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Habit formation and the pareto-efficient provision of public goods

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Abstract
This paper examines the implications of habit formation in private and public goods consumption for the Pareto-efficient provision of public goods, based on a two-period model with nonlinear taxation. Under weak leisure separability, and if the public good is a flow-variable such that the government directly decides on the level of the public good in each period, habit formation leads to a modification of the policy rule for public good provision if, and only if, the degrees of habituation differ for private and public good consumption. By contrast, if the public good supply is time-invariant, the presence of habit formation generally alters the policy rule for public good provision.

1 Introduction

This paper examines the implications of adaptation/habituation in private and public goods consumption for the efficient provision of public goods under optimal income taxation. The purposes are to characterize how such habituation modifies the policy rule for public good provision, and identify conditions under which the policy rule for public good provision derived in model-economies without any habituation remains valid also in the presence of habit formation.

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People adapt to most circumstances in life, and the degree to which people adapt can be substantial. Although the importance of adaptation has been widely recognized in the context of consumption (e.g., Clark et al. 2008) and labor market behavior (e.g., Woittiez and Kapteyn 1998; Clark 1999; Fuhrer 2000), it has so far played a minor role in normative economic theory of taxation and public expenditure. In fact, Becker and Murphy (1988) argue that adaptation has no important implications for normative economic theory and, in particular, the insights gained from optimal taxation theory if people are fully aware of their adaptation-behavior when making their consumption choices.

Yet, recent research shows that adaptation in private good consumption may affect optimal tax policy in second-best economies with skill heterogeneity (see Guo and Krause 2011; Koehne and Kuhn 2014). It also shows that adaptation to environmental damage directly affects the policy rule for Pigouvian taxation (Aronsson and Schöb 2018). The present paper supplements this research by examining public good provision when consumers adapt both in terms of their private and public goods consumption through internal habit formation.

While there is growing evidence on the importance of adaptation to private consumption (e.g., Lucas 2007; Luhmann et al. 2012; Weimann et al. 2015), the evidence of adaptation to public goods has received less attention so far. Chattopadhyay and Graham (2008) interpret differences in the victimization rate that cannot be explained by other factors as a proxy for differences in crime norms across respondents and show that although being a crime victim has a negative effect on happiness, this effect becomes smaller when the crime norm is higher (see also Graham 2011). This suggests that people may adapt to crime norms and thus also to the public good 'inner security'. Levinson (2012, 2013) finds that fluctuations of the current day's local air quality affect happiness while changes in the local annual average do not. Apparently, people adapt to changing levels of the public good 'air quality' while remaining sensitive to short-term fluctuations. Taking account of the long-run impact of public good provision thus leads to different conclusions than looking at the short-run implications only. This is the approach we follow in our theoretical analysis below.

Our contribution is to characterize the effects that adaptation has on the optimality condition for a public good in an intertemporal context with heterogeneous agents, where individual productivity is private information. We thereby focus on a two-period model, which is the simplest framework to capture the inherent dynamics of adaptation with heterogeneous and rational consumers, in which the government raises tax revenue to redistribute income and provide a public good, and where the consumers adapt both with respect to their private and public goods consumption. Following Pollak (1970), adaptation is modeled as internal habit formation, which adds a time-dimension to the marginal willingness to pay for public goods.

Depending on how frequently the government can adjust the public good provision, we consider two polar cases. The first case assumes that the government decides on the level of the public good in each period. This exemplifies a flow-variable public good such as abatement of environmental flow pollution. In the special case where the preferences are weakly leisure separable, habit formation does not affect the policy rule for public good provision if the degrees of habituation in private and public goods consumption are the same. It only modifies this policy rule if the degrees of habituation differ for private and public good consumption, in which case the effects are indistinguishable from the effects of a shift in the marginal rate of transformation. However, if the preferences are not weakly leisure separable, it always affects the policy rule for public good provision via the self-selection constraint.

