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ANALYSIS

The polluter pays principle and potential conflicts in society

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ABSTRACT

The conventional implementation of polluter pays principle (PPP) in many countries is based on the use of an environmental tax, which is determined proportionally to the amount of emissions of the polluting substances. In this paper we show that this practice is not adequate because of its real negative impact if the pollutant accumulates to a stock in the environment. Using a specific mathematical model we find, that in many cases there is a danger of an unavoidable conflict between the interests of society as a whole and the interests of private business, generated by these procedures of PPP implementation. This paper also presents a mathematical formula which expresses the time period, when the conflict arises. We call it "the time boundary of investment expediency". Some results of a numerical simulation for the calculation of this quantity for different investment initiatives are also presented in this article. On the basis of the model analysis, we suggest "a corrected" amount of environmental tax which covers the negative effect on social welfare. We find that it should be dependent on the lifetime of the production project, not only on the amount of emitted pollution. The study gives some practical tools for strengthening governance in the environmental sector and for the evaluation of investment initiatives from a "quality of growth" point of view.

1. Introduction

A conceptual analysis of long-run decisions about the economy and the environment as an application of capital theory has been presented in the paper of Baumgartner et al. (2002). The authors show that if a pollutant accumulates to a stock in the environment, than there is an inter-temporal leverage effect to the associated social cost of pollution, depending on the lifetime of pollutant. They used a specific mathematical model where degradation rate of the pollutant and per unit social cost are the parameters. When analyzing this model they concluded that in this case (stock pollution) the longer the time horizon, the less likely is the innovation of the new technique.

This conclusion has been made under a very important assumption: all social costs that society incurs due to the damage from pollution are taken into account within the investment decision making. It is a crucial idea of this paper's background. We found that a similar effect plays the key role for potential conflicts between society and business in long-run decisions. For our analysis we used the model from Baumgartner et al. (2002) with a few modifications for our purposes.

According to environmental legislation in Russia and in some other countries (OECD, 1997) the polluter must pay to the state budget proportionally to the amount of emissions. It is a kind of environmental tax; its size depends on the harm from the specific polluting substance. At the same time producers

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must make their own efforts to reduce pollution, in order to avoid the penalty for emissions exceeding the permitted (by environmental standards) level. In our consideration we denote by g the environmental cost of the producer, including the environmental tax (per unit of emission).

PPP is implemented in the form of payments for negative environmental impact as an instrument of environmental regulation in Russia and in some other former Soviet countries (Ukraine, Belarus). Russia, the richest country with natural resource between them, has also the significant financial flows to the state budget from the separate ("resource") tax on natural resource extraction, because all underground deposits have a status of federal property. These resources are mostly used for financing social services. Moreover, the total annual amount of this resource tax is permanently increasing during the last few years due to the growth of international oil prices and this circumstance allowed the reduction of the value added tax in Russia. However, in this article we explore the payments for negative impact (environmental tax), because only this tax can be considered as a form of PPP implementation.

There exist many factors which determine the environmental tax in different circumstances. Sometimes it is determined by the cost of equipment to trap the specific polluting substance calculated per unit of emissions. In other cases it may be the per unit (of emission) cost of the difference in the so-called hedonic price (for housing and accommodations) and so on. Anyway, usually this amount is far from the monetary evaluation of a negative impact on social welfare. We shall not discuss the problem of the adequate monetary evaluation of so-called "social costs" of pollution and other unavoidably jointly produced high entropy by-products (Faber et al., 1998; Baumgartner, 2000). However we show, that even in an ideal case, when the social costs are totally estimated and taken into account, there is a danger of a potential conflict between the interests of society and those of private business. The crucial circumstance for this conflict is the conventional implementation of the polluter pays principle (PPP), when an environmental tax exists in the form of a payment proportional to the amount of emissions but does not depend on the lifetime of the pollutant. We explore the situation where a polluting substance is accumulated to a stock in the environment, which can be considered as a "capital bad", supplying welfare to decreasing environmental disservices (Baumgartner et al., 2002).

