Working Paper in Economics No. 759

Can the environment be an inferior good? A theory with context-dependent substitutability and needs

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Department of Economics, April 2019

ISSN 1403-2473 (Print)
ISSN 1403-2465 (Online)

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Can the environment be an inferior good? A theory with context-dependent substitutability and needs [a]

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April 15, 2019

Abstract

Theoretical models often assume the environment to be a normal good, irrespective of one's income. However, *a priori*, nothing prohibits an environmental good from being normal for some individuals and inferior for others. We develop a conceptual framework in which private consumption and an environmental public good act as substitutes or complements for satisfying different needs. Subsequently, the environment can switch between normal and inferior depending on one's income and environment. If the environment is inferior for some range of income, then the willingness to pay for environmental preservation becomes non-monotonic, thereby having implications for benefit transfers.

Keywords: substitutability, environmental public goods, context, willingness to pay, inferior goods, needs

JEL Classification: D11, H41, Q50

[a]We are particularly grateful to Inge van den Bijgaart and Laurent Faucheux for their valuable discussions and feedback. We are also thankful to Stefan Baumgärtner and Thomas Sterner for their helpful comments on the paper. This paper has also benefited from the comments of an anonymous referee of the FAERE Working Paper series.

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1 Introduction

Is the environment a normal, inferior, or luxury good?[1] This question is crucial to assess the need for environmental protection and the design of prevention policies.

There is extensive debate on how the environment should be categorized. Empirical evidence suggests that the willingness to pay (WTP) for the environment increases with income, characterizing the environment as either a normal good (e.g., Kristrom and Riera, 1996; Horowitz and McConnell, 2003; Jacobsen and Hanley, 2009; Tyllianakis and Skuras, 2016) or a luxury good (e.g., Martini and Tiezzi, 2014; Tyllianakis and Skuras, 2016).[2] When no positive income effect on the WTP is found in an empirical study, concerns are usually raised about the construct validity of the stated preference method (Bishop and Boyle, 2017). However, "how concerned one should be about [the] lack of an income effect in individual studies is a matter of judgment [...] the good being valued could be an inferior good or simply neutral with respect to income" (ibid., p. 480). As the income effect on the WTP varies across income ranges (Ready et al., 2002; Barbier et al., 2017), and most studies have been carried out in developed countries (Drupp, 2018),[3] the possibility that some environmental goods are inferior may have been overlooked. However, a negative income effect emerges in certain evaluation studies.[4] Huhtala (2010) and Vo and Huynh (2017) interpret the negative sign of the income effect they find regarding recycling and groundwater protection programs, respectively, as evidence of the inferiority of the environmental goods they study. When the environment is considered an inferior good, the WTP for environmental protection decreases with a rise in income, thereby leading to a conflict between economic development and environmental preservation.

An assumption of normality is often made, either explicitly or implicitly, in theoretical models on the WTP for environmental goods, through the properties of the utility function.[5] Although some models (e.g., Kotchen, 2005) may assume inferiority instead of normality, the two categories cannot coexist—the environmental good is either normal or inferior. However, it is not necessary *ex ante* that an environmental good "must be normal or inferior in all ranges of income, and cannot switch back and forth. While it may seem improbable that poor people choose clean environments, middle-income people prefer to trade clean environments for other goods, and rich people prefer clean environments, no economic fundamentals would be violated by such a pattern" (Tiezzi and Martini, 2014, p.14). To date, however, such a variation in

[1]Our analysis can be generalized to other public goods.

[2]Following Flores and Carson (1997) and Ebert (2003), the environmental good is considered normal (luxury) if the WTP increases less (more) than proportional to the income. Likewise, an environmental good is considered inferior if the WTP decreases with income.

[3]In their meta-analysis on the WTP for biodiversity, Jacobsen and Hanley (2009) mainly identify studies from developed countries. While 112 studies of their sample have been conducted in Europe, North America, and Australia, only 33 studies have been conducted in developing countries, including Africa, Asia, and South America. The meta-analyses of Schläpfer (2006) and Horowitz and McConnell (2003) mostly refer to studies in developed countries. Kristrom and Riera (1996) find a positive income effect on the WTP based on European datasets.

[4]In their meta-analysis, Horowitz and McConnell (2003, footnote 2) report that about 5 percent of the studies find such an effect in their sample.

[5]For example, a constant elasticity of substitution (CES) utility implies normality, as shown in Appendix A.3.

preferences has not been encompassed within a *single* microeconomic theoretical framework.

