Heterogeneous substitutability preferences and the value of environmental public goods

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Abstract: We study how heterogeneity in preferences regarding the limited substitutability of environmental public goods vis-a-vis private consumption goods affects the economic value society attaches to those public goods. We show that while mean marginal willingness to pay (WTP) for the environmental public good decreases in society's mean degree of substitutability, mean WTP increases in the heterogeneity of limited preferencesm for limited substitutability. Accounting for the heterogeneity of limited substitutability preferences increases the value of environmental public goods, such as those derived from environmental quality, compared to the standard assumption of homogeneous substitutability preferences. Illustrations based on experimental data to estimate preference heterogeneity suggest that this effect can be quantitatively sizable. These findings are relevant, among others, for environmental cost-benefit analysis and for the national accounting of environmental public goods.

JEL-Classification: Q51, Q56, H41

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1 Introduction

Limited substitutability is at the heart of sustainability debate and a key determinant of the economic value of goods and services from nature (Drupp 2018, Gerlagh and van der Zwaan 2002, Meya et al. 2020, Neumayer 2010). If a person or society can easily substitute a public good or service associated with ecosystems or biodiversity, then the economic value of this environmental public good is typically low (e.g. Meya et al. 2020). Conversely, when public goods are difficult to substitute, their value tends to be very high so that they make up a large share of the comprehensive consumption value (Gerlagh and van der Zwaan 2002). While the literature has so far concentrated on representative agent models or has assumed equal substitutability preferences, preferences regarding the limited substitutability of environmental public goods by human-made goods may differ substantially across individuals.

In this paper, we study how heterogeneous preferences for the limited degree of substitutability of environmental public goods vis-avis market goods across a population of individuals affect the economic value society attaches to (environmental) public goods. On a methodological level, we examine an extension of the equal-preference model that has been applied to non-market valuation, for instance, by Ebert (2003) and Baumgärtner et al. (2017a). Specifically, we consider a continuum of individuals that derive utility from a pure-public good and a private consumption good in a constant elasticity of substitution (CES) form. We assume that individuals differ in how well they perceive environmental public goods to be substitutable by or complementary to human-made consumption goods. We first consider a general case for how substitutability preferences may be distributed and examine how a mean preserving spread of substitutability preferences affects society's mean marginal willingness to pay (WTP) for an environmental public good. Subsequently, we assume that substitutability preferences are normally distributed in society. This allows us to obtain closed-form solutions for how the heterogeneity of preferences affects the value of environmental public goods.

We find that mean marginal WTP for environmental public goods within society increases in the heterogeneity of substitutability preferences, except for the special case in which the availability of environmental goods and human-made goods is the same. Thus, an environmental public good is more valuable from a societal perspective—holding the average degree of substitutability preferences within society fixed—the stronger individuals differ in their degree of substitutability. Assuming that substitutability preferences are normally distributed within society, we find that—compared to the standard case of homogeneous substitutability—considering a heterogeneous distribution exponentially increases the societal value of environmental public goods.

Subsequently, we will estimate heterogeneous substitutability preferences for environmental goods and income empirically. To this end, we plan to leverage the framework of generalized dictator games that has been used to estimate preferences for trading-off equity and efficiency between a giver and receiver in monetary rewards (e.g., Andreoni and Miller 2002, Fisman et al. 2007, 2015). Varying the price of giving across multiple contexts allows estimating the preferences of a CES function at an individual level. We plan to apply this to study trade-offs between individual rewards and the tree planting to obtain a first measure of the heterogeneity of preferences for limited substitutability.

We illustrate our theoretical results with estimates of heterogeneous substitutability preferences for giving. For now, we rely on data on the limited substituability of keeping a monetary reward and giving it towards an anonymous other person from three experiments (Bos and Drupp 2022, Bos et al. 2023, Fisman et al. 2007) as a proxy for the substitutability of complementarity in general giving.[1] This data suggest that giving and keeping are substitutes on average but that there is a considerable degree of preference heterogeneity. We use these estimations to illustrate how WTP depends on the heterogeneity of limited substitutability preference. These show that accounting for preference heterogeneity may substantially increase mean WTP for environmental public goods as compared to the standard case of equal preferences. Our results thus imply that accounting for heterogeneous substitutability preferences can have important implications for non-market valuation, policy appraisal and accounting (e.g., Bastien-Olvera and Moore 2021, Drupp and Hänsel 2021, Sterner and Persson 2008).

[1]Subsequently, we will use this framework to study the degree of limited substituability between keeping monetary rewards and donating to planting trees.

Our theoretical model is most closely related to Gollier (2019), who studies uncertain substitutability of environmental goods on the ecological discount rate and shows that an increase in risk concerning substitutability decreases the discount rate with which environmental goods should be discounted. However, while uncertainty may resolve over time as knowledge improves, potentially via investments into knowledge that targets the degree of substitutability (Fenichel and Zhao 2015), heterogeneities of substitutability preferences are likely to remain considerable within society and, importantly, are relevant and potentially pervasive even in a static context. While there is, to our knowledge, no empirical study that explores potential heterogeneity in preferences regarding the substitutability of (non-market) goods, preference heterogeneity has been shown to be substantial for other more well-explored preference parameters, such as those relating to time and riks (e.g. Andersen et al. 2008, Barsky et al. 1997, Falk et al. 2018, Von Gaudecker et al. 2011). Thus, on a conceptual level, our analysis also relates to the literature on aggregating heterogeneous preferences, such as time preferences (e.g. Gollier and Zeckhauser 2005, Heal and Millner 2014, Freeman and Groom 2015).

Our empirical estimation approach is most closely related to the literature on generalized dictator games (e.g., Andreoni and Miller 2002, Fisman et al. 2007, 2015) and drivers of donations in giving behavior in the field (e.g., Karlan and List 2007, Huck et al. 2015). While studies employing the generalized dictator game framework have so far focussed on monetary trade-offs across individuals, estimating preferences for balancing equity and efficiency, the donations literature has explored variable prices of giving using various matching procedures but—as far as we are aware—in between-subject designs without estimating heteorenous elasticities of substitution between keeping and giving.

The paper is structured as follows. We present a stylized model, where individuals have heterogeneous substitutability preferences in Section 2. In Section 3 we present our theoretical results. We first consider any mean preserving spread. We then specify substitutability preferences to be normally distributed to obtain closed-form solutions for how societal mean WTP depends on preference heterogeneity. Section 4 lays out the strategy for identifying heterogeneous substitutability preferences, while Section 5 provides illustrative results. Section 6 discusses selected shortcomings and concludes.

2 Model

We consider a society that consists of a continuum of individuals, labelled $i = 1, \dots, n$, and a single time period. An individual derives her utility from consuming a private, market-traded consumption good, C, and an environmental public good, E, which is non-rival and non-excludable in consumption, so that all households benefit from the same quantity.

