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Discussion Paper No. 4.05

**Welfare Measurement under Threats of
Environmental Catastrophes**

by

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Welfare Measurement under Threats of Environmental Catastrophes

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March 2005

Abstract

Welfare measures under threats of environmental catastrophes are studied using the "parable" apparatus of Weitzman and Löfgren [22]. The occurrence probability of the catastrophic events is driven (at least partly) by anthropogenic activities such as natural resource exploitation. Without external effects, the green NNP is a genuine welfare measure vis-à-vis a particular parable economy. Often, however, the occurrence hazard constitutes a public bad, treated as an externality by agents who ignore their own contribution to its accumulation. In such cases the green NNP, although accounting for the event hazard rate per se, fails to properly internalize future effects on the hazard rate of current economic activities and as a result overestimates welfare. The bias term associated with the green NNP is derived and expressed in a simple and interpretable form.

Keywords: green NNP; environmental catastrophes; hazard rate; uncertainty

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1 Introduction

In a widely cited paper, Weitzman [17] has shown how to relate national accounting to a welfare measure at any given time. The method has since been extended and applied in a wide range of environmental related issues, including sustainability [18, 4, 5], technical change and economic growth [3, 18, 22], intergenerational equity [9], and pollution abatement policies [12]. The recent books of Weitzman [21] and Aronsson et al. [1] provide detailed accounts on this line of research. In this note we apply the green accounting methodology to situations involving threats of environmental catastrophes which are (at least partly) induced by anthropogenic activities. Examples of such catastrophic events include nuclear accidents [8, 2], global warming related calamities [15, 10], pollution-related events [7, 16], and biodiversity loss and species extinction [14, 11]. All these events are classified as "catastrophic" because their abrupt occurrence inflicts a significant damage, which should not be ignored in the national accounts. Moreover, the conditions that trigger the events are not completely understood or controlled, and the exact occurrence time cannot be predicted in advance. The nature of the events and the scale of the damage inflicted often render complete insurance schemes infeasible.

The presence of environmental threats has undesirable welfare implications and a question arises regarding whether these implications are captured by measures such as the green NNP. The answer depends on whether the market prices that underlie the NNP properly account for the environmental hazard, which in turn depends on whether the hazard involves external effects. Without external effects, the event risk is fully reflected by the market prices and the green NNP can be related to a stationary-equivalent welfare measure by means of the "parable" apparatus of Weitzman and Löfgren [22]. We show that the green NNP represents the stationary consumption rate of a "nonchalant" parable economy that, up to the occurrence date, consumes all of its income regardless of the event threat.

Environmental hazards, however, are often fraught with externalities, as individual agents tend to treat the hazard as a public bad. Indeed, the

green accounting methodology is very explicit in requiring that accounting is "comprehensive", implying that no effect is left out, including external hazard effects (see [3, 18, 22] and references they cite for studies of green accounting with external effects in an economic growth context). When agents ignore their own contribution to hazard accumulation and the stocks of the mitigating environmental resources decrease over time, the green NNP overestimates welfare. This is so because the market prices of the hazard-mitigating assets, while reflecting the current hazard per se, fail to properly account for future changes in its rate due to current exploitation activities.

To focus attention on environmental hazards, we consider in Section 2 a simple economy with a single composite consumption good and two capital goods, of which one is the environmental capital affecting the probability of the event occurrence. (Extensions to more general settings, such as in [19, 20, 6], will not change the nature of the results.) In Section 3, a stationary-equivalent welfare measure under event uncertainty is defined and compared to the green NNP. The two cases – when the event hazard is internalized and when it is treated by agents as an externality – are considered and contrasted. Section 4 concludes.

2 The economy

Except for the modifications needed to account for the environmental events, we follow the formulation of Weitzman [17, 18] and Weitzman and Löfgren [22]. We consider an economy with a single composite consumption good, denoted C , and several capital assets, of which we single out a natural resource capital stock Q . The other capital stocks, denoted K , represent the traditional stocks used for production as well as other environmental assets. For the present purpose no generality is lost by considering a two-dimensional capital vector (K, Q) . The constant (consumption) discount rate is denoted r .