The second case assumes that the government provides a fixed level of the public good to be consumed in both periods. This is interpretable in terms of a state-variable public good, where instantaneous contributions and depreciation have negligible effects on the stock, which can be exemplified by certain types of infrastructure and environmental amenities. For this type of public good provision, we show that habituation generally affects the policy rule for public good provision. Whereas habit formation in private good consumption works in the direction of over-provision of the public good, relative to the policy rule applicable in an economy without habituation, habit formation in public good consumption works in the opposite direction. Indeed, under rather conventional assumptions about the properties of the utility function, the optimal policy rule implies under-provision of the public good relative to the policy rule that would follow in the absence of habituation, if the degrees of habituation in private and public goods consumption coincide.

In Sects. 2 and 3 below, we use the two variants of the model to analyze how habit formation in private and public goods consumption affects the efficient provision of public goods. The model is based on the self-selection approach to optimal taxation originally developed by Stern (1982) and Stiglitz (1982), where a nonlinear income tax is used for revenue collection and redistribution. In this respect, we follow Boadway and Keen (1993), who were the first to analyze public good provision in such a framework, and extend their analysis to an economy with habit formation. Section 4 concludes.

2 A model with a time-variable supply of public goods

Consider a two-period economy where the consumers derive utility from a private good, leisure, and a public good. There are two types of consumers that differ in their innate ability, which is reflected in the before-tax wage rate, meaning that the high-ability type (type 2) earns a higher before-tax wage rate than the low-ability type (type 1). n^i denotes the number of individuals of ability-type i. True ability (and, consequently, the before-tax wage rate) is private information.

All individuals are assumed to share a common utility function, meaning that the utility facing any individual of ability-type i ($i = 1, 2$) is given by

$$U^i = U\left(c^i, \ell^i, x^i - \alpha c^i, g, G - \rho g\right). \tag{1}$$

In Eq. (1), c and x denote private good consumption in the first and second period, respectively, ℓ denotes leisure, defined as a time-endowment normalized to one minus the hours of work, i.e., $\ell = 1\text{-}l$, and g and G denote the public good provision in the first and second period. The individual works in the first period and is retired in the second, implying that the leisure-argument in the utility function refers to the first period. The parameters $\alpha \in [0,1]$ and $\rho \in [0,1]$ reflect the intensities of habit formation. As such, $\alpha = 0$ indicates no habit formation at all whereas $\alpha = 1$ implies full habituation in private good consumption. The interpretation of ρ is analogous in terms of public good consumption. We assume that there is no habit formation with respect to leisure, as otherwise the utility derived from leisure when retired would depend on the leisure choice in the first period.[1] The utility function is increasing in each separate argument and strictly quasi-concave. Discounting—if it occurs—is implicit in this formulation.

Whereas ability is private information, we assume that income from labor and capital is observable at the individual level, and that the government has access to general labor income and capital income taxes. As such, the government can implement any desired combination of work hours and savings for each ability-type, and thus effectively control l^i, c^i, and x^i for $i=1, 2$, subject to relevant constraints. We can, therefore, characterize the social decision-problem such that the government (or social planner) chooses work hours and private good consumption for each ability-type and the level of the public good in each period to reach a Pareto efficient resource allocation subject to an overall resource constraint and self-selection constraint. We apply the conventional assumption that the government wants to redistribute from the high-ability to the low-ability type, meaning that the self-selection constraint that may bind is the one preventing high-ability individuals from mimicking the low-ability type. Based on these assumptions, the social decision-problem can be written as follows:

$$\max_{l^i,c^i,x^i(i=1,2),g,G} \quad U\left(c^1, \ell^1, x^1 - \alpha c^1, g, G - \rho g\right) \tag{2}$$

such that

$$\mu : U\left(c^2, \ell^2, x^2 - \alpha c^2, g, G - \rho g\right) \geq \overline{U}^2 \tag{3a}$$

$$\lambda : U\left(c^2, \ell^2, x^2 - \alpha c^2, g, G - \rho g\right) \geq U\left(c^1, 1 - \frac{w^1}{w^2} l^1, x^1 - \alpha c^1, g, G - \rho g\right) \equiv \hat{U}^2 \tag{3b}$$

$$\gamma : \sum_i n^i w^i l^i - \sum_i n^i c^i - \sum_i \frac{n^i x^i}{1+r} - g - \frac{G}{1+r} = 0 \tag{3c}$$

This resource allocation problem means choosing work hours, private consumption, and the public good to maximize utility of the low-ability type subject to a minimum utility restriction for the high-ability type in (3a). The weak inequality (3b) is the