Households differ in their preferences regarding the substitutability of an environmental public good by a manufactured consumption good. Utility is ordinal and preferences are represented by constant-elasticity-of-substitution (CES) utility function:

$$U_i(C, E; \eta_i) = \left(\alpha C^{1-\eta_i} + (1-\alpha)\, E^{1-\eta_i}\right)^{\frac{1}{1-\eta_i}}\,, \qquad (1)$$

where $\alpha \in (0, 1)$ is the utility share of the market-traded good, and $\eta_i \in (0, \infty)$ is individual i's inverse of the elasticity of substitution between the public good and the private consumption good, θ_i. The parameter η_i thus captures the limited degree of substituability or the increasing degree of complementarity; for $\eta < 1$ ($\eta > 1$), the two goods are considered substitutes (complements) in utility.[2] The utility function is strictly concave, preferences are homothetic, and both the private consumption good and the environmental public good are assumed to be normal goods.

To focus our analysis, we consider a setting in which all individuals are endowed with identical levels of income, $Y > 0$, and thus with identical levels of the private consumption good, C, and with identical levels of the environmental public good, $E > 0$. This means that all differences in the evaluation of the environmental public good, E, are caused by differences in substitutability preferences and not by an unequal endowment with income or the enjoyed level of the environmental public good.[3] As we consider a single private consumption good, all income is spent on this, i.e. $C = Y/P$, which further simplifies to $C = Y$ with private consumption good as numeraire, that is $P = 1$.

[2]We formally study the model with the elasticity of complementarity, η, instead of the elasticity of substitution throughout for reasons of analytical tractability (cf., Gollier 2019).

[3]See Baumgärtner et al. (2017a) for an examination of unequal income and Meya (2020) for a treatment of unequal endowment with an environmental (local) public good.

The marginal willingness to pay (WTP), $\omega_i(Y, E; \eta_i)$ for one unit of E is the marginal rate of substitution between the public good and private consumption:[4]

$$\omega_i(Y, E; \eta_i) := \frac{\partial U_i(Y, E; \eta_i)/\partial E}{\partial U_i(Y, E; \eta_i)/\partial Y} \overset{(1)}{=} \frac{1-\alpha}{\alpha} \left(\frac{Y}{E}\right)^{\eta_i}. \tag{2}$$

Thus, individual WTP for the environmental public good is a simple function of the ratio of income and the environmental public good to the power of the individual-specific elasticity of complementarity, weighted by the relative utility share parameters of private consumption to public good consumption. Observe from Eq. (2) that the elasticity of complementarity equals the income elasticity of WTP for the environmental public good, which is defined as $\eta_i := \frac{\partial \omega_i}{\partial Y} \frac{Y}{\omega_i}$ (cf. Ebert 2003, Kovenock and Sadka 1981).

3 Analysis

3.1 Heterogeneous substitutability

We now turn to the societal value of the environmental good. This is motivated by a key result of public economics (Lindahl-Samuelson-condition): Pareto-efficiency requires that public goods are supplied to the extent that the sum of individuals' marginal WTPs equals the marginal (opportunity) cost of supplying the public good (Lindahl 1928, Samuelson 1954). Thus aggregate marginal WTP is meaningful without interpersonal comparison in utility or the specification of a welfare function.

For the remainder η is a distributed variable that describes the continuous distribution of the inverse of the elasticity of substitution in the population of individuals. Society's mean marginal WTP (or 'societal marginal WTP') is the expected value for a given distribution of η:

$$\overline{\omega}(Y, E; \eta) = \mathbb{E}\left[\omega(Y, E; \eta) | \, \eta\right] \overset{(2)}{=} \mathbb{E}\left[\frac{1-\alpha}{\alpha} \left(\frac{Y}{E}\right)^{\eta} | \, \eta\right] = \frac{1-\alpha}{\alpha} \, \mathbb{E}\left[\left(\frac{Y}{E}\right)^{\eta} | \, \eta\right]. \tag{3}$$

[4]Marginal WTP (sometimes referred to as 'virtual' or 'Lindahl price'), ω, can be interpreted as the price the individual would have been willing to pay if the level of the public good, E, had been freely chosen on a hypothetical market (e.g. Flores and Carson 1997, Ebert 2003).

This mean marginal WTP is a measure for societal WTP, as aggregate WTP is the sum of individual WTPs, which is the mean multiplied by the number of individuals.[5]

Proposition 1

Let η denote the inverse of the elasticity of substitution between a public and private good. Then any mean preserving spread in η, i.e. substitutability preference heterogeneity, increases the economic value of the public good. The only exception is the case where the level of income and the environmental public good are identical.

Proof. For $Y \neq E$ it holds that $k(Y) = (Y/E)^\eta$ is a convex function in η, for positive levels of income and the environmental good, $Y > 0$ and $E > 0$. Therefore, by Jensen's inequality, $\mathbb{E}\left[(Y/E)^\eta\right]$ increases by any mean-preserving spread of η. As $\alpha \in (0, 1)$, Eq. (3) is a positive function of $\mathbb{E}\left[(Y/E)^\eta\right]$. Hence, $\overline{\omega_i}(Y, E; \eta)$ also increases by any mean-preserving spread of η. For $Y = E$, however, $k(Y) = 1$ is constant, as is $\mathbb{E}\left[(Y/E)^\eta\right]$, and thus remains unaffected by a mean-preserving spread of η. □

We illustrate Proposition 1 in Figure 1 for a simple case with two individuals that exhibit a low elasticity of complementarity (i.e. a high elasticity of substitutability), η_{low}, and a high elasticity of complementarity, η_{high}. Figure 1 shows that mean marginal WTP when the two individuals have heterogeneous preferences regarding the limited substitutability of environmental public goods vis-a-vis private consumption goods or income, $\overline{\omega}(Y, E; \eta)$, is higher than the marginal WTP at mean elasticity of complementarity, $\omega_i(Y, E; \mu_\eta)$. Mean marginal WTP, $\overline{\omega}(Y, E; \eta) = \mathbb{E}\left[\omega(Y, E; \eta) | \, \eta\right]$, increases with a mean-preserving spread in the elasticity of complementarity.[6]