In Section 2 we describe the mathematical model and express in its terms the most important quantitative factors for decision-making: the firm's profit and the social benefit of the investment initiative. In Section 3 we analyze the model and conclude about potential conflicts between the interests of society and of private business. We also obtain an analytical expression of a time when the conflict arises, which we call "the time boundary of investment expediency". Results of a numerical simulation are presented in this section. We conclude that economic imperfections (Munasinghe, 1995) may influence the quality of growth in the context of sustainability (Panayotou, 1995). Section 4 is devoted to looking for an alternative procedure of PPP implementation, which can allow one to avoid this conflict. In other words, we try to find "a corrected" amount of environmental tax which covers the negative effect on social welfare. Some conclusions and policy implications are drawn in Section 5.

2. The investment decision: firm's profit and social benefit

Following the paper by Baumgartner et al. (2002) we introduce the per unit social cost of pollution in each period of time and denote it by $d>0$. It includes "all direct and indirect costs of society incurred due to the danger from pollution" in one time period. (Baumgartner et al., 2002, p.7). We do not discuss here how we can calculate this cost. Anyway, it might be far from the environmental tax and the polluter's environmental costs. In practice, usually $g \ll d$, because many negative impacts are not taken into account.

We consider a project of investment in a new enterprise (or to modernization of an existing enterprise). The outcomes of this project will be produced goods and, at the same time, negative effects on the environment. Emissions can accumulate to a stock pollution. Below, by "firm" we mean the business actor which makes the investment decision.

Now we can introduce the model.

The Model

M1. New investment results in the production of a consumption good at a constant level q which is sold by price p in every year i, $i=1,\dots,n$. We call n the lifetime of the project, $n>1$.
M2. The production cost is $c>0$ per unit of consumption good and it does not depend on the time period.
M3. The present value of the fixed cost of investment is $f>0$ and there is no deterioration of the production capital.
M4. An emission from production is $e>0$ per unit of consumption good.
M5. The negative impact of pollution on social welfare is proportional to the quantity of the accumulated stock. It is estimated as $d>0$ per unit of pollution stock in each year.
M6. The initial pollution stock is equal to zero.
M7. The discount rate is $r>0$ in each year.
M8. The pollutant accumulates to a stock in the natural environment. A constant fraction of the accumulated pollution stock naturally degrades; the natural degradation rate is $\delta \in (0,1)$.
M9. The total environmental cost of the producer, including the environmental tax, is $g>0$ per unit of emission.

The net present value of the firm's profit we denote by $\pi(n)$, where n is the firm's time horizon. It is easy to show that:

$$\pi(n) = \sum_{i=1}^{n} \frac{q(p-c-ge)}{(1+r)^i} - f \qquad (1)$$

The inequality $\pi(n)>0$ is a necessary condition for the positive investment decision.

Now we try to estimate the benefit for society from this project. Denote this benefit by $B(n)$. Simple calculation shows that:

$$B(n) = q(p-c) \cdot a(n,r) - dqe \sum_{t=1}^{n} \frac{1-(1-\delta)^t}{\delta(1+r)^t} - f, \tag{2}$$

where $a(n,r) = \sum_{t=1}^{n} \frac{1}{(1+r)^t}$.

We can also consider the case where there is no natural degradation of the polluting substance in the environment, i.e., $\delta=0$ In this case the amount of the pollutant stock in the environment at the end of time period t and the social cost are equal to (see also (Baumgartner et al., 2002))

$$S_t = qet \quad \text{and} \quad D_t = dS_t = dqet$$

This implies that the social benefit for $\delta=0$ may be represented by the formula:

$$\begin{aligned} B(n) &= q(p-c) \sum_{t=1}^{n} \frac{1}{(1+r)^t} - dqe \sum_{t=1}^{n} \frac{t}{(1+r)^t} - f \\ &= q(p-c) \frac{1}{r} \left[1 - \frac{1}{(1+r)^n} \right] - dqe \sum_{t=1}^{n} \frac{t}{(1+r)^t} - f \end{aligned} \tag{3}$$

3. Conflict of interests

Obviously, $\pi(n)$ is an increasing function with respect to n. One can see that the longer is the time horizon, the more likely is the considered project to be launched. On other hand, the function representing the social benefit $B(n)$ is not monotonic one in general (See Lemma in Appendix). It monotonically increases for all n if $(p-c)\delta \geq de$. But if $(p-c)\delta < de$ it increases while $n<\beta$,

$$\beta = \frac{\ln\left(1 + \frac{\delta(p-c)}{de}\right)}{\ln(1-\delta)} - 1. \tag{4}$$

If $n>\beta$ and $(p-c)\delta < de$ the function $\pi(n)$ is decreasing.