[1] As long as leisure time is (at least partly) used to gain experiences, this assumption accords well with empirical evidence discussed in Dunn et al. (2011), according to which people seem to adapt more to material than experiential purchases.

self-selection constraint ensuring that each high-ability individual weakly prefers the allocation intended for his/her type (the left-hand side) over the allocation intended for the low-ability type. A potential mimicker receives the utility on the right-hand side of the weak inequality (3b). In our model, such a mimicker will consume as much as the low-ability type in both periods. Yet, since the mimicker is more productive, he/she can earn the same income as the low-ability type with less effort (since $w^1/w^2 < 1$). The resource constraint in Eq. (3c), finally, means that output is used for private and public goods consumption, where the marginal rate of transformation is set to one in both periods. μ, λ, and γ are Lagrange multipliers attached to each respective constraint.

We would like to examine how the policy rules for public good provision must be adjusted to reflect the possibility of habituation in private and public consumption, compared to the standard case where the degrees of habituation are zero. To this end, it is convenient to define *period-specific* marginal rates of substitution between the public good and the private good for each true ability-type ($i = 1$, 2) and the potential mimicker. By using the short notation $c_1^i = c^i$, $c_2^i = x^i - \alpha c^i$, $g_1 = g$, and $g_2 = G - \rho g$, we have

$$MRS^i_{g_1,c_1} = \frac{U^i_{g_1}}{U^i_{c_1}}, MRS^i_{g_2,c_2} = \frac{U^i_{g_2}}{U^i_{c_2}} \quad \text{for } i = 1, 2 \quad M\hat{R}S^2_{g_1,c_1} = \frac{\hat{U}^2_{g_1}}{\hat{U}^2_{c_1}}, \text{and } M\hat{R}S^2_{g_2,c_2} = \frac{\hat{U}^2_{g_2}}{\hat{U}^2_{c_2}},$$

where the sub-scripts attached to the utility function denote partial derivatives. The policy rules for public good provision are then summarized in Proposition 1.

Proposition 1 *With a variable public good supply, the Pareto efficient provision of the public good satisfies*

$$1 = \frac{1 + \alpha/(1+r)}{1 + \rho/(1+r)} \sum_i n^i MRS^i_{g_1,c_1} + \frac{\lambda_1^*}{1 + \rho/(1+r)} \left(MRS^1_{g_1,c_1} - M\hat{R}S^2_{g_1,c_1} \right) \quad (4a)$$

$$1 = \sum_i n^i MRS^i_{g_2,c_2} + \lambda_2^* \left(MRS^1_{g_2,c_2} - M\hat{R}S^2_{g_2,c_2} \right) \quad (4b)$$

where $\lambda_1^* = \lambda \hat{U}^2_{c_1}/\gamma$ *and* $\lambda_2^* = \lambda \hat{U}^2_{c_2}(1 + r)/\gamma$.

Proof: see the Appendix.

Equation (4b) takes the same form as in the absence of any habituation (e.g., Boadway and Keen 1993), because there is no additional period beyond period 2 in which an increase in G causes disutility. The policy rule for public good provision in the first period, given by Eq. (4a), however, now depends directly on the degrees of habit formation in private and public good consumption. To interpret Eq. (4a), consider first the special case where the utility functions are weakly leisure separable, which means that Eq. (1) can be rewritten as

$$U^i = U\left(c^i, \ell^i, x^i - \alpha c^i, g, G - \rho g\right) = \tilde{U}\left(h(c^i, x^i - \alpha c^i, g, G - \rho g), \ell^i\right). \quad (5)$$

Equation (4a) then reduces to read

$$1 = \frac{1 + \alpha/(1 + r)}{1 + \rho/(1 + r)} \sum_i n^i MRS^i_{g_1,c_1} \tag{6}$$

Note first that Eq. (6) coincides with the first-best policy rule that would follow if individual ability were public information, since utility function (5) implies $MRS^1_{g_1,c_1} = M\hat{R}S^2_{g_1,c_1}$ and $MRS^1_{g_2,c_2} = M\hat{R}S^2_{g_2,c_2}$. The intuition is based on the logic of the Atkinson and Stiglitz (1976) theorem: under weak leisure separability, income redistribution can be dealt with solely through the income tax, which means that the use of other policy instruments (in this case public good provision) is guided by concerns for efficiency.