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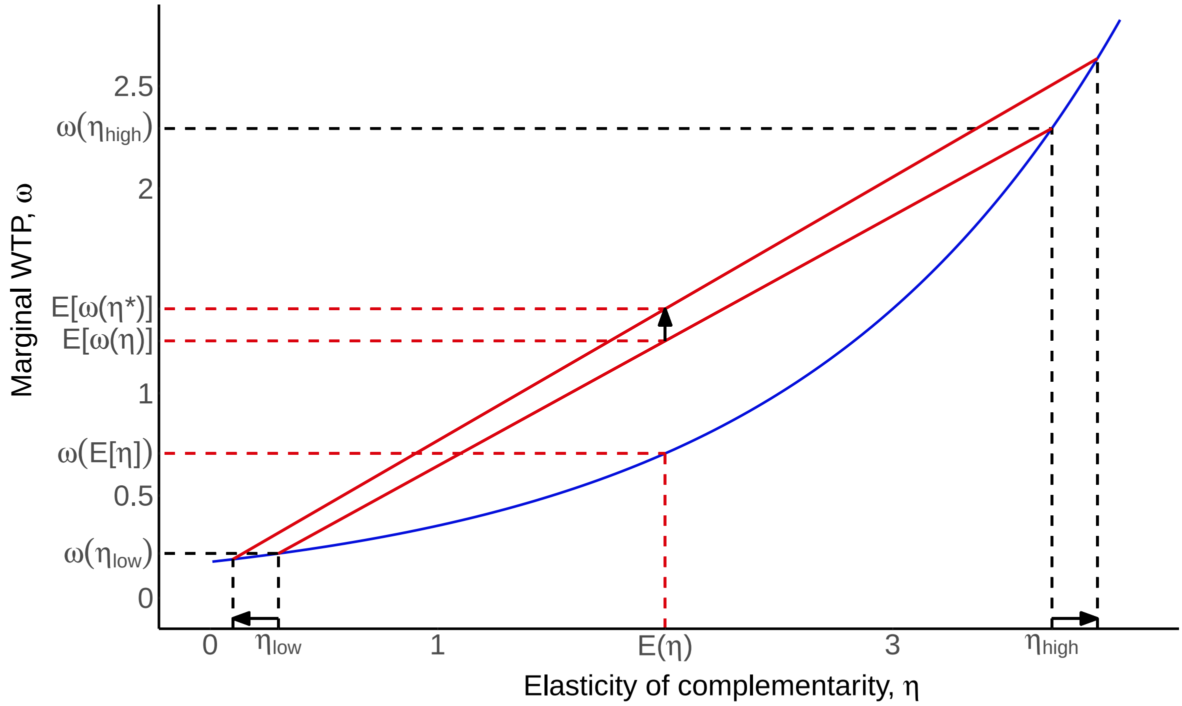
[5]Note that, as substitutability preferences are the only source of heterogeneity in our model, in the special case, where all individuals have the same substitutability preferences, i.e. $\forall i : \eta_i = \eta$, society's mean marginal WTP, $\overline{\omega}$, equals individual marginal WTP, ω_i (Eq. 2).

[6]Technically, the effect of preference heterogeneity in the elasticity of complementarity, η, on the mean marginal WTP is analogue to the effect of uncertainty about substitutability on the ecological discount rate as analyzed by Gollier (2019) in an intertemporal context.

Figure 1: Heterogenous substitutability preferences and marginal WTP.



Notes: Illustration with two individuals with a low elasticity of complementarity (i.e. a high elasticity of substitutability), η_{low}, and a high elasticity of complementarity, η_{high}. If marginal WTP (blue) is a convex function of limited substitutability and preferences are heterogeneous, then Jensen's inequality implies that mean marginal WTP based on heterogenous complementarity preferences, $\mathbb{E}[\omega(\eta)]$, is higher than marginal WTP at the mean elasticity of complementarity, $\omega(\mathbb{E}[\eta])$. Mean marginal WTP based on heterogenous preferences increases with a mean-preserving spead in the elasticity of complementarity from $\mathbb{E}[\omega(\eta)]$ to $\mathbb{E}[\omega(\eta^*)]$.

3.2 Normally distributed substitutability

We now study a special case of $\eta \sim \mathcal{N}(\mu_\eta, \sigma_\eta^2)$, where μ_η is the mean of the elasticity of substitution between a public and private good in society and σ_η the corresponding standard deviation. The assumption of a normally distributed η has been previously taken to study uncertainty about the degree of substitutability (Gollier 2019) as well as to show that the effect of income inequality on WTP for environmental public goods can extend to heterogeneous preference (Baumgärtner et al. 2017a, Appendix 11).

Mean marginal WTP is the expected value of individual WTP's (see Appendix A.1)

$$\begin{aligned}\overline{\omega}(\mu_\eta, \sigma_\eta) =& \frac{1-\alpha}{\alpha} (Y/E)^{\mu_\eta + \frac{\sigma_\eta^2}{2}\ln(Y/E)} \\ =& \frac{1-\alpha}{\alpha} \exp\left[\mu_\eta \ln(Y/E)\right] \exp\left[\frac{\sigma_\eta^2}{2}\ln(Y/E)^2\right],\end{aligned} \tag{4}$$

which is strictly positive for $Y > 0$ and $E > 0$. Equation (4) shows that $\overline{\omega}$ exponentially increases in both the spread and the mean of the elasticity of complementarity. Conducting comparative statics with respect to μ_η or σ_η establishes Proposition 2.

Proposition 2

Consider the elasticity of complementarity, η, to be normally distributed with mean, μ_η, and standard deviation, σ_η. It holds:

1. Mean marginal WTP, $\overline{\omega}$, increases (decreases) in μ_η if and only if the endowment with income is higher (lower) than with the public good

$$\frac{\partial \overline{\omega}}{\partial \mu_\eta} \gtreqless 0 \iff Y \gtreqless E; \tag{5}$$

2. Mean marginal WTP, $\overline{\omega}$, increases in σ_η, except if endowment with income equals endowment with the public good

$$\frac{\partial \overline{\omega}}{\partial \sigma_\eta} \begin{cases} = 0, & \text{if} \quad Y = E \\ > 0, & \text{otherwise} \end{cases}; \tag{6}$$

3. The positive effect of σ_η on mean marginal WTP, $\overline{\omega}$, increases (decreases) in μ_η if and only if the level of income is higher (lower) than that of the public good

$$\frac{\partial^2 \overline{\omega}}{\partial \sigma_\eta \partial \mu_\eta} \gtreqless 0 \iff Y \gtreqless E; \tag{7}$$

Proof. See Appendix A.2. □

Proposition 2.1 shows that the effect of mean substitutability on mean marginal WTP for the environmental public good depends on its relative scarcity vis-a-vis private consumption goods or income. If the environmental public good E is scarcer than income Y, mean WTP for the environmental public good increases as the degree of mean complementarity increases (or, equivalently, as mean substitutability decreases), that is the larger μ_η (Proposition 2.1).

Proposition 2.2 is a special case of Proposition 1 for a specific probability density function featuring a mean-preserving spread. We illustrate the effect of heterogeneity in complementarity preferences, σ_η on societal WTP for the environmental public good below in Figure 4.

Proposition 2.3 shows that the extent to which mean marginal WTP, $\overline{\omega}$, increases with complementarity preference heterogeneity, σ_η, is amplified (reduced) in the mean degree of complementarity, if the environmental public good is relatively more (less) scarce than income.

To compare the cases of heterogeneous and homogeneous substitutability preferences, one can consider the ratio between $\overline{\omega}$ with σ_η-heterogeneous preferences and $\overline{\omega}$ without heterogeneous preferences, that is with $\sigma_\eta = 0$, while holding everything else constant. This *'heterogeneity factor'*

$$h(\sigma_\eta) := \frac{\overline{\omega}(\mu_\eta, \sigma_\eta)}{\overline{\omega}(\mu_\eta, 0)} \overset{(4)}{=} Y^{\frac{\sigma_\eta^2}{2}\ln(Y/E)} = \exp\left[\frac{\sigma_\eta^2}{2}\ln(Y/E)^2\right], \tag{8}$$

is independent of μ_η and strictly positive, given our assumptions of $Y > 0$ and $E > 0$ (cf. Propositions 1 and 2.2). The heterogeneity factor equals unity in the special cases of $E = Y$ or $\sigma_\eta = 0$. Thus, when substitutability preferences are heterogeneous (and private and public goods are supplied in different amounts), mean WTP increases—relative to the standard homogeous preference case—by a factor that is an exponential function of the heterogeneity of substitutability preferences, σ_η.