The special role of the environmental stock Q is manifest via its effect on the hazard rate $h(Q)$ of abrupt occurrence of some detrimental event such that $h(Q)dt$ measures the conditional probability that the event will

occur during $[t, t + dt]$ given that it has not occurred by time t when the resource stock is Q . Let T represent the random event-occurrence time with the probability distribution and density functions $F(t)$ and $f(t)$, respectively. For a given $Q(t)$ process, the hazard $h(Q(t))$ is related to the distribution $F(t)$ according to $h(Q(t)) = f(t)/(1 - F(t)) = -d[\ln(1 - F(t))]/dt$, yielding

$$F(t) = 1 - e^{-\Omega(t)} \quad \text{and} \quad f(t) = h(Q(t))e^{-\Omega(t)}, \quad (2.1)$$

where

$$\Omega(t) = \int_0^t h(Q(\tau))d\tau. \quad (2.2)$$

Let I_K and I_Q represent the net investment rates in K and Q , respectively,

$$\dot{K}(t) = I_K(t) \quad \text{and} \quad \dot{Q}(t) = I_Q(t). \quad (2.3)$$

Given the capital stocks (K, Q) , consumption-investment decisions are constrained to the convex production possibilities set $S(K, Q)$, i.e., the combination (C, I_K, I_Q) is feasible if

$$(C, I_K, I_Q) \in S(K, Q). \quad (2.4)$$

Let $\varphi(K, Q)$ denote the post-event value function, representing the maximal present value of all future consumption streams from the occurrence time T onward discounted to time T , given that $K = K(T)$ and $Q = Q(T)$. At time t prior to occurrence, a feasible consumption-investment policy $\{C(\tau), I_K(\tau), I_Q(\tau), \tau \geq t\}$ gives rise to the expected present value (discounted to time t)

$$\begin{aligned} E_T \left\{ \int_t^T C(\tau) e^{-r(\tau-t)} d\tau + e^{-r(T-t)} \varphi(K(T), Q(T)) | T > t \right\} = \\ \int_t^\infty \left\{ C(\tau) \frac{1 - F(\tau)}{1 - F(t)} + \frac{f(\tau)}{1 - F(t)} \varphi(K(\tau), Q(\tau)) \right\} e^{-r(\tau-t)} d\tau = \\ \int_t^\infty \{ C(\tau) + h(Q(\tau)) \varphi(K(\tau), Q(\tau)) \} e^{-R(\tau, t)} d\tau, \end{aligned}$$

where

$$R(\tau, t) = r(\tau - t) + [\Omega(\tau) - \Omega(t)] = \int_t^\tau [r + h(Q(s))] ds \quad (2.5)$$

and E_T denotes expectation with respect to the distribution of T . The maximal present value of all feasible consumption streams at time t is, therefore, given by

$$V(K, Q) = \max_{\{C(\tau), I_K(\tau), I_Q(\tau)\}} \int_t^\infty \{C(\tau) + h(Q(\tau))\varphi(K(\tau), Q(\tau))\} e^{-R(\tau, t)} d\tau \quad (2.6)$$

subject to (2.3) and (2.4), given $K = K(t)$ and $Q = Q(t)$. Notice that $V(K, Q)$ depends on t only through the initial capital stocks $K(t)$ and $Q(t)$ (changing t and keeping the initial stocks fixed is equivalent to a mere shift of the origin of the time index). It is assumed that (2.6) admits a unique solution.

The damage function is defined as

$$\psi(K, Q) = V(K, Q) - \varphi(K, Q), \quad (2.7)$$

such that the expected loss associated with occurrence during $[t, t + dt]$ is $\psi(K(t), Q(t))h(Q(t))dt$. For example, a "doomsday" event that ceases all further economic activities entails $\varphi(K, Q) = 0$ and $\psi(K, Q) = V(K, Q)$. Recurrent events may destroy some appreciable amounts D_K and D_Q of the existing capital stocks, in which case $\varphi(K, Q) = V(K - D_K, Q - D_Q)$, or affect the production feasibility set S , changing the possibilities (and welfare) for post-event performance. Regardless of the exact specification, we assume that the damage function is known and sufficiently large to rule out the possibility of complete insurance coverage. When the extent of damage is also subject to uncertainty, we take ψ to represent its expected value.