Note also that Eq. (6) takes the same general form as in the absence of any habituation, except for the simple scale factor attached to the sum of the within-period marginal rates of substitution. The intuition behind this scale factor is that increased public (private) consumption in the first period gives rise to a utility loss in the second period, which depends on the degree of habituation, ρ (α). The factor $1 + r$ discounts each such future utility loss to present value. Thus, ρ and α affect the marginal willingness to pay for g in opposite directions, albeit symmetrically. An obvious implication is that the effects of habit formation on the policy rule for public good provision are indistinguishable from the effects of a corresponding shift in the marginal rate of transformation.[2] If the two degrees of habituation are the same, i.e., $\alpha = \rho \in [0, 1]$, then the efficiency condition for public good provision would take the same form as in the absence of any habit formation, meaning that we end up with the Samuelson condition for such an economy, $1 = \sum_i n^i MRS^i_{g_1,c_1}$.

The fact that the policy rule takes the same form as in the absence of any habit formation does not imply that the levels of the public good are the same as well (for a general discussion see Wilson 1991; Gaube 2005). Except in very special cases, the level of public good provision will typically be affected by habit formation. This is because $MRS^i_{g_1,c_1}$ (for $i = 1, 2$) depends on α and ρ according to Eq. (5). A special case where this dependence vanishes is where the utility function is quasi-linear in the sense of being additively separable in c_1, ℓ, and g_1, and linear in c_1. In this special case, Eq. (6) uniquely determines g_1, such that habituation does not affect the level of public good provision in the first period if $\alpha = \rho$. It also means under-provision (over-provision) in level terms in the first period if $\rho >\ (<)\, \alpha$ compared to the efficient public goods level without habituation. However, even if these restrictive conditions were satisfied, habit formation still affects the level of public good provision in the second period through the $MRS^i_{g_2,c_2}$-functions.

Going back to Proposition (1), which does not presuppose leisure separability, we can see from Eqs. (4a) and (4b) that an additional mechanism enters the policy rule:

[2] Equation (6) can alternatively be written as $\frac{1+\rho/(1+r)}{1+\alpha/(1+r)} = \sum_i n^i MRS^i_{g_1,c_1}$.
Thus, public good provision would satisfy Eq. (6) also in the absence of any habituation if the marginal rate of transformation is adjusted accordingly.

the government can relax the self-selection constraint by underproviding (overproviding) the public good relative to the policy rule in Eq. (6) if the marginal willingness to pay for the public good increases (decreases) in leisure time. Therefore, if leisure is not weakly separable from the other goods in the utility function, public good provision should supplement the income tax as an instrument for redistribution. This policy incentive takes the same general form as in the absence of any habit formation (e.g., Boadway and Keen 1993).

3 Time-invariant supply of public goods

We now turn to the other extreme case where the public good is time-invariant. We show in the Appendix that this change of assumption modifies the first-order conditions for public good provision, whereas all other aspects of the model remain as in Sect. 2. Let us then redefine g_1 and g_2 such that $g_1 = g$ and $g_2 = g(1-\rho)$, while the other notation is the same as above. The policy rule for public good provision is characterized in Proposition 2.

Proposition 2 *With a time-invariant public good, the Pareto efficient provision of the public good satisfies*

$$\begin{aligned}1 = \sum_i n^i MRS^i_{g_1,c_1}\left(1+\frac{\alpha}{1+r}\right) + \sum_i n^i \frac{MRS^i_{g_2,c_2}(1-\rho)}{1+r} \\ + \frac{\lambda}{\gamma}\left[\hat{U}^2_{c_1}\left(MRS^1_{g_1,c_1} - M\hat{R}S^2_{g_1,c_1}\right) + \hat{U}^2_{c_2}\left(MRS^1_{g_2,c_2} - M\hat{R}S^2_{g_2,c_2}\right)(1-\rho)\right].\end{aligned} \tag{7}$$

Proof: See the Appendix.