In our study, we develop a conceptual framework in which the categorization of environmental goods as luxury, normal, or inferior can vary with the *context*, defined both with respect to income and environmental quality. Our contribution is twofold. First, by allowing the income elasticity of the WTP to vary across both income and environmental quality ranges, we extend the theoretical literature that examines how this elasticity varies in different ranges of income only (e.g., Barbier et al., 2017). Second, our study is the first, to the best of our knowledge, to propose an endogenous categorization of environmental goods in which the income elasticity of the WTP can be negative over some ranges of income and environmental quality, thereby allowing the environment to be an inferior good in certain contexts. This framework offers interesting perspectives when it comes to benefit transfers, the most commonly applied non-market valuation technique (Johnston et al., 2015). The transfer of an estimated WTP for a specific environmental good from one region to another must consider the contingency that the environmental good is categorized differently in the two regions. If the adjustment of the estimated WTP in the former region does not allow for potential inferiority of the good in the latter region, then benefit transfer might be distorted, resulting in incorrect policy recommendations. Given the common practice of benefit transfers that assume an unit income elasticity of the WTP (Barbier et al., 2017; Czajkowski et al., 2017), the WTP would be misestimated if the environment is perceived as an inferior good in the recipient region.

Let us describe our methodology. We consider a consumer problem in which the environment is a public good, and thus, exogenously given. This public good can be local and vary over space, implying that individuals are faced with different contexts in terms of income and environment. We use climate change as an illustrative example. Climate change affects local climates, which are local public goods. For simplicity, we will illustrate our theoretical results assuming that climate change reduces the quality of local climates.[6]

First, we establish that the categorization of environmental goods is intricately linked to Edgeworth-Pareto (E-P) *substitutability*.[7] Inferiority can only prevail if income and environmental quality are substitutes, that is, if the marginal utility of environmental quality decreases with income. This is in line with Vo and Huynh (2017), who claim that the existence of substitutes to groundwater protection programs in Vietnam, such as tap water, reduces consumers' WTP for these programs with an increase of their income. We use this result to show that the

[6]Few locations may not fit this assumption. For example, in extreme northern latitudes, climate change can benefit countries in terms of expanding agriculture and reducing energy expenditure (Arent et al., 2014; Costinot et al., 2016).

[7]There are various definitions of *substitutability* between goods. Refer to Samuelson (1974) for an overview of these definitions. Throughout the study, we use the term *substitutability* with italicized letters when referring to the terminology, thereby encompassing both substitutability and complementarity. We always refer to E-P *substitutability*, unless stated otherwise.

widely used CES utility function[8] and its derivatives imply complementarity (i.e., the marginal utility of environmental quality increases with income), which means that environmental public goods are bound to be normal or luxury goods in such frameworks.

To avoid this limitation, we develop a theoretical framework that allows *substitutability* between income and environmental quality, henceforth *indirect substitutability*,[9] to vary across contexts. This framework is built upon the ideas that *(i)* individuals have different needs or desires, which can be satisfied by combining environmental and private goods, and that *(ii)* the two types of goods may interact differently for satisfying different needs. For example, goods can be complements for the satisfaction of some needs and substitutes for others. Having different interactions between goods for satisfying different needs implies that, depending on how the relative importance of the needs changes across contexts, the *indirect substitutability* can change too. The relationship between income and environmental quality could switch from substitutability to complementarity and vice-versa when the context changes. Subsequently, the categorization of environmental goods as normal, luxury, or inferior may vary over a range of income and environmental qualities.

We can illustrate this framework with an example of the quality of the local climate. The quality of the local climate interacts with private goods for satisfying different needs. For example, in the case of housing, when adaptation solutions are available at a cost, private expenditures and the quality of the local climate act as substitutes for facilitating good living conditions. For other needs, such as recreational activities, the quality of the local climate can act as a complement to private consumption. Depending on their needs, different individuals may value a marginal change in the climate quality differently. When needs depend on the context (income and the local climate), the categorization of the climate as a normal or an inferior environmental public good can change along with the context. Therefore, the WTP for the mitigation of climate change may change non-monotonically with a change in the income.

While considering that the satisfaction of every need partly relies on environmental quality, we distinguish the case in which the overall private consumption contributes to the satisfaction of all needs from the case in which different private goods specifically contribute toward the satisfaction of each need. When private goods are need-specific, a hierarchy of needs can occur, with clear-cut implications in terms of *substitutability*. In both cases, we illustrate our conceptual framework with utility functional forms that exhibit *context-dependent substitutability*. Both negative and positive income effects on the WTP are allowed, depending on the context. For example, for some parameters of the functions, an environmental good is normal for very low levels of income corresponding to the satisfaction of basic needs. The environmental good becomes an inferior good for higher but still relatively low-income levels and, eventually switches back to normality for higher-income levels. A similar pattern occurs over the range of

[8]Refer to Flores and Carson (1997), Ebert (2003) or Baumgärtner et al. (2017a) for applications.

[9]*Indirect substitutability* refers to the *substitutability* between income and environmental quality within the indirect (maximized) utility function, and not to the *substitutability* between goods within the utility function.

environmental quality.

The remainder of the paper is organized as follows. Section 2 identifies the link between the income effect on the WTP and the *substitutability* between income and environmental quality, thereby drawing implications for the categorization of environmental public goods. It also discusses this link in relation to what has been done in the theoretical literature. Section 3 introduces our proposal of context-dependent *substitutability* based on needs. Section 4 discusses the results and implications of our framework. The Appendix gathers the proofs and mathematical details.

2 *Substitutability* and the categorization of environmental goods

We first establish the links between *Substitutability* and the categorization of environmental goods in the standard framework, without referring to needs.