Let P_K and P_Q be the *current-value* costate variables of K and Q , and define the functions

$$Y(K, Q, P_K, P_Q) = \max_{(C, I_K, I_Q) \in S(K, Q)} \{C + P_K I_K + P_Q I_Q\} \quad (2.8)$$

and

$$G(K, Q, P_K, P_Q) = Y(K, Q, P_K, P_Q) - h(Q)\psi(K, Q). \quad (2.9)$$

We now show that the following conditions hold along the optimal trajectory $\{K^*(\tau), Q^*(\tau), C^*(\tau), I_K^*(\tau), I_Q^*(\tau), P_K^*(\tau), P_Q^*(\tau)\}$ corresponding to (2.6):

$$Y(K^*, Q^*, P_K^*, P_Q^*) = C^* + P_K^* I_K^* + P_Q^* I_Q^*, \quad (2.10)$$

$$\dot{P}_K^*(\tau) - rP_K^*(\tau) = -\partial G/\partial K \quad (2.11)$$

and

$$\dot{P}_Q^*(\tau) - rP_Q^*(\tau) = -\partial G/\partial Q, \quad (2.12)$$

where the dot indicates derivative with respect to τ and the derivatives on the right-hand side of (2.11) and (2.12) are evaluated at the optimal arguments.

Condition (2.11) can be rewritten, using the property $\partial V/\partial K = P_K^*$, as

$$\dot{P}_K^* - [r + h(Q^*)]P_K^* = -[\partial Y/\partial K + h(Q^*)\partial\varphi/\partial K], \quad (2.11^*)$$

while condition (2.12) assumes different forms depending on whether the effect of Q on the hazard $h(Q)$ is internalized. If the hazard is treated by agents as an externality, the dependence of h on Q is ignored and h is taken as an exogenous function of time evolving along the equilibrium path $h^*(\tau) = h(Q^*(\tau))$. In this case, $\partial G/\partial Q = \partial Y/\partial Q + h^*(\tau)\partial\varphi/\partial Q - h^*(\tau)P_Q^*$, yielding

$$\dot{P}_Q^* - [r + h^*(\tau)]P_Q^* = -[\partial Y/\partial Q + h^*(\tau)\partial\varphi/\partial Q], \quad (2.12^*)$$

where we use the property $\partial V/\partial Q = P_Q^*$. However, when agents account for the change in hazard due to their own resource exploitation, the effect of Q on h is internalized, $\partial G/\partial Q = \partial Y/\partial Q + h(Q)\partial\varphi/\partial Q - h(Q)P_Q - h'(Q)\psi$ and (2.12) becomes

$$\dot{P}_Q^* - [r + h(Q^*)]P_Q^* = -[\partial Y/\partial Q + h(Q^*)\partial\varphi/\partial Q - h'(Q^*)\psi]. \quad (2.12^{**})$$

To verify that (2.10), (2.11^{*}) and (2.12^{*}) are necessary conditions for a solution of (2.6) when $h(\tau) = h(Q(\tau))$ and $\Omega(\tau)$ are treated as exogenous functions of time, notice that, with the effective discount rate $r + h(\tau)$, the current-value Hamiltonian is $C + h(\tau)\varphi + P_K I_K + P_Q I_Q$ and the conditions follow from the Maximum Principle.

When the effect of Q on h is internalized, we treat Ω as a third state variable satisfying $d\Omega/d\tau = h(Q)$ (c.f. (2.2)) with the initial value $\Omega(t)$, and define the present-value (discounted to time t) Hamiltonian

$$H = [C + h(Q)\varphi(K, Q)]e^{-R(\tau, t)} + \lambda_K I_K + \lambda_Q I_Q + \mu h(Q), \quad (2.13)$$

where λ_K , λ_Q and μ are the present-value costates of K , Q and Ω , respectively. Noting (2.5), $d\mu/ds = -\partial H/\partial\Omega = [C(s) + h(Q(s))\varphi(K(s), Q(s))]$ $e^{-R(s, t)}$. Integrating from τ to ∞ along the optimal path and using the transversality condition $\lim_{s \rightarrow \infty} \mu(s) = 0$, gives $\mu^*(\tau) = -V(K^*(\tau), Q^*(\tau))e^{-R^*(\tau, t)}$. With the current-value costates $P_K(\tau) = \lambda_K(\tau)e^{R^*(\tau, t)}$ and $P_Q(\tau) = \lambda_Q(\tau)e^{R^*(\tau, t)}$, conditions (2.10), (2.11*) and (2.12**) follow from the Maximum Principle.