To elaborate on Proposition 2, we start once again with the special case where the utility functions are weakly leisure separable. Equation (7) then simplifies to read

$$1 = \sum_i n^i MRS^i_{g_1,c_1}\left(1+\frac{\alpha}{1+r}\right) + \sum_i n^i \frac{MRS^i_{g_2,c_2}(1-\rho)}{1+r}. \tag{8}$$

By analogy to Eq. (6), Eq. (8) is also interpretable as a first-best policy rule, which carries over to the second-best under weak leisure separability by the logic of the Atkinson and Stiglitz (1976) theorem. The right-hand side measures the sum of the individuals' marginal willingness to pay for the public good in the first and second period, respectively. Habituation in private good consumption works to scale up each individual's marginal willingness to pay for the public good in the first period through the factor $1 + \alpha/(1 + r) \geq 1$. Similarly, habituation in public good consumption scales down the marginal willingness to pay for the public good in the second period via the factor $1 - \rho \leq 1$.[3]

[3] With a time-invariant public good, it is no longer possible to reinterpret the effects of habituation in terms of a scale factor attached to the marginal rate of transformation, as we did with a time-variant public good in (6).

If the degrees of habituation in private and public goods consumption are equal such that $\alpha = \rho \equiv \sigma$, Eq. (8) can be rewritten as follows:

$$1 = \sum_i n^i \left(MRS^i_{g_1,c_1} + \frac{MRS^i_{g_2,c_2}}{1+r} \right) + \sigma \sum_i n^i \left(MRS^i_{g_1,c_1} - MRS^i_{g_2,c_2} \right) \frac{1}{1+r}, \quad (9)$$

where the first term on the right-hand side is the sum of all consumers' marginal willingness to pay for the public good, based on the period-specific marginal rates of substitution in both periods, while the second is proportional to the degree of habit formation. Therefore, habit formation matters for the policy rule even when the two degrees of habituation are the same, as long as the period-specific marginal rates of substitution change over time.

Equation (9) points at an interesting—albeit somewhat unlikely—special case: if (i) the degrees of habit formation in private and public goods consumption are the same, and (ii) the sum of the within-period marginal willingness to pay for the public good is constant over time, i.e., $\sum_i n^i MRS^i_{g_2,c_2} = \sum_i n^i MRS^i_{g_1,c_1}$, then Eq. (9) would take the same form as in the absence of any habit formation. A sufficient (not necessary) condition for (ii) to apply is that the marginal willingness to pay for the public good is constant over time for both types such that $MRS^i_{g_2,c_2} = MRS^i_{g_1,c_1}$ for $i = 1, 2$. In this special case, the Samuelson condition for an economy without habituation coincides with the Samuelson condition for an economy where the two degrees of habituation are equal, because σ vanishes from the policy rule. However, for the reasons discussed in Sect. 2, this does not mean that the levels of public good provision coincide as well.

Yet, since the effective measure of public good consumption in the second period is $g(1-\rho)$, a more likely scenario would be $MRS^i_{g_2,c_2} > MRS^i_{g_1,c_1}$. To see this, note that Eqs. (14) and (15) in the Appendix together imply $U^2_{c_1} > U^2_{c_2}$ and add the (plausible) assumption that $U^1_{c_1} > U^1_{c_2}$.[4] A sufficient (but not necessary) condition for the inequality $MRS^i_{g_2,c_2} > MRS^i_{g_1,c_1}$ to hold would then be that the utility function takes the following additively separable and time-invariant form in public good consumption:

$$U^i = U\left(c^i_1, \ell^i, c^i_2, g_1, g_2\right) = u\left(c^i_1, c^i_2\right) + \psi(\ell^i) + \phi\left(g_1\right) + \phi\left(g_2\right). \quad (10)$$

Therefore, this plausible special case implies *under-provision* of the public good relative to the policy rule corresponding to a standard model without habit formation, if the degrees of habituation in private and public good consumption coincide:

4 The condition $U^1_{c_1} > U^1_{c_2}$ always holds in a first-best resource allocation where $\lambda = 0$.

$$1 < \sum_i n^i \left(MRS^i_{g_1,c_1} + \frac{MRS^i_{g_2,c_2}}{1+r} \right). \tag{11}$$

The effect of habituation in public consumption thus dominates the effect of habituation in private consumption when $MRS^i_{g_2,c_2} > MRS^i_{g_1,c_1}$, which means that the case where $\alpha = \rho$ is not neutral in terms of the policy rule for a time-invariant public good.