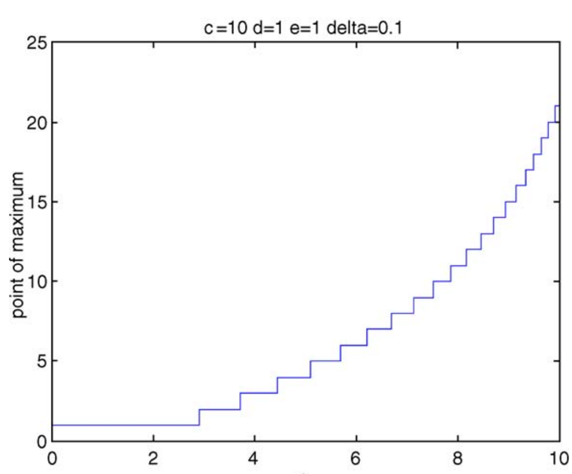

Fig. 1 – Dynamics of a "point of potential conflict" dependent on market price *p* of the produced commodity. Production cost *c*, emissions *e*, assimilation coefficient *δ* and negative impact of pollution on social welfare *d*>0 per unit of pollution stock are fixed.

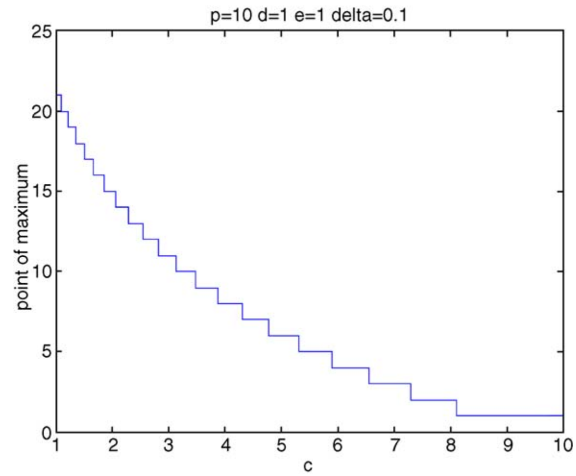

Fig. 2 – Dynamics of a "point of potential conflict" dependent on production cost *c*. Market price *p* of produced commodity, emissions *e*, negative impact of pollution on social welfare *d*>0 per unit of pollution stock and assimilation coefficient *δ* are fixed.

So if $n>\beta$ the society as a whole is not interested in a continuation of this project. If the project is implemented by private business and the company has to pays the total social cost, it is also not very interested in this investment. We call β, defined by (2), *the time boundary of investment expediency*. It might be also considered as a time indicator of "uneconomic growth" on the micro-level (Daly and Farley, 2003).

However, as we indicated above, the polluting company in Russia must pay an environmental tax proportional to the amount of emissions. Therefore it does not pay the total social cost and its profit is determined by formula (1). So the company is not sensitive to the boundary of investment expediency, which is important for society. In other words, the existing procedure of the polluter pays principle (PPP) implementation (i.e., payment proportional to the amount of emissions) generates a potential conflict between private business and society as a whole. While $n>\beta$ the social benefit from the project is decreasing and the interests of society require the project not to proceed. At the same time the private company is interested in its continuation.

Our model allows us to make a modeling simulation in order to determine the time boundary of investment expediency (the "point of potential conflict") for specific projects depending on the main quantitative parameters (e, d, f, r, q and $\delta \in (0,1)$).

We show some results of such modeling in Figs. 1–3.

Figs. 1 and 2 show the case when the polluting substance accumulates to a stock in the natural environment and the natural degradation rate of this pollutant is $\delta \in (0,1)$. One can see that even when the project is profitable from the commercial point of view ($c<0.5\ p$) it may be not desirable for society if its lifetime is more that 5–6 years. In this situation there is a real danger of conflict of interests.