Alternatively, one can ask how high the mean elasticity of complementarity with homogeneous preferences needs to be to give the same mean marginal WTP as in a situation with preference heterogeneity. This *'heterogeneity equivalent'*, μ_η^*, is implicitly defined as $\overline{\omega}(\mu_\eta^*, 0) = \overline{\omega}(\mu_\eta, \sigma_\eta)$. Inserting Eq. (4) and rearranging we have

$$\mu_\eta^* = \frac{\sigma_\eta^2}{2}\ln(Y/E) + \mu_\eta, \tag{9}$$

where the heterogeneity equivalent mean degree of limited substitutability, μ_η^*, is larger (lower) than the mean degree of limited substitutability with homogeneous substitutability preferences, μ_η, if and only if there are more (less) private goods Y than public goods

E. Note, in the case of $E = Y$ the heterogeneity equivalent is equal to mean η.Eq. (9) shows how representative agent models can account for heterogeneity in the underlying preferences data in their parametrization of CES-preferences

Since both the heterogeneity and mean of substitutability preferences affect mean marginal WTP, it is interesting to study which is the stronger effect. Comparing the elasticity of mean marginal WTP with respect to heterogeneity in substitutability preferences, $\left|\psi_{\overline{\omega},\sigma_\eta}\right|$, with the elasticity of mean marginal WTP with respect to the mean substitutability preference, $\left|\psi_{\overline{\omega},\mu_\eta}\right|$, establishes Proposition 3.

Proposition 3

Mean marginal WTP changes more elastically with σ_η than with μ_η if and only if σ_η is larger (lower) than income weighted absolute μ_η:

$$\left|\psi_{\overline{\omega},\sigma_\eta}\right| \gtreqless \left|\psi_{\overline{\omega},\mu_\eta}\right| \quad \text{if and only if} \quad \sigma_\eta \gtreqless \frac{2}{\left|\ln(Y/E)\right|}\left|\mu_\eta\right|. \tag{10}$$

Proof. The elasticity of $\overline{\omega}$ with respect to μ_η and elasticity of $\overline{\omega}$ with respect to σ_η are

$$\left|\psi_{\overline{\omega},\mu_\eta}\right| := \left|\frac{\partial\overline{\omega}}{\partial\mu_\eta}\frac{\mu_\eta}{\overline{\omega}}\right| \overset{\text{(A.16)}}{=} \left|\ln(Y/E)\mu_\eta\right| = \left|\ln(Y/E)\right|\left|\mu_\eta\right|, \tag{11}$$

$$\left|\psi_{\overline{\omega},\sigma_\eta}\right| := \left|\frac{\partial\overline{\omega}}{\partial\sigma_\eta}\frac{\sigma_\eta}{\overline{\omega}}\right| \overset{\text{(A.18)}}{=} \left|\frac{\ln(Y/E)^2}{2}\sigma_\eta\right| \overset{\sigma_\eta\geq 0}{=} \frac{\ln(Y/E)^2}{2}\sigma_\eta. \tag{12}$$

It thus directly follows that

$$\begin{aligned}
\left|\psi_{\overline{\omega},\sigma_\eta}\right| \gtreqless \left|\psi_{\overline{\omega},\mu_\eta}\right| \quad &\overset{(11)(12)}{\Longleftrightarrow} \quad \frac{\ln(Y/E)^2}{2}\sigma_\eta \gtreqless \left|\ln(Y/E)\right|\left|\mu_\eta\right| \\
&\overset{Y\neq E}{\Longleftrightarrow} \quad \sigma_\eta \gtreqless 2\frac{\left|\ln(Y/E)\right|}{\ln(Y/E)^2}\left|\mu_\eta\right| \\
&\Longleftrightarrow \quad \sigma_\eta \gtreqless 2\left|\frac{\ln(Y/E)}{\ln(Y/E)^2}\right|\left|\mu_\eta\right| \\
&\Longleftrightarrow \quad \sigma_\eta \gtreqless \frac{2}{\left|\ln(Y/E)\right|}\left|\mu_\eta\right|.
\end{aligned} \tag{13}$$

□

Observe from Proposition 3 that $l(Y/E) := \frac{2}{\left|\ln(Y/E)\right|}$ decreases the more unequal the endowment of income and the environmental public good are. Thus, the higher the inequality in endowment of Y and E, the more likely it is that mean marginal WTP reacts more elastically to preference heterogeneity vis-a-vis mean preferences.

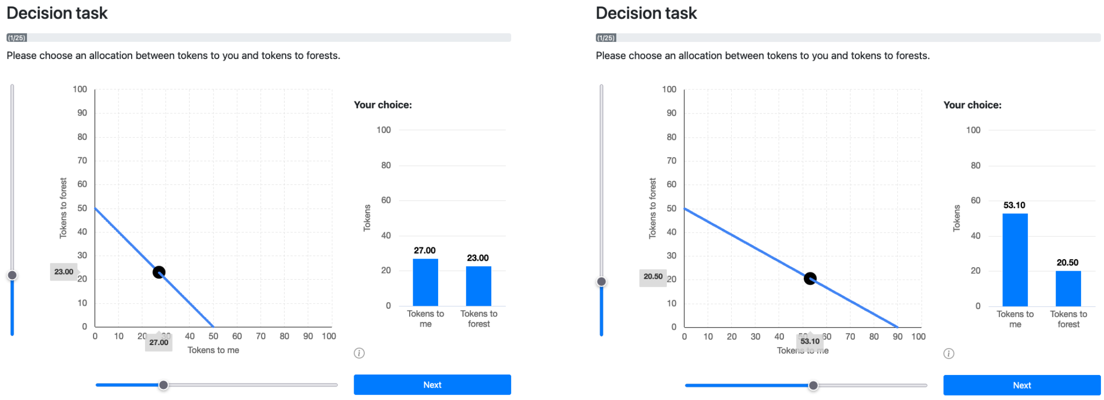
4 Estimation of heterogeneous preferences

We start with the preference parameters. To this end, we estimate heterogeneous substitutability preferences, η_i, as well as the utility share parameter, α. We plan to elicit this for the substitutability between keeping resoures as individual income and giving them towards planting trees, as a proxy for a well-recognized environmental public good. For now, for the sake of preliminary illustration, we draw on data on the substitutability between keeping resoures as individual income and giving them towards some other individual. This is akin to estimating preferences for trading-off equity and efficiency between a giver and receiver in monetary rewards using the framework of generalized dictator games (e.g., Andreoni and Miller 2002, Fisman et al. 2007, 2015). The approach confronts subjects with a series of dictators games, in which a subjects decides on what to keep from a fixed budget and what to give to another participant (or towards planting trees), that feature exogenously varied relative prices of giving. Figure 2 illustrates the experimental choice environment. Varying the price of giving across multiple contexts, usually across 20 to 50 rounds that feature different budget lines, allows estimating the preferences parameters of a CES function at an individual level using a maximum likelihood estimation (see Fisman et al. (2007) or Appendix A.3 for more details).