Returning to the general case in the Proposition 2, the second line of Eq. (7) is a consequence of the self-selection constraint. Here, the second term is scaled by one minus the degree of habit formation in public good consumption. As such, the incentive faced by the government to offset mimicking in the future period is weaker under habit formation than in the absence of habit formation. The intuition is, of course, that public good consumption in the second period matters less the larger the degree of habituation. Finally, if the degrees of habituation in public and private goods consumption coincide such that inequality (11) applies, this under-provision result will be reinforced by the self-selection constraint if leisure is complementary with the public good in the sense that the marginal willingness to pay for the public good increases in leisure time, and counteracted if the opposite applies.

4 Summary and discussion

This paper analyzes the implications of habit formation in private and public goods consumption for the Pareto efficient provision of public goods. We consider two versions of the model: one in which the government directly decides on the supply of the public good in each period (a flow-variable public good) and the other where the public good is fixed over time (with an interpretation in terms of a state-variable). The take home messages of the paper are summarized below.

In general, habituation in public good consumption leads to under-provision of the public good and habituation in private good consumption to over-provision of the public good relative to a policy rule for an economy without habituation. This holds irrespective of whether the public good is fixed or can be varied over the periods.

An interesting special case arises when the degrees of habituation in private and public goods consumption are the same, in which the two versions of the model give quite different results. First, with a variable public good supply, and if the preferences are characterized by weak leisure separability, habituation does not change the policy rule for public good provision if the two degrees of habituation coincide. Thus, to the extent that habituation to private and public consumption is roughly the same (a reasonable baseline assumption in the absence of empirical evidence pointing elsewhere), this suggests that the Samuelson condition derived for an economy without any habituation, or the second-best analogue thereof, provides a reasonable approximation of the efficient supply of a flow-variable public good.

Second, with a time-invariant public good supply, even the special case with equal degrees of habituation in private and public goods consumption does not in general imply that conventional policy rules for public good provision surface. Instead, the policy rule for this special case typically means under-provision of the public good relative to the policy rule that would apply in the absence of any habituation. Therefore, based on the assumption that the rates of habituation to private and public consumption are positive and of similar magnitudes, conventional policy rules that neglect habituation are likely to imply under-provision of state-variable public goods such as air-quality and infrastructure.

Appendix

Proof of Proposition 1:

The Lagrangean corresponding to the social decision-problem is given by

$$L = U\left(c^1, \ell^1, x^1 - \alpha c^1, g, G - \rho g\right) + \mu\left[U\left(c^2, \ell^2, x^2 - \alpha c^2, g, G - \rho g\right) - \overline{U}^2\right]$$
$$+ \lambda\left[U\left(c^2, \ell^2, x^2 - \alpha c^2, g, G - \rho g\right) - U\left(c^1, 1 - \frac{w^1}{w^2} l^1, x^1 - \alpha c^1, g, G - \rho g\right)\right]$$
$$+ \gamma\left[\sum_i n^i w^i l^i - \sum_i n^i c^i - \sum_i \frac{n^i x^i}{1+r} - g - \frac{G}{1+r}\right].$$

By using the short notations $c_1^i = c^i$, $c_2^i = x^i - \alpha c^i$ $(i = 1,\ 2)$, $g_1 = g$, and $g_2 = G - \rho g$, the social first-order conditions for private and public goods consumption can be written as

$$\frac{\partial L}{\partial c^1} = U^1_{c_1} - \alpha U^1_{c_2} - \lambda(\hat{U}^2_{c_1} - \alpha \hat{U}^2_{c_2}) - \gamma n^1 = 0 \tag{12}$$

$$\frac{\partial L}{\partial x^1} = U^1_{c_2} - \lambda \hat{U}^2_{c_2} - \frac{\gamma n^1}{1+r} = 0 \tag{13}$$

$$\frac{\partial L}{\partial c^2} = (\mu + \lambda)(U^2_{c_1} - \alpha U^2_{c_2}) - \gamma n^2 = 0 \tag{14}$$

$$\frac{\partial L}{\partial x^2} = (\mu + \lambda) U^2_{c_2} - \frac{\gamma n^2}{1+r} = 0 \tag{15}$$