In Fig. 3 one can see the case when there is no natural degradation of the pollutant in the environment. A conflict of

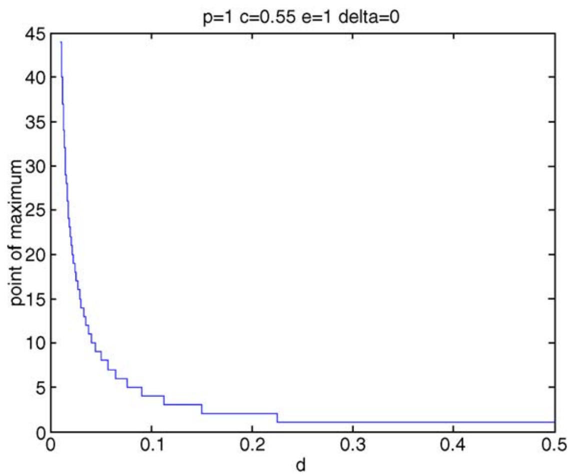

Fig. 3 – Dynamics of a "point of potential conflict" dependent on negative impact of pollution on social welfare *d* per unit of pollution stock. There is no natural degradation of the polluting substance in the environment, i.e., $\delta=0$. Market price *p* of produced commodity, production cost *c*, emissions *e*, assimilation coefficient δ and negative impact of pollution on social welfare $d>0$ per unit of pollution stock are fixed.

interests may arise within the time period 4–10 years even if the negative impact of pollution on social welfare d per unit of pollution stock is less than $0.1p$, i.e., it is comparatively small.

In our simulation modeling we have assumed that the total environmental cost of the producer, including the environmental tax, is (per unit of emission) equal to the negative impact of the pollution on social welfare (per unit of pollution stock), i.e., $g=d$. One can see that even in this optimistic case there is an unavoidable potential for conflict if $(p-c)\delta<de$ and $n<\beta$, where β is defined by formula (4).

We arrive at the conclusion that the conventional implementation of PPP in many cases leads to a divergence between private decision and socially optimal ones (Munasinghe, 1999). Eliminating such a policy distortion would help to reduce environmental harm. It is especially important for transitional countries where economic growth is considered as a first priority objective for governmental policy (Munasinghe and Cruz, 1995; Reed, 1996; Warford et al., 1997; World Bank, 1997; Glazyrina, 1998).

4. Alternative approach to PPP implementation

The analysis presented in the previous sections demonstrates that a "simple decision" in PPP implementation (when the environmental tax is determined proportional to the amount of emissions and does not depend on the lifetime of a project) is not adequate to the real negative impact if the pollutant accumulates to a stock in the environment. Now we shall try to find "a corrected" amount for the environmental tax which covers the negative effect on social welfare. Let us denote by h the amount of the environmental tax for the investment project described by the model in Section 2. We obtained that the present (discounted) value of the total negative impact on social welfare in the monetary form is equal to:

$$D(n) = dqe\sum_{t=1}^{n}\frac{1-(1-\delta)^t}{\delta(1+r)^t}$$

(see formula (2)). On the other hand, h must satisfy the equation:

$$D(n) = h\sum_{t=1}^{n}\frac{1}{(1+r)^t}$$

It is obvious that h depends on the lifetime of the project n and this is a very important factor. So we suppose that $h=h(n)$ and

$$h(n) = de\frac{\sum_{t=1}^{n}\frac{1-(1-\delta)^t}{\delta(1+r)^t}}{\sum_{t=1}^{n}\frac{1}{(1+r)^t}} \tag{5}$$

One can see that $h(n)$ is a monotonically increasing function with respect to n (see Appendix). So the next conclusion is that the longer is the project lifetime, the higher is the need for the environmental tax.

More precisely, let P_1 and P_2 be two investment projects with the same parameters p, c, d, e, δ. Denote by n_i the lifetime of the project P_i and by h_i the annual environmental tax which is imposed on the project P_i (or on the company, which carries out this project into practice), $i=1,2$. If $n_1>n_2$ then $h_1>h_2$ despite both enterprises emitting the same pollutant and producing the equal annual emissions.