For the illustration of the effect of preference heterogeneity, we use estimates of η_i and α from three experiments (Fisman et al. 2007, Bos and Drupp 2022, Bos et al. 2023), amounting to individual-level preference estimates of 326 subjects. The mean and standard deviation of the degree of limited substituability, μ_{eta} and σ_{eta}, are very sensitive to estimates with very large elasticities. We consider different winsorization levels besides showcasing the full data, respecting only the inner 99, 95, and 90 percentile values for individual-level estimates of η (see Table 1 for further descriptive details).

While the median estimate of the elasticity of complementarity is 0.66, the mean, μ_{eta}, is 16.75 in the full sample but only 1.11 with 90 percentile winsorization. The corresponding values of the standard deviation of the elasticity of complementarity, σ_{eta}, are 218.43 in the full sample and only 1.11 with 90 percentile winsorization. While we also estimate heterogeneous values of α, we use the mean value of 0.68 throughout.

Figure 2: Illustration of experimental choice setting.



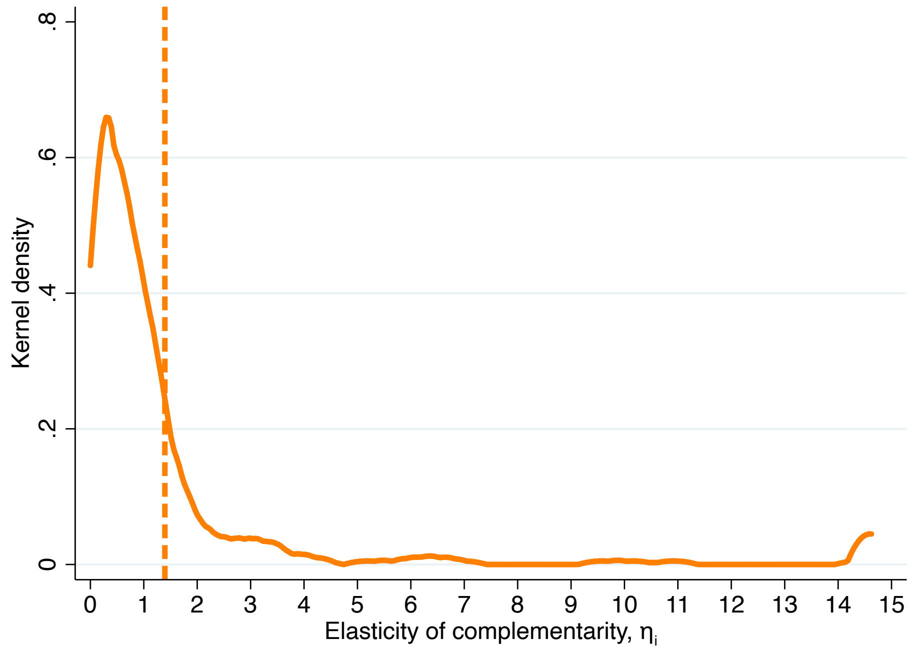
Notes: This figure shows two exemplary choice contexts where a subject ("giver") decides—by setting and then shifting the curser in the figure or the sliders at the axis—between keeping part of a buget to herself and giving it to some other person or towards other causes, such as planting trees.

Table 1: Overview of estimates of the elasticity of complementarity.

Sample	μ_η	σ_η	Min	Max
Full	16.75	218.43	0	3836.55
99 percentile	11.75	120.43	0	1977.21
95 percentile	1.39	2.63	0	14.62
90 percentile	1.11	1.42	0	6.02

We illustrate the distribution of estimates for the elasticity of complementarity (or the income elasticity of WTP) for the case of 95 percentile winsorization in Figure 3 using kernel density smoothing. Inidividual estimates of η_i clearly do not follow a normal distribution, as we see a substantial skew towards higher values of η_i. As a consequence, we will illustrate three sets of results in the subsequent section for how mean marginal WTP depends on substitutability preferences: We contrast marginal WTP for the mean degree of substitutability with preference heterogeneity assuming a normal distribution as well as with heterogeneous individual-level estimations of the elasticity of complementarity.

Figure 3: Distribution of the elasticity of complementarity.



Notes: Kernel density plot, with zero bandwith, of the distribution of estimates of individual elasticities of complementarity (or the income elasticity of WTP), η_i, for the 95 percentile winsorization. The orange dashed vertical line shows the mean elasticity of complementarity of 1.39.

5 Illustration of results

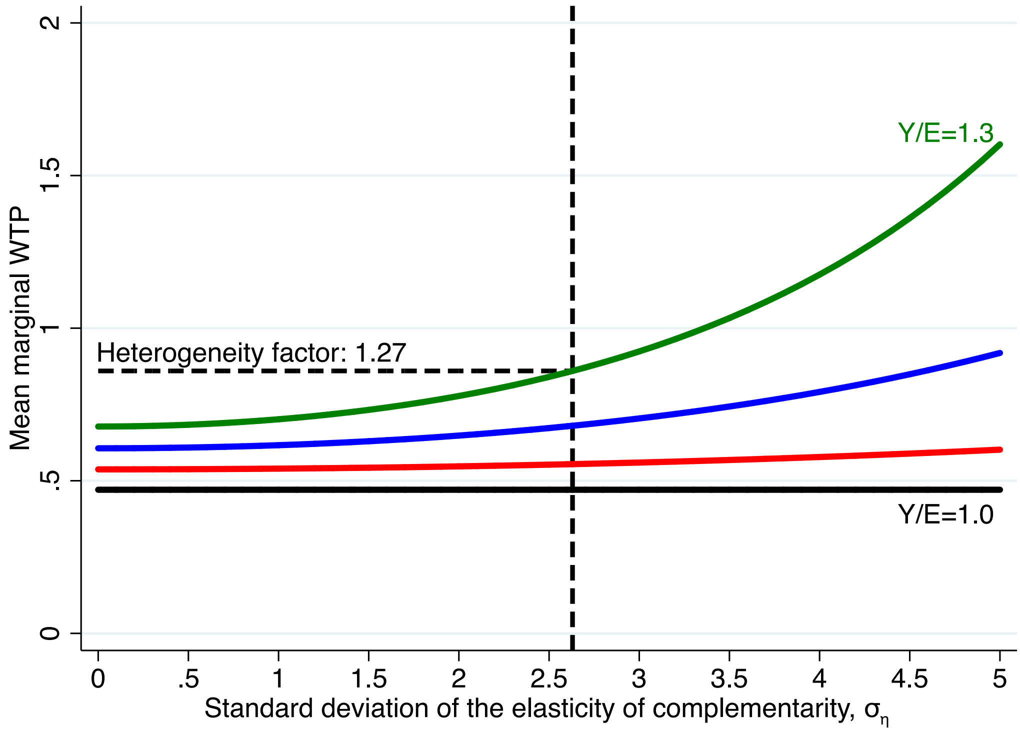
To illustrate how mean marginal WTP depends on preference heterogeneity, we have to specify all parameters and variables that affect individual and mean WTP (Equations 2 and 4): the levels of the environmental public good, E, and of the market-traded consumption good, C, or income, Y, the utility share parameter of the market-traded good, α, as well as individual estimates of the income elasticity of WTP, as the inverse of the elasticity of substitution between the public good and income, η_i, capturing the limited degree of substituability or the preference for complementarity, including its population mean, μ_{eta}, and standard deviation, σ_{eta}.