$$\frac{\partial L}{\partial g} = U^1_{g_1} - \rho U^1_{g_2} + \mu\left[U^2_{g_1} - \rho U^2_{g_2}\right] + \lambda\left[U^2_{g_1} - \rho U^2_{g_2} - \left(\hat{U}^2_{g_1} - \rho \hat{U}^2_{g_2}\right)\right] - \gamma = 0 \tag{16}$$

$$\frac{\partial L}{\partial G} = U^1_{g_2} + \mu U^2_{g_2} + \lambda\left[U^2_{g_2} - \hat{U}^2_{g_2}\right] - \frac{\gamma}{1+r} = 0 \tag{17}$$

Starting with the policy rule for the second period provision, *G*, we can substitute Eqs. (13) and (15) into Eq. (17) to derive

$$\frac{U^1_{g_2}}{U^1_{c_2}}\left[\lambda\hat{U}^2_{c_2}+\frac{\gamma n^1}{1+r}\right]+\frac{U^2_{g_2}}{U^2_{c_2}}\frac{\gamma n^2}{1+r}-\lambda\hat{U}^2_{g_2}-\frac{\gamma}{1+r}=0. \tag{18}$$

Rearrangements give

$$\frac{U^1_{g_2}}{U^1_{c_2}}\frac{\gamma n^1}{1+r}+\frac{U^2_{g_2}}{U^2_{c_2}}\frac{\gamma n^2}{1+r}-\lambda\hat{U}^2_{c_2}\left[\frac{U^1_{g_2}}{U^1_{c_2}}-\frac{\hat{U}^2_{g_2}}{\hat{U}^2_{c_2}}\right]-\frac{\gamma}{1+r}=0, \tag{19}$$

which is equivalent to Eq. (4b) in Proposition 1. Turning to the optimal public good provision in the first period, g, note first that Eq. (17) implies

$$\rho U^1_{g_2}+\rho\mu U^2_{g_2}+\rho\lambda\left[U^2_{g_2}-\hat{U}^2_{g_2}\right]-\frac{\rho\gamma}{1+r}=0.$$

Substituting into Eq. (16) gives

$$U^1_{g_1}+\mu U^2_{g_1}+\lambda\left[U^2_{g_1}-\hat{U}^2_{g_1}\right]-\gamma\left(1+\frac{\rho}{1+r}\right)=0. \tag{20}$$

By using Eqs. (12) and (14), Eq. (20) can be rewritten as

$$\frac{U^1_{g_1}}{U^1_{c_1}}\left[\alpha U^1_{c_2}+\lambda(\hat{U}^2_{c_1}-\alpha\hat{U}^2_{c_2})+\gamma n^1\right]+\frac{U^2_{g_1}}{U^2_{c_1}-\alpha U^2_{c_2}}\gamma n^2-\lambda\hat{U}^2_{g_1}-\gamma\left(1+\frac{\rho}{1+r}\right)=0. \tag{21}$$

Rearranging Eq. (21) gives

$$\begin{aligned}&\frac{U^1_{g_1}}{U^1_{c_1}}\gamma n^1+\frac{U^1_{g_1}}{U^1_{c_1}}\alpha\left[U^1_{c_2}-\lambda\hat{U}^2_{c_2}\right]+\frac{U^2_{g_1}}{U^2_{c_1}}\frac{U^2_{c_1}}{U^2_{c_1}-\alpha U^2_{c_2}}\gamma n^2\\&+\lambda\hat{U}^2_{c_1}\left[\frac{U^1_{g_1}}{U^1_{c_1}}-\frac{\hat{U}^2_{g_1}}{\hat{U}^2_{c_1}}\right]-\gamma\left(1+\frac{\rho}{1+r}\right)=0.\end{aligned} \tag{22}$$

Equation (13) implies

$$U^1_{c_2}-\lambda\hat{U}^2_{c_2}=\frac{\gamma n^1}{1+r}. \tag{23}$$

Similarly, combining Eqs. (14) and (15) gives

$$\frac{U^2_{c_1}}{U^2_{c_1}-\alpha U^2_{c_2}}=\frac{(1+r)U^2_{c_2}+\alpha U^2_{c_2}}{(1+r)U^2_{c_2}}=1+\frac{\alpha}{1+r}. \tag{24}$$

Using Eqs. (23) and (24) in Eq. (22) gives Eq. (4a) in Proposition 1.