However, the growth of $h(n)$ is limited. Using the formula of a geometric progression we obtain (see Appendix):

$$h(n) = \frac{de}{\delta}\left(\frac{\delta(1+r)}{r+\delta}-\frac{(1-\delta)r}{r+\delta}\frac{1-(1-\delta)^n}{(1+r)^n-1}\right). \tag{6}$$

and

$$T(d,r,\delta) = \lim_{n\to\infty} h(n) = \frac{de}{\delta}\left(\frac{\delta(1+r)}{r+\delta}-\frac{(1-\delta)r}{r+\delta}\lim_{n\to\infty}\frac{1-(1-\delta)^n}{(1+r)^n-1}\right)$$
$$= de\frac{1+r}{r+\delta} \tag{7}$$

Let us call the indicator $T(d,r,\delta)$ defined by (7) the *upper bound of the environmental tax* $h(n)$ *with given* d, r, δ. This indicator gives information about the maximal environmental costs per unit of the commodity produced for a future investment project. In addition, it might give an opportunity to take into account the total negative impact and adequate responsibility of the producer at the early stage of negotiations between the government (as a representative of society, the owner of natural resources and/or ecosystem services) and the business company.

It is essential that the "correct size" of the environmental tax $h(n)$ should depend on a discount rate and on the rate of natural degradation of the polluting substance δ. To be accurate we should write $h=h(n,r,\delta)$. From Lemma 3 in the Appendix we can see, that $h(n,r,\delta)$ is a decreasing function with respect to r and δ. This means, that:

(1) the larger is the rate of discount, the lower is the environmental tax;

(2) the lower is the rate of natural degradation of the pollutant, the higher is the environmental tax.

The size of the discount rate r is one of the most problematic issue in environmental discussions. Many scholars think that a zero discount rate is the most appropriate for social interests, given the long time horizon involved (Chichilnisky, 1996; Broome, 1992). Our model shows that in this case the upper bound of the environmental tax is

$$T(d, r = 0, \delta) = \frac{de}{\delta}.$$

The environmental tax, determined by formulas (5) or (6) may give an opportunity for reducing environmental damage associated with economic growth.

5. Conclusion

Our model analysis shows that the time horizon of decision makers is very important in the context of the quality of economic growth.

Indeed, consider that a business company which assesses a project, has a k-year time horizon and has profit maximization as a main criterion. The project might be approved because the company's profit monotonically increases, whether $k>\beta$ or $k<\beta$, (see formula (4)). If the company follows PPP in its conventional implementation (i.e., when the environmental tax is determined as proportional to the amount of emissions) and, in addition, creates some extra employment possibilities, then it can argue that it is being socially responsible. Real environmental danger, especially, potential irreversible changes cannot be seen from private company's point of view. Next, the implementation of projects connected with natural resource use depends on central (or regional) authority decisions in Russia. Politicians and governmental officials usually have an even a shorter time horizon l, $l<k<\beta$, comparable with period between elections. So if this project will make an input to economic growth and employment, the implementation might be approved because the central or the regional authorities do not see its long-term dangerous negative environmental consequences.

Society as a whole, in its turn, taking into account the long-term impact and the interests of future generations, has a time horizon $N>\beta$. According to its interests sometimes it is reasonable to disallow a project. However, society as a whole is not an actor in the same sense as business and the central authorities. If society does not have power and developed institutions which represent properly societal interests, its interests will not be taken into account in decision-making. This kind of governance can be seen in transitional countries, including Russia. So the crucial issue is the enhancement of institutional structures in transitional countries. Building the institutional capacity, participation of wide panel of experts and representatives from political opposition in decision-making processes seem to be a simple theoretical solution, but such kind of initiative in reality usually meet the strong obstacles generated by institutionalized corruption.

We have found that there is a potential conflict of interests between private business and society as a whole if the polluter pays principle is implemented conventionally. It is a *qualitative consequence* from our model analysis. On the other hand, we have shown that the number β represented by (4) is the time when the a potential conflict of interests between private business and society arises, and it is our *quantitative result*.

Inducing a new, "corrected" environmental tax system with payments according to (5) and (6) seems to provide a solution to the potential conflict. But we should remember two important circumstances.

First, it is necessary that there is a political will to change the existing conventional system of PPP implementation. The introduction of a new system implies the total environmental costs of producers will increase. Governmental bodies as mentioned above, not always, but very often have shorter time horizons, than society needs. They look at environmental restrictions as obstacles to fast economic development. Many of them are sure that (1) the economic growth is the first priority, (2) environmental issues might be taken into account when the goal of sufficient growth has been achieved, and it is their *ideological choice* (Söderbaum, 2000, 2004). Due to their short time horizon of decision-making, governmental officials usually concentrate on a short-term economic benefits rather than on long run environmental values. A high level of institutionalized corruption which is common in many transitional countries also leads to a divergence between private and socially oriented governmental decisions (Voinov et al., 1999a,b; Yavlinsky, 1998). Anyway, ultimately the decision taken reflects the ideological orientations of these actors.