It is instructive to consider the equivalent formulations (2.11) and (2.11*) (or (2.12) and (2.12*)-(2.12**)) under two extreme specifications of the damage function. For "doomsday" events φ vanishes and (2.11*) shows the main effect of the hazard in increasing the effective rate of discount. When the damage is vanishingly small, G reduces to Y (c.f. (2.9)) and (2.11)-(2.12) reduce to the conditions corresponding to an event-free economy.

In fact, equations (2.11) and (2.12) describe the evolution of the competitive market prices in an economy operating under the occurrence hazard $h(Q)$. To see this, suppose that at time t prior to occurrence, the economy owns the capital stocks (K, Q) . With these stocks, the consumption equivalent of $Y(K, Q, P_K(t), P_Q(t))\delta$ can be produced during an infinitesimal time interval $[t, t + \delta]$. With probability $1 - h(Q)\delta$ the event will not occur during the interval, leaving the value $V(K, Q)e^{-r\delta}$. With probability $h(Q)\delta$ the event occurs, leaving the value $\varphi(K, Q)e^{-r\delta}$. The expected value at time $t + \delta$ (discounted to time t) is thus

$$Y(K, Q, P_K(t), P_Q(t))\delta + V(K, Q)e^{-r\delta} - h(Q)\delta e^{-r\delta}\psi(K, Q).$$

Alternatively, $P_Q(t)\varepsilon$ units of consumption can be traded for ε units of the environmental stock, producing $Y(K, Q + \varepsilon, P_K(t), P_Q(t))\delta$ during the same short interval, and possessing a stock worth $V(K, Q + \varepsilon)e^{-r\delta}$ with probability $1 - h(Q + \varepsilon)\delta$ that the event will not occur during $[t, t + \delta]$, or $\varphi(K, Q + \varepsilon)e^{-r\delta}$

with probability $h(Q + \varepsilon)\delta$ of occurrence. The discounted expected value in this case is

$$\begin{aligned} -P_Q(t)\varepsilon + Y(K, Q + \varepsilon, P_K(t), P_Q(t))\delta &+ V(K, Q + \varepsilon)e^{-r\delta} \\ &- h(Q + \varepsilon)\delta e^{-r\delta}\psi(K, Q + \varepsilon). \end{aligned}$$

In equilibrium agents are indifferent between these two options. At time $t + \delta$, $\partial V/\partial Q = P_Q(t + \delta)$, and the arbitrage condition becomes

$$-P_Q(t)\varepsilon + \frac{\partial Y}{\partial Q}\delta\varepsilon + P_Q(t + \delta)\varepsilon e^{-r\delta} - \frac{\partial(h\psi)}{\partial Q}\varepsilon\delta e^{-r\delta} = 0.$$

With $e^{-r\delta} = 1 - r\delta + o(\delta)$, we obtain, after neglecting terms of order $o(\varepsilon\delta)$ and dividing by $\varepsilon\delta$, $\dot{P}_Q - rP_Q = -\partial G/\partial Q$, as stated in (2.12). Condition (2.11) can be verified in the same way.

Having verified that P_K^* and P_Q^* are the competitive prices, we identify $Y^*(t) \equiv Y(K^*(t), Q^*(t), P_K^*(t), P_Q^*(t))$ of (2.10) with the green NNP. We turn now to investigate the relation between the green NNP and a stationary-equivalent welfare index for the economy.