For the preference parameters, we use estimates derived in the preceding section. The amount of human made goods, C, or of income, Y, compared to environmental public goods, E, is particularly hard to quantify. At the macro-scale, Elhacham et al. (2020) compare the weight of material output from human activity ("anthropogenic mass") with the weight of the global living, natural biomass. They find that in 2020 the anthropogenic mass equals the natural biomass. Moreover, they find that the anthropogenic mass has increased massively, doubling approximately every 20 years. Even if natural biomass was constant, this suggests that the relative abundance of human made goods was much lower in the recent past and will be much higher in the near future. However, anthropogenic mass does not readily translate into income, and an individual only holds a small fraction of global anthropogenic mass or income. Likewise, global living, natural biomass does not radily translate into a metric of environmental public goods. Without a proper reference, we revert to illustrating our results of how heterogeneity in substitutability preferences affects WTP for a range of ratios between income and environmental public goods.

In Figure 4 we illustrate how mean marginal WTP, $\overline{\omega}(\mu_{eta}, \sigma_{eta})$, depends on the standard deviation of the elasticity of complementarity (or income elasticity of WTP), assuming that the elasticity follows a normal distribution. It depicts how mean marginal WTP depends on the standard deviation of the elasticity of complementarity, σ_{eta} for a mean elasticity of $\mu_{eta} = 1.39$ (i.e., for the 95 percentile winsorization) and values of the ratio between income and environmental public goods, E/Y, of 1.0 to 1.3. We additionally highlight the mean marginal WTP for the 95 percentile winsorization, $\overline{\omega}(\mu_{eta} = 1.39, \sigma_{eta} = 2.63)$. This is 27(12)[3] percent higher than the WTP in the homogeneous preference case when $E/Y = 1.3(1.2)(1.1)$.

We also compute individual marginal WTPs and aggregate them without assuming any specific distribution for the elasticity of complementarity based on the 95 percentile winsorization. The resulting distribution of individual marginal WTPs is illustrated in Figure 5 as a kernel density plot and shows that the distribution of marginal WTPs is highly skewed towards high WTP values. Mean WTP for the distribution of individual WTPs is 88 percent higher than in the homogeneous preference case, and thus leads to a much higherupward adjustment as when assuming that preference heterogeneity regarding limited substitutability follows a normal distribution.

Figure 4: Effect of preference heterogeneity on mean marginal WTP.



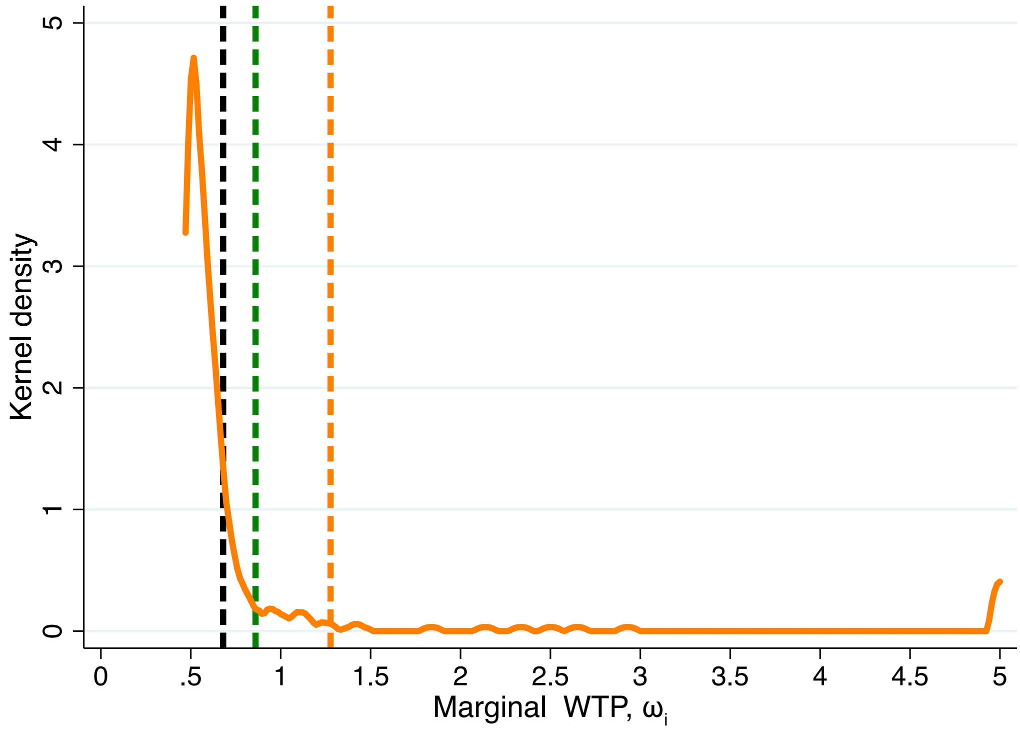
Notes: This figure shows mean marginal WTP, $\overline{\omega}(\mu_\eta, \sigma_\eta)$, (Eq. (4)) as a function of the standard deviation of the elasticity of complementarity, measured by σ_η for different ratios between income and the environmental public good. The dashed vertical line depicts the standard deviation of the elasticity of complementarity for the 95 percentile winsorization. This leads to a mean marginal WTP that is factor 1.27 higher than mean marginal WTP under preference homogeneity.

6 Discussion and Conclusion

The value of environmental public goods is an increasing and convex function of the degree to which it is considered complementary with private consumption goods. While this observation is almost a first principle of economics and has been at the heart of economic discussion on sustainability and natural capital, it has important, so-far underappreciated implications for the valuation of environmental public goods.

The convexity of marginal WTP implies that any mean preserving spread in substitutability preferences increases the society's aggregate value of environmental public goods. When individual elasticities of complementarity follow a normal distribution,

Figure 5: Distribution of individual marginal WTPs.



Notes: This figure shows a kernel density plot, with zero bandwith, of individual marginal WTPs, capped at a value of 5 for visual pruposes, for $Y/E = 1.3$. The vertical orange dashed line depicts mean marginal WTP from this empirical distribution, while the vertical green dashed line depicts mean marginal WTP assuming that the elasticity of complementarity, η, is normally distributed. The black dashed line depicts mean marginal WTP for homogeneous preferences.

the societal value of environmental public goods increases exponentially in preference heterogeneity, except for the special case in which the environmental public good and other consumption goods are enjoyed in exactly the same amount. We further derive a 'heterogeneity factor' with which WTPs derived based on homogeneous preferences need to be scaled up in the presence of heterogeneity, and also compute a 'heterogeneity equivalent' degree of substitutability to be used in representative agent analyses when the complementarity preferences are heterogeneous and follow a normal distribution.