Second, an adequate evaluation of social costs is still a very difficult problem. Environmental legislation in transitional countries usually underestimates these costs, so the way to "corrected" environmental taxes seems to be far off in practice. While the danger of potential conflict exists, it means that society needs alternative, non-monetary arguments to advocate its long-term interests (Söderbaum, 2000, 2004). It should be noted that this conflict may arise in a country with conventional implementation of PPP whether it is transitional or developed. But in transitional countries, under conditions of limited democracy and weakness of public institutions we can expect the most negative consequences.

We come to a problem, broadly discussed now in Russia. Is the authoritarian model of development more appropriate than the democratic one for transitional countries in order to provide human welfare? Supporters of the authoritarian point of view argue that it is more efficient under conditions of limited resources, as governmental bodies need not spend effort, money and time on public discussion, looking at political compromises and so on. We think, however, that it is an illusion and our model analysis is an additional argument for democracy in the broadest sense.

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Appendix A

Lemma 1. *A) $B(n)$ is an increasing function if one of two following conditions holds: (i) $(p-c)\delta \geq de$; or (ii) $(p-c)\delta < de$ and $n < \dfrac{\ln\left(1-\dfrac{\delta(p-c)}{de}\right)}{\ln(1-\delta)} - 1$ B) $B(n)$ is decreasing function, if $(p-c)\delta < de$ and $n > \dfrac{\ln\left(1-\dfrac{\delta(p-c)}{de}\right)}{\ln(1-\delta)} - 1$*

Proof. Indeed, $B(n)$ is increasing function if

$$B(n+1) > B(n)$$

By simple calculation we can see, that

$$B(n+1) - B(n) = q(p-c)\frac{1}{(1+r)^{n+1}} - dqe\frac{1-(1-\delta)^{n+1}}{\delta(1+r)^{n+1}}$$
$$= \frac{1}{(1+r)^{n+1}}\left[q(p-c) - \frac{dqe}{\delta}(1-(1-\delta)^{n+1})\right].$$

So $B(n+1) > B(n)$ is equivalent to

$$(1-\delta)^{n+1} > 1 - \frac{\delta(p-c)}{de},$$

and, therefore, it holds, if

$$1 - \frac{\delta(p-c)}{de} \leq 0;$$

$$1 - \frac{\delta(p-c)}{de} > 0 \quad \text{and} \quad n+1 < \log_{1-\delta}\left(1-\frac{\delta(p-c)}{de}\right) = \frac{\ln\left(1-\dfrac{\delta(p-c)}{de}\right)}{\ln(1-\delta)}.$$

Conditions (A) and (B) immediately follow from two these inequalities. □

Lemma 2. *The function $h(n)$ defined by formula (5) is monotonously increasing one for all n.*

Proof. Indeed, we can present the function $h(n)$ as

$$h(n) = \frac{de}{\delta}\left(1 - \frac{\sum_{t=1}^{n} \frac{(1-\delta)^t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{1}{(1+r)^t}}\right) \tag{A1}$$

Let us consider the expression

$$\frac{\delta}{d}(h(n+1) - h(n))$$
$$= \frac{\sum_{t=1}^{n} \frac{(1-\delta)^t}{(1+r)^t} \cdot \sum_{t=1}^{n+1} \frac{1}{(1+r)^t} - \sum_{t=1}^{n+1} \frac{(1-\delta)^t}{(1+r)^t} \cdot \sum_{t=1}^{n} \frac{1}{(1+r)^t}}{\sum_{t=1}^{n+1} \frac{1}{(1+r)^t} \cdot \sum_{t=1}^{n} \frac{1}{(1+r)^t}}.$$

The numerator of the right side of this equation is equal to

$$\sum_{t=1}^{n} \frac{(1-\delta)^t - (1-\delta)^{n+1}}{(1+r)^{t+n+1}}.$$

which is positive for all if $\delta \neq 0$. It means that $h(n+1) > h(n)$ for each n. □

Lemma 3. *The function $h(n,r,\delta)$ defined by formula (5) is a decreasing function with respect to r and δ.*

Proof. It is obvious from definition (5) that $h(n,r,\delta)$ is a decreasing function with respect to δ.

