuals’ entire remaining lifetimes. The two last terms represent increased future utilities of lower future pollution levels, in each of the two future live states (as healthy and as ill). D(H;I) here unambiguously increases with E, D(H;H) and D(I;I) almost certainly also increase,\textsuperscript{11} while the effect on D(I;H) is ambiguous.\textsuperscript{12}

The relative magnitudes of Q(H) and Q(I) cannot, as in earlier cases, be decided unambiguously without imposing further conditions. In particular, we may easily have Q(I) > Q(H) at least given that $v_E > u_E$.

Note that while the values of immediate improvements in environmental quality, as derived in (17)-(18), are expressed as functions of the values of gaining health, V(H)-V(I), no similar terms appear directly in the current expressions (21)-(22). The reason is that the latter expressions take into consideration the compounded effect of all future such changes (from healthy to ill and back), which are built into the terms D(i,j).

5. Conclusions and final remarks

The purpose of this paper has been to present a framework for, and the start of, an analysis of the values of environmental improvements for purely selfish individuals, where we explicitly consider the expected rates of transition between healthy, ill and dead states, and the utilities experienced in respective live states. The analysis

\textsuperscript{11} This is most obvious for D(H;H). Here the effect is unambiguous given that $\mu_0 + \mu_i \geq 0$, which implies that the overall escape rate from illness does not fall when the environment improves.

\textsuperscript{12} Intuitively, the last effect follows because health is sustained for longer while alive, which in turn increases the likelihood that death occurs before illness.
incorporates effects of environmental changes on mortality and morbidity and on direct welfare in “healthy” and “ill” states, in continuous time when environmental effects can be either immediate or long-lasting. The first step in the analysis is to derive relevant concepts of value of statistical life in good health (VSL(H)) and in illness (VSL(I)), respectively. We show that VSL(H) and VSL(I) are naturally derived from purely immediate trade-offs between mortality risk and money and do not involve particular concerns e.g. for baseline risk or risk aversion, topics that have received much attention in recent literature (as further discussed in the introduction). I then go on to consider individuals’ valuation of two types of environmental changes. First, I consider values of an instantaneous environmental change that only affects environmental quality “today”. I next consider values of “environmental investments” defined by environmental quality improvements that last indefinitely. I demonstrate how these values depend on the direct welfare effects of environmental changes, as well as the effects on mortality and morbidity rates in each of the two states, and how they relate to the derived VSL and VSI concepts.

The main objective of this analysis has been to build a starting point and basis for more practical applications, both theoretical and empirical. Several theoretical extensions of the current model appear natural. One obvious extension is to variable mortality and morbidity rates (increasing with age), which have been studied by others, e.g. Johansson (1995, 2001, 2002) but only in the context of models with a single live state and with only selfish individuals. Another obvious extension is to incorporate inter-personal factors such as altruism or direct inter-personal utility of others’ survival, which has been studied by e.g. Johansson (1994), Jones-Lee (1992) and Strand (2004b), but only without concern for morbidity and assuming and time-invariant mortality rates. A third issue is to make considerations for the presence of
insurance or other financial markets and the way in which these may modify the realized path of consumption; see e.g. Johansson (2002) and Strand (2003) for starts of such analyses.

For such a model to suitable for realistic empirical applications, it is likely that extensions of the above types (to variable transition rates, inter-personal concerns, and the presence of financial markets) are necessary. An implementable model, building on such an extended framework, may then be built and calibrated to actual (time-variable) frequencies of mortality and morbidity (or relevant morbidity factors that are likely to be affected by environmental quality), estimated environmental effects on morbidity and mortality, and realistic considerations with respect to inter-personal concerns. Such an exercise will encounter a number of both theoretical and practical problems that this paper does not address, the overcoming of which should form an important basis for the future research agenda in this area. One practical problem to notice here is the need for an appropriate specification of individuals’ utility functions, in particular what is the correct trade-off between money and environmental quality. This trade-off is generally unobservable, and further population surveys are necessary to uncover them.
References