We further lay out a strategy to empirically estimate heterogeneous preferences for limited substitutability and illustrate the approach with data on limited substitutability between keeping money and giving it to some other individual. This illustration thus assumes that preferences for the limited substitutability of giving generalize across domains that we seek to relax subsequently. We use data from three prior experiments to illustrate how heterogeneous complementarity preferences affect society's mean marginal WTP for environmental public goods using a highly stylized setting. We find that considering preference heterogeneity for limited substitutability that follows a normal distribution can substantially increase the estimated mean marginal WTP as compared to considering homogeneous preferences. We further find that complementarity preferences—for our proxy of general giving—do not follow a normal distribution and are skewed towards high degrees of complementarity. We show that mean marginal WTP computed based on the heterogeneity in the actual preference data—without assuming a specific distribution—yields a much more sizable increase in mean WTP as compared to the assumption of homogeneous preferences.

Our analysis is limited in several dimensions. First, we confine our analysis to homogeneous income and environmental global public goods to isolate the effect of heterogeneous substitutability preferences. Ebert (2003) has shown in an equal-preference model that the elasticity of substitution also determines benefit incidence of conservation policies. When there is a suitable human-made substitute for the environmental public good, richer individuals can better substitute losses in the environmental good than poorer individuals. Thus, it might be worthwhile to generalize our heterogeneous-preference model to heterogeneous income in order to study the correlation between income and the elasticity of substitution, that is how substitutability preferences for public goods differ along the income distribution and what this implies for the aggregate WTP for public goods. Likewise, it would be interesting to investigate the extensions that consider an unequal availability of local environmental goods (cf., Meya 2020).

Second, and relatedly, we considered a standard constant elasticity of substitution (CES) utility function and focused on a constant elasticity of complementarity (i.e. the inverse of the CES) for reasons of analytical tractability. Little is known empirically about appropriate values of these elasticities. A number of studies have estimated proxies of the elasticity of complementarity (elasticity of substitution) via a direct (inverse) relationship with the income elasticity of WTP (e.g., Baumgärtner et al. 2017a, Drupp 2018, Drupp and Hänsel 2021, Drupp et al. 2023). Most estimates of (constant) income elasticites of WTP—and thus of the elasticity of complementarity—typically range between 0.3 and 1, suggesting that environmental public goods are considered substitutes to private consumption goods or income.[7] Yet, there is also evidence for non-constant income elasticities (e.g., Barbier et al. 2017). While there is some theoretical research on non-constant elasticities of substitution (e.g., Baumgärtner et al. 2017, Drupp 2018) that studies how elasticities vary with the level of E relative to a basic needs threshold, little is know empirically about how well income elasticities map into elasticities of substitution or complementarity. Our experimental analysis will therefore also try to test how well choices can be rationalized by CES.

Third, we assumed a normally distributed elasticity of complementarity, η, following contributions by Baumgärtner et al. (2017a) and Gollier (2019). Again, little is known on how substitutability preferences for public goods are distributed in society and we seek to inform this empirically. While assuming a normal distribution might seem a natural choice for a distributed variable, this also comes with a caveat. For a positive standard deviation the normal distribution implies that in the left tail of the distribution there are some negative values of η_i. As η_i is the inverse of the elasticity of substitution, θ_i, this allows for some negative values of the elasticity of substitution, which is only defined for positive values. However, it is not possible to obtain a mean marginal WTP in closed-form solution for a log-normally distributed η_i or a normal distribution truncated at zero. Future version of this manuscript might thus consider probability density functions that only allow for positive real values for η_i, which, however, will likely require resorting to simulations. Thus, while there are limits to what we can represent with close-form solutions theoretically, we also illustrate how mean marginal WTP depends on the actual distribution of heterogeneous preferences using our experimental data.

Fourth, we consider a purely static context. It might be interesting for future analyses to study heterogeneous preferences in a dynamic setting, to obtain ecological discount

[7]More recently, however, Heckenhahn and Drupp (2022) found income elasticities larger than unity in a German meta-analysis.

rates (vis-a-vis the discount rate for consumption goods) and relative price changes of environmental goods (e.g. Drupp 2018, Drupp and Hänsel 2021, Gollier 2010, Hoel and Sterner 2007, Traeger 2011, Weikard and Zhu 2005).

Finally, our analysis considers a pure statistical effect only. Yet, heterogeneous preferences for the limited substitutability of environmental public goods may also affect a number of other determinants of the WTP for environmental public goods, via education, sorting or political economy channels. We leave these avenues for future research.

Despite these caveats, our theoretical results, and very rough empirical illustrations, suggest an important role for considering preference heterogeneity regarding the limited substitutability of environmental public goods. Our findings are relevant, among others, for cost-benefit analysis, national accounting of environmental public goods derived from natural capital, and policies aimed at sustainability.

A Appendix

A.1 Mean marginal WTP

The density function for normally distributed η with mean μ_η and standard deviation σ_η is

$$f_{\text{norm}}(\eta;\mu_\eta,\sigma_\eta) = \frac{1}{\sqrt{2\pi\sigma_\eta^2}} \exp\left(-\frac{(\eta-\mu_\eta)^2}{2\sigma_\eta^2}\right). \tag{A.14}$$