3 Welfare measurement

To define a stationary-equivalent welfare measure corresponding to the value $V(K(t), Q(t))$, consider a "parable model" *à la* Weitzman and Löfgren [22] of an (hypothetical) economy possessing at time t (prior to occurrence) the capital stocks $(K(t), Q(t))$ which allow to produce the net output Y^P and is under the risk of event occurrence at some future random time T . From time t to occurrence, all net output is consumed and the capital stocks are kept fixed at $(K(t), Q(t))$. Thus, the output and hazard rate also remain fixed at Y^P and $h = h(Q(t))$, respectively. Upon occurrence, the value $\varphi = \varphi(K(t), Q(t))$ is obtained. The expected present value of the nonchalant parable policy $C^P = Y^P$ is

$$\begin{aligned} V^P(K(t), Q(t)) &= E_T\left\{\int_t^T C^P e^{-r(\tau-t)}d\tau + e^{-r(T-t)}\varphi|T > t\right\} \\ &= \int_t^\infty [C^P + h\varphi]e^{-(r+h)(\tau-t)}d\tau = \frac{C^P + h\varphi}{r + h} \quad (3.1) \end{aligned}$$

(the adjective "nonchalant" is attached to the parable policy to reflect the property that all output is consumed regardless of the hovering event threat).

The parable consumption rate $C^P = Y^P$ constitutes a welfare index for the parable economy because it describes the stationary rate of consumption that can be supported prior to occurrence. To establish a link with the real economy, we look for the parable output Y^P that gives rise to $V^P(K(t), Q(t)) = V(K(t), Q(t))$ of (2.6), denote it by $W(t)$ and interpret this quantity as the stationary-equivalent welfare measure appropriate for the real economy. Observing (3.1) and (2.7), the welfare index we seek is

$$\begin{aligned} W(t) &= [r + h(Q(t))]V(K(t), Q(t)) - h(Q(t))\varphi(K(t), Q(t)) \\ &= rV(K(t), Q(t)) + h(Q(t))\psi(K(t), Q(t)), \end{aligned} \quad (3.2)$$

which exceeds the standard index rV by the expected immediate damage at time t .

It turns out that when the effect of Q on the hazard rate h is internalized, the NNP equals the welfare measure defined by (3.2). However, when the hazard is treated by agents as an externality, the NNP introduces a bias, as established by the following Proposition:

Proposition 1. (a) *When the effect of Q on the hazard rate h is internalized,*

$$W^*(t) = Y^*(t) \quad (3.3)$$

and the NNP agrees with the welfare measure (3.2) evaluated at $(K^(t), Q^*(t))$.*

(b) *When the hazard is treated by agents as an externality, i.e., when $h(\tau) = h(Q(\tau))$ and $\Omega(\tau)$ are taken as exogenous functions of time,*

$$W^*(t) = Y^*(t) + Z^*(t) \quad (3.4)$$

where

$$Z^*(t) = - \int_t^\infty \dot{h}^*(\tau) \psi(K^*(\tau), Q^*(\tau)) e^{-R^*(\tau, t)} d\tau. \quad (3.5)$$

Proof: (a) When the effect of Q on h is accounted for, the property $dH/d\tau = \partial H/\partial\tau$ of the present value Hamiltonian (2.13) implies

$$dH(\tau, t)/d\tau = -r[C^*(\tau) + h(Q^*(\tau))\varphi(K^*(\tau), Q^*(\tau))]e^{-R^*(\tau, t)}.$$

Integrating from t to ∞ along the optimal path and using the transversality condition $\lim_{\tau \rightarrow \infty} H(\tau, t) = 0$ (see [13]), gives

$$H(t, t) = rV(K^*(t), Q^*(t)). \quad (3.6)$$

Recalling that $P_K^*(\tau) = \lambda_K^*(\tau)e^{R^*(\tau, t)}$, $P_Q^*(\tau) = \lambda_Q^*(\tau)e^{R^*(\tau, t)}$ and $\mu^*(\tau) = -V(K^*(\tau), Q^*(\tau))e^{-R^*(\tau, t)}$ (see Section 2), the Hamiltonian (2.13) at $\tau = t$ reduces to

$$H(t, t) = Y^*(t) - h(Q^*(t))\psi(K^*(t), Q^*(t)).$$

Comparing with (3.6) and (3.2) verifies (3.3).