To prove the same for the variable r we calculate the partial derivative of $h(n,r,\delta)$ with respect to r:

$$h_r'(n,r,\delta)$$
$$= de\frac{\sum_{t=1}^{n} \frac{t(1-\delta)^t}{(1+r)^{t+1}} \cdot \sum_{t=1}^{n} \frac{1}{(1+r)^t} - \sum_{t=1}^{n} \frac{(1-\delta)^t}{(1+r)^t} \cdot \sum_{t=1}^{n} \frac{t}{(1+r)^{t+1}}}{\delta\left(\sum_{t=1}^{n} \frac{1}{(1+r)^t}\right)^2}.$$

We can re-write the numerator of the right side of this equation in the form

$$\sum_{t=1}^{n}\sum_{i=1}^{n} \frac{t(1-\delta)^t}{(1+r)^{t+i+1}} - \sum_{t=1}^{n}\sum_{i=1}^{n} \frac{i(1-\delta)^t}{(1+r)^{t+i+1}}$$
$$= \sum_{i=1}^{n} \frac{t(1-\delta)^t}{(1+r)^{2t+1}} + \sum_{t=2}^{n}\sum_{i=1}^{t-1} \frac{t(1-\delta)^t}{(1+r)^{t+i+1}}$$
$$+ \sum_{t=1}^{n-1}\sum_{i=t+1}^{n} \frac{t(1-\delta)^t}{(1+r)^{t+i+1}} - \sum_{t=1}^{n} \frac{t(1-\delta)^t}{(1+r)^{2t+1}}$$
$$- \sum_{t=2}^{n}\sum_{i=1}^{t-1} \frac{i(1-\delta)^t}{(1+r)^{t+i+1}} - \sum_{t=1}^{n-1}\sum_{i=t+1}^{n} \frac{i(1-\delta)^t}{(1+r)^{t+i+1}}$$
$$= \sum_{t=2}^{n}\sum_{i=1}^{t-1} \frac{t(1-\delta)^t}{(1+r)^{t+i+1}} + \sum_{t=1}^{n-1}\sum_{i=t+1}^{n} \frac{t(1-\delta)^t}{(1+r)^{t+i+1}}$$
$$- \sum_{t=2}^{n}\sum_{i=1}^{t-1} \frac{i(1-\delta)^t}{(1+r)^{t+i+1}} - \sum_{t=1}^{n-1}\sum_{i=t+1}^{n} \frac{i(1-\delta)^t}{(1+r)^{t+i+1}}.$$

Change the order of summation in the second and fourth sums in the last part of this equality and obtain

$$\sum_{t=2}^{n}\sum_{i=1}^{t-1} \frac{t(1-\delta)^t + i(1-\delta)^i - i(1-\delta)^t - t(1-\delta)^i}{(1+r)^{t+i+1}}$$
$$= \sum_{t=2}^{n}\sum_{i=1}^{t-1} \frac{(t-1)((1-\delta)^t - (1-\delta)^i)}{(1+r)^{t+i+1}}. \tag{A2}$$

From $0 < 1-\delta < 1$ it follows that expression in (A2) is negative, whence $h(n,r,\delta)$ is decreasing function with respect to r. □

Lemma 4. *The function $h(n)$, defined by (5) also satisfies the formula (6).*

Proof. Using the formula of a geometric progression we obtain

$$\sum_{t=1}^{n}\frac{1}{(1+r)^t}=\frac{1}{1+r}\frac{\frac{1}{(1+r)^n}-1}{\frac{1}{1+r}-1}=\frac{\frac{1-(1+r)^n}{(1+r)^n}}{-r}=\frac{(1+r)^n-1}{r(1+r)^n},$$

$$\sum_{t=1}^{n}\frac{(1-\delta)^t}{(1+r)^t}=\frac{1-\delta}{1+r}\frac{\frac{(1-\delta)^n}{(1+r)^n}-1}{\frac{1-\delta}{1+r}-1}=\frac{1-\delta}{r+\delta}\frac{(1+r)^n-(1-\delta)^n}{(1+r)^n}.$$