Mean marginal WTP is then given as expected value

$$\begin{aligned}
\overline{\omega}(\mu_\eta,\sigma_\eta) &= \mathbb{E}\left[\omega(Y,E;\eta)\right] \\
&= \int_{-\infty}^{+\infty} f_{\text{norm}}(\eta;\mu_\eta,\sigma_\eta)\,\omega(Y,E;\eta)\,d\eta \\
&\overset{(2),(A.14)}{=} \int_{-\infty}^{+\infty} \frac{1}{\sqrt{2\pi\sigma_\eta^2}} \exp\left(-\frac{(\eta-\mu_\eta)^2}{2\sigma_\eta^2}\right) \frac{1-\alpha}{\alpha}\,(Y/E)^\eta\,d\eta \\
&= \frac{1-\alpha}{\alpha} \int_{-\infty}^{+\infty} \frac{1}{\sqrt{2\pi\sigma_\eta^2}} \exp\left(-\frac{(\eta-\mu_\eta)^2}{2\sigma_\eta^2}\right) \exp\left(\ln\left((Y/E)^\eta\right)\right)\,d\eta \\
&= \frac{1-\alpha}{\alpha} \int_{-\infty}^{+\infty} \frac{1}{\sqrt{2\pi\sigma_\eta^2}} \exp\left(-\frac{(\eta-\mu_\eta)^2}{2\sigma_\eta^2} + \eta\,\ln(Y/E)\right)\,d\eta \\
&= \frac{1-\alpha}{\alpha} \int_{-\infty}^{+\infty} \frac{1}{\sqrt{2\pi\sigma_\eta^2}} \exp\left(\frac{-(\eta-\mu_\eta)^2 + 2\sigma_\eta^2\,\eta\,\ln(Y/E)}{2\sigma_\eta^2}\right)\,d\eta \\
&= \frac{1-\alpha}{\alpha} \int_{-\infty}^{+\infty} \frac{1}{\sqrt{2\pi\sigma_\eta^2}} \exp\left(\frac{-\left[\eta-(\mu_\eta+\sigma_\eta^2\ln(Y/E))\right]^2}{2\sigma^2} + \ln(Y)\left[\mu_\eta + \frac{\sigma_\eta^2}{2}\ln(Y/E)\right]\right)\,d\eta \\
&= \frac{1-\alpha}{\alpha} \int_{-\infty}^{+\infty} \frac{1}{\sqrt{2\pi\sigma_\eta^2}} \exp\left(\frac{-\left[\eta-(\mu_\eta+\sigma_\eta^2\ln(Y/E))\right]^2}{2\sigma^2}\right) \exp\left(\ln(Y/E)\left[\mu_\eta + \frac{\sigma_\eta^2}{2}\ln(Y/E)\right]\right)\,d\eta \\
&= \frac{1-\alpha}{\alpha} \exp\left(\ln(Y/E)\left[\mu_\eta + \frac{\sigma_\eta^2}{2}\ln(Y/E)\right]\right) \int_{-\infty}^{+\infty} \frac{1}{\sqrt{2\pi\sigma_\eta^2}} \exp\left(\frac{-\left[\eta-(\mu_\eta+\sigma_\eta^2\ln(Y/E))\right]^2}{2\sigma^2}\right)\,d\eta \\
&\overset{\mu'_\eta:=\mu_\eta+\sigma_\eta^2\ln(Y/E)}{=} \frac{1-\alpha}{\alpha} \exp\left(\ln\left((Y/E)^{\mu_\eta+\frac{\sigma_\eta^2}{2}\ln(Y/E)}\right)\right) \underbrace{\int_{-\infty}^{+\infty} \frac{1}{\sqrt{2\pi\sigma_\eta^2}} \exp\left(\frac{-\left[\eta-\mu'_\eta\right]^2}{2\sigma^2}\right)\,d\eta}_{=1} \\
&= \frac{1-\alpha}{\alpha} \exp\left(\ln\left((Y/E)^{\mu_\eta+\frac{\sigma_\eta^2}{2}\ln(Y/E)}\right)\right) \\
&= \frac{1-\alpha}{\alpha}\,(Y/E)^{\mu_\eta+\frac{\sigma_\eta^2}{2}\ln(Y/E)}.
\end{aligned} \tag{A.15}$$

A.2 Proof of Proposition 2

1. Differentiating mean marginal WTP (Eq. (4)) with respect to μ_η yields

$$\frac{\partial \overline{\omega}}{\partial \mu_\eta} = \ln(Y/E)\frac{1-\alpha}{\alpha}\,(Y/E)^{\mu_\eta + \frac{\sigma_\eta^2}{2}\ln(Y/E)} \overset{(4)}{=} \ln(Y)\,\overline{\omega}, \tag{A.16}$$

for which the sign is fully determined by $\ln(Y/E)$, since $\alpha \in (0,1)$ and $Y, E > 0$. It thus holds

$$\frac{\partial \overline{\omega}}{\partial \mu_\eta} \gtreqless 0 \iff \ln(Y/E) \gtreqless 0 \iff Y/E \gtreqless 1 \iff Y \gtreqless E. \tag{A.17}$$

2. Rearranging Eq. (4) to $\overline{\omega} = \frac{1-\alpha}{\alpha}(Y/E)^{\mu_\eta}\ \exp\left[\frac{\sigma_\eta}{2}\ln(Y/E)^2\right]$ and taking the derivative with respect to σ_η gives

$$\frac{\partial \overline{\omega}}{\partial \sigma_\eta} = \frac{1-\alpha}{\alpha}(Y/E)^{\mu_\eta}\ \exp\left[\frac{\sigma_\eta}{2}\ln(Y/E)^2\right]\ \frac{\ln(Y/E)^2}{2} \overset{(4)}{=} \frac{\ln(Y/E)^2}{2}\,\overline{\omega}, \tag{A.18}$$

which is non-negative as $Y, E, \overline{\omega} > 0$. $\frac{\partial \overline{\omega}}{\partial \sigma_\eta}$ is zero for the special case of $Y = E$, and strictly positive otherwise.

3. Differentiating Eq. (A.18) with respect to μ_η gives

$$\frac{\partial^2 \overline{\omega}}{\partial \sigma_\eta \partial \mu_\eta} = \frac{\ln(Y/E)^2}{2}\ \frac{\partial \overline{\omega}}{\partial \mu_\eta} \overset{(A.18)}{=} \frac{\ln(Y/E)^3}{2}\,\overline{\omega}, \tag{A.19}$$

for which the sign is determined by $\ln(Y/E)$ since $\overline{\omega} > 0$. It holds:

$$\frac{\partial^2 \overline{\omega}}{\partial \sigma_\eta \partial \mu_\eta} \gtreqless 0 \iff Y \gtreqless E.$$

A.3 Notes on the estimation of heterogeneous elasticities of complementarity

The experimental setting allows an individual to keep a share, π_s, of the overall budget in terms of experimental tokens, m, to oneself and give the other share of the budget to another individual (or to planting trees), π_o. Assuming a standard CES function:

$$U_s(\pi_s, \pi_o) = [\alpha(\pi_s)^\rho + (1-\alpha)(\pi_o)^\rho]^{1/\rho},$$

where ρ is a CES substitutability parameter that maps into the elasticity of complementarity, $\eta = 1 - \rho$, and into the elasticity of substitution, $\theta = 1/(1-\rho)$.

We can maximize utility of the giver, s, by solving:

$$max \quad U_s(\pi_s, \pi_o) \quad w.r.t. \quad p_s * \pi_s + p_o * \pi_o = m \tag{A.20}$$

$$\pi_s + (p_o/p_s)\,\pi_o = m/p_s \tag{A.21}$$

$$\pi_s + p\pi_o = m' \tag{A.22}$$

This yields the following term, which is the starting point of Andreoni and Miller (2002) and Fisman et al. (2007):

$$\pi_s(p, m') = \frac{[\alpha/(1-\alpha)]^{1/(1-\rho)}}{p^{-\rho/(\rho-1)} + [\alpha/(1-\alpha)]^{1/(1-\rho)}} m' \tag{A.23}$$

$$= \frac{A}{p^r + A} m' \tag{A.24}$$

where $r = ((-\rho/(1-\rho))$ and $A = [\alpha/(1-\alpha)]^{(1/(1-\rho)}$.

As the share of tokens allocated to oneself, π_s, is limited between zero and one, one needs to use a two-limit Tobit model. The log-likelihood estimation to identify the two parameters ρ and α draws on the Nelder-Mead Simplex Method.

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