(b) When $h(\tau)$ and $\Omega(\tau)$ are taken as exogenous functions of time, the present-value Hamiltonian is

$$H(\tau, t) = [C + h(\tau)\varphi(K, Q)]e^{-R(\tau, t)} + \lambda_K I_k + \lambda_Q I_Q \quad (3.7)$$

and the property $dH/d\tau = \partial H/\partial\tau$ gives

$$\begin{aligned} dH(\tau, t)/d\tau &= \{\dot{h}^*(\tau)\varphi(K^*(\tau), Q^*(\tau)) - \\ &\quad [r + h^*(\tau)][C^*(\tau) + h^*(\tau)\varphi(K^*(\tau), Q^*(\tau))]\}e^{-R^*(\tau, t)}. \end{aligned}$$

Integrating from t to ∞ along the optimal path and using the transversality condition $\lim_{\tau \rightarrow \infty} H(\tau, t) = 0$ implies

$$H(t, t) = [r + h^*(t)]V(K^*(t), Q^*(t)) - Z^*(t). \quad (3.8)$$

where

$$\begin{aligned} Z^*(t) &= \int_t^\infty \{[h^*(t) - h^*(\tau)][C^*(\tau) + h^*(\tau)\varphi(K^*(\tau), Q^*(\tau))] \\ &\quad + \dot{h}^*(\tau)\varphi(K^*(\tau), Q^*(\tau))\}e^{-R^*(\tau, t)}d\tau \end{aligned} \quad (3.9)$$

Taking the derivative of (3.9) with respect to t gives $\dot{Z}^*(t) - [r + h^*(t)]Z^*(t) = \dot{h}^*(t)\psi(K^*(t), Q^*(t))$, which is integrated along the optimal path to yield (3.5).

Again, $P_K^*(\tau) = \lambda_K^*(\tau)e^{R^*(\tau, t)}$, $P_Q^*(\tau) = \lambda_Q^*(\tau)e^{R^*(\tau, t)}$ and the Hamiltonian (3.7) evaluated at the optimal policy at $\tau = t$ becomes

$$H(t, t) = Y^*(t) + h^*(t)\varphi(K^*(t), Q^*(t)). \quad (3.10)$$

Comparing (3.8) and (3.10), noting (3.2), verifies (3.4). \square

Part (a) provides a precise meaning to the welfare significance of the NNP without externalities in terms of the nonchalant parable. The bias term Z^* introduced in part (b) stems from the failure of the market prices to fully account for the effect of Q on the hazard rate. The bias vanishes for non-influential events (i.e., $\varphi = V$ and $\psi = 0$) or when h is independent of Q (see (3.5)). Often the environmental stock mitigates the hazard (i.e., $h'(Q) < 0$), in which case resource extraction above replenishment increases the occurrence threat over time and gives rise to $Z^*(t) < 0$. The presence of the externality enhances the tendency to overexploit the environmental resource. Although the shrinking stock Q is included in the green NNP, the ensuing increase in the hazard rate is not properly represented by its price and the NNP provides an over-optimistic measure of welfare.

4 Concluding comments

The notion that current market prices contain all the information relevant to determine long-term welfare is appealing, but its validity is subject to the assumption of comprehensibility. The green accounting literature has long recognized that this assumption is an idealization because of the pervasiveness of market failures. Here we find that, without externalities, the green NNP can still be interpreted as a welfare measure also in the presence of event uncertainty. This can be done because markets respond properly to the environmental threats by adjusting the time preferences from the "bare" discount rate r to the effective rate $r + h$ and modifying the prices associated with the relevant capital stocks.

Often, however, agents treat the event hazard as an externality, hence the comprehensibility requirement is violated and the green NNP tends to overestimate welfare. If the hazard-affecting environmental asset is at or near a steady state, the hazard rate is approximately constant over time and the NNP bias disappears. Otherwise, neglecting to account for their own contribution to increasing the hazard, agents overexploit the environmental resource, reducing the (expected) welfare for the whole economy. Standard regulation techniques, such as a Pigouvian tax on the exploitation of the hazard-mitigating resource based on its marginal hazard effect, can induce agents to internalize the effect and increase welfare to the value indicated by the green NNP.

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