Therefore,

$$h(n)=\frac{d}{\delta}\frac{\sum_{t=1}^{n}\frac{1}{(1+r)^t}-\sum_{t=1}^{n}\frac{(1-\delta)^t}{(1+r)^t}}{\sum_{t=1}^{n}\frac{1}{(1+r)^t}}=\frac{d}{\delta}\left(1-\frac{\sum_{t=1}^{n}\frac{(1-\delta)^t}{(1+r)^t}}{\sum_{t=1}^{n}\frac{1}{(1+r)^t}}\right)$$
$$=\frac{d}{\delta}\left(1-\frac{r(1-\delta)}{r+\delta}\frac{(1+r)^n-(1-\delta)^n}{(1+r)^n-1}\right)$$
$$=\frac{d}{\delta}\left(1-\frac{r(1-\delta)}{r+\delta}+\frac{1-(1-\delta)^n}{(1+r)^n-1}\right)$$
$$=\frac{d}{\delta}\left(\frac{\delta(1+r)}{r+\delta}-\frac{(1-\delta)r}{r+\delta}\frac{1-(1-\delta)^n}{(1+r)^n-1}\right).$$

□

REFERENCES

Baumgartner, S., 2000. Ambivalent Joint Production and the Natural Environment. An Economic and Thermodynamic Analysis. Phisica-Verlag, Heidelberg–New York.

Baumgartner, S., Faber, M., Proops, J.L.R., 2002. How environmental concerns influences the investment decision: an application of capital theory. Ecological Economics 40 (1), 1–12.

Broome, J., 1992. Counting the Cost of Global Warming. White Horse Press, London.

Chichilnisky, G., 1996. An axiomatic approach to sustainable development. Social Choice and Welfare 13, 231–257.

Daly, H.E., Farley, J., 2003. Ecological Economics. Principles and Applications. Island Press.

Faber, M., Proops, J.L.R., Baumgartner, S., 1998. All production is joint production — a thermodynamic analysis. In: Faucheux, S., Gowdy, J., Nikolai, I. (Eds.), Sustainability and Firms. Technological Change and Changing Regulatory Environment. Edard Elgar, Cheltenham, pp. 131–158.

Glazyrina, I.P., 1998. Looking for a path to sustainability in eastern Siberia. Ecosystem Health 4 (4), 248–255.

Munasinghe, M., 1995. Making economic growth more sustainable. Ecological Economics 15, 121–127.

Munasinghe, M., 1999. Is environmental degradation an inevitable consequence of economic growth: tunneling through the environmental Kuznets curve. Ecological Economics 29, 89–110.

Munasinghe, M., Cruz, W., 1995. Economywide policies and environment. Lessons from experience. World Bank Environment Paper, vol. 10. World Bank, Washington, DC.

OECD, 1997. Environmental financing in Russian Federation. OECD Proceedings, Paris.

Panayotou, T., 1995. Environmental degradation at different stages of economic development. In: Ahmed, I., Doeleman, J.A. (Eds.), Beyond Rio: the Environmental Crisis and Sustainable Livelihood in the Third World. International Labor Office, Geneva, pp. 32–57.

Reed, D., 1996. Structural Adjustment, the Environmental and Sustainable Development. Earthscan Publishers, London.

Söderbaum, Peter, 2000. Ecological Economics. A Political Economics Approach to Environment and Development. Earthscan, London.

Söderbaum, P., 2004. Decision processes and decision-making in relation to sustainable development and democracy. The Journal of Interdisciplinary Economics 14, 41–60.

Voinov, A., Glazyrina, I., Pavoni, B., Zharova, N., 1999a. Environmental management, crime and information. Russian case study. In: Wehrmeyer, W., Mulugetta, Y. (Eds.), Growing Pains. Environmental Management in Developing Countries. Greenleaf Publishing, pp. 117–131.

Voinov, A., Glazyrina, I., Pavoni, B., Zharova, N., 1999b. Environmental management in uncertain economies. In: Wehrmeyer, W., Mulugetta, Y. (Eds.), Growing Pains. Environmental Management in Developing Countries. Greenleaf Publishing, pp. 148–159.

Warford, J., Munasinghe, M., Cruz, W., 1997. The Greening of Economic Policy Reforms, Vol 1 (Principles). World Bank, Washington, DC.

World Bank, 1997. Expanding the Measures of Wealth. World Bank, Washington, DC.

Yavlinsky, G., 1998. Russia's phony capitalism. Foreign Affairs 77 (3), 67–79.