Proof of Proposition 2

Let $g_1 = g$ and $g_2 = g(1-\rho)$. Equations (12)–(15) continue to hold under a time-invariant public good, while Eqs. (16) and (17) are replaced by a single first-order condition for public good provision, which is given by

$$U^1_{g_1} + U^1_{g_2}(1-\rho) + (\mu+\lambda)[U^2_{g_1} + U^2_{g_2}(1-\rho)] - \lambda[\hat{U}^2_{g_1} + \hat{U}^2_{g_2}(1-\rho)] - \gamma = 0. \tag{25}$$

By using Eqs. (12)–(15), Eq. (25) can be written as

$$\begin{aligned} &\frac{U^1_{g_1}}{U^1_{c_1}}\left[\alpha U^1_{c_2} + \lambda(\hat{U}^2_{c_1} - \alpha\hat{U}^2_{c_2}) + \gamma n^1\right] + \frac{U^1_{g_2}(1-\rho)}{U^1_{c_2}}\left[\lambda\hat{U}^2_{c_2} + \frac{\gamma n^1}{1+r}\right] \\ &\quad + \frac{U^2_{g_1}}{U^2_{c_1} - \alpha U^2_{c_2}}\gamma n^2 + \frac{U^2_{g_2}(1-\rho)}{U^2_{c_2}}\frac{\gamma n^2}{1+r} - \lambda[\hat{U}^2_{g_1} + \hat{U}^2_{g_2}(1-\rho)] - \gamma = 0. \end{aligned} \tag{26}$$

Rearranging Eq. (26), and rewriting the first term in the second row, gives

$$\begin{aligned} &\frac{U^1_{g_1}}{U^1_{c_1}}\gamma n^1 + \frac{U^1_{g_1}}{U^1_{c_1}}\alpha\left[U^1_{c_2} - \lambda\hat{U}^2_{c_2}\right] + \frac{U^1_{g_2}(1-\rho)}{U^1_{c_2}}\frac{\gamma n^1}{1+r} + \frac{U^2_{g_1}}{U^2_{c_1}}\frac{U^2_{c_1}}{U^2_{c_1} - \alpha U^2_{c_2}}\gamma n^2 \\ &\quad + \frac{U^2_{g_2}(1-\rho)}{U^2_{c_2}}\frac{\gamma n^2}{1+r} + \lambda\hat{U}^2_{c_1}\left[\frac{U^1_{g_1}}{U^1_{c_1}} - \frac{\hat{U}^2_{g_1}}{\hat{U}^2_{c_1}}\right] + \lambda\hat{U}^2_{c_2}\left[\frac{U^1_{g_2}}{U^1_{c_2}} - \frac{\hat{U}^2_{g_2}}{\hat{U}^2_{c_2}}\right](1-\rho) - \gamma = 0. \end{aligned} \tag{27}$$

Substituting Eqs. (23) and (24) into Eq. (27) gives

$$\begin{aligned} &\frac{U^1_{g_1}}{U^1_{c_1}}\left[1 + \frac{\alpha}{1+r}\right]\gamma n^1 + \frac{U^1_{g_2}(1-\rho)}{U^1_{c_2}}\frac{\gamma n^1}{1+r} + \frac{U^2_{g_1}}{U^2_{c_1}}\left[1 + \frac{\alpha}{1+r}\right]\gamma n^2 \\ &\quad + \frac{U^2_{g_2}(1-\rho)}{U^2_{c_2}}\frac{\gamma n^2}{1+r} + \lambda\hat{U}^2_{c_1}\left[\frac{U^1_{g_1}}{U^1_{c_1}} - \frac{\hat{U}^2_{g_1}}{\hat{U}^2_{c_1}}\right] + \lambda\hat{U}^2_{c_2}\left[\frac{U^1_{g_2}}{U^1_{c_2}} - \frac{\hat{U}^2_{g_2}}{\hat{U}^2_{c_2}}\right](1-\rho) - \gamma = 0. \end{aligned} \tag{28}$$

which is Eq. (7) in Proposition 2. □

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