Consider a consumer whose utility U is derived from *(i)* private consumption c and *(ii)* the public environmental quality E. For now, we consider a single consumption good; this assumption will be relaxed in subsection 3.2.

Notations The set of strictly positive real numbers is denoted by $\mathbb{R}_+^* =]0,+\infty)$. Subscripts are used to denote function derivatives, for example, for the utility function we write $U_i \equiv \frac{\partial U}{\partial i}$ and $U_{ij} \equiv \frac{\partial^2 U}{\partial i \partial j}$ for $i,j \in \{c,E\}$.

Assumption 1 *The utility function $U : \mathbb{R}_+^{*2} \longmapsto \mathbb{R}$ is continuous and twice differentiable, strictly increasing, and concave in each of its arguments, i.e., $U_i > 0$ and $U_{ii} \leq 0$ for $i \in \{c,E\}$.*

Most environmental goods are non-market goods, and environmental quality is a public rather than a private good. Essentially, it cannot be chosen by the consumer and is considered exogenous to the problem of utility maximization (Ebert, 2003). The objective of the consumer is to maximize own utility $U(c,E)$ by choosing consumption c, subject to a budget constraint depending on the given price p and income Y and the given environmental quality E. As Y and E are both exogenous to the consumer, we define the context of consumption choices as follows.

Definition 1 (Context) *The context is defined as the endowment of the consumer in terms of both income and environmental quality, that is, $(Y,E) \in \mathbb{R}_+^{*2}$.*

Given context (Y,E) and price p, the following optimization problem defines the indirect (maximized) utility

$$V(Y,E,p) = \max_c \; U(c,E) \quad s.t. \quad pc = Y \text{ and } E \text{ fixed}. \tag{1}$$

Denoting the demand function derived from this problem by $c^*(Y,E,p)$, indirect utility can be expressed as

$$V(Y,E,p) = U(c^*(Y,E,p),E)\,. \tag{2}$$

In the simple case of an aggregate consumption good, whenever $U_c > 0$, we have $c^* = Y/p$ at the optimum, and thus $V(Y,E,p) = U(Y/p,E)$.

When dealing with a public good, one can determine the value attributed to this non-market good by measuring the WTP of an individual for the increased supply of this good. The WTP to improve environmental quality by ΔE is a utility-constant measure defined as the variation in income necessary to compensate for the variation in environmental quality:[10]

$$V(Y,E,p) = V(Y - WTP,\ E + \Delta E, p). \tag{3}$$

Eq. (3) states that a consumer whose preferences are represented by U is indifferent between *(i)* giving up from her budget the amount $WTP(= \Delta Y)$ for improving environmental quality by $\Delta E > 0$ and *(ii)* remaining in the initial situation (i.e., no change in income and no environmental improvement). As the utility function is differentiable, we can establish that the WTP is equal to the marginal rate of substitution between income and environmental quality weighted by the marginal environmental change dE:

$$WTP(Y,E,p) = \frac{V_E}{V_Y} dE\ . \tag{4}$$

This marginal WTP corresponds to the Lindahl price.[11]

2.1 Categorization of environmental public goods

The categorization of an environmental good as normal or inferior depends on the sign of the income effect $\frac{\partial WTP}{\partial Y}$, that is, how the WTP varies with income. This effect is empirically studied through the income elasticity of the WTP,

$$\varepsilon^{WTP} = \frac{\frac{\partial WTP}{WTP}}{\frac{\partial Y}{Y}} = \frac{\partial WTP}{\partial Y} \frac{Y}{WTP}, \tag{5}$$

which has the same sign as the income effect since $Y > 0$ and $WTP > 0$. We categorize environmental goods as inferior, normal, or luxury according to the value of the income elasticity of the WTP (Flores and Carson 1997; Ebert 2003).[12]

[10]We consider the compensating variation as the Hicksian measure of welfare.

[11]Given the level of environmental quality E, the Lindahl price is the WTP for an additional unit or a unitary improvement in environmental quality.

[12]There is a debate about whether the income elasticity of demand or the income elasticity of the WTP for environmental services is the best indicator to categorize an environmental good as normal or luxury. While the former elasticity informs about the categorization of private goods, by definition, we follow Flores and Carson (1997) and Ebert (2003), who consider that the latter provides better information about the categorization of environmental public goods.

Definition 2 (Categorization of environmental goods) *An environmental good is*

- *inferior if the WTP for increasing the environmental good decreases with income ($\varepsilon^{WTP} < 0$);*
- *normal if the WTP for increasing the environmental good increases less than proportional to the income ($0 < \varepsilon^{WTP} < 1$); and*
- *luxury if the WTP for increasing the environmental good increases more than proportional to the income ($\varepsilon^{WTP} > 1$).*

Typically, the empirical literature finds $0 < \varepsilon^{WTP} < 1$ (Kristrom and Riera, 1996; Flores and Carson, 1997; Barton, 2002; Jacobsen and Hanley, 2009; Wang et al., 2013). This means that the environment is a normal good. An income elasticity of the WTP that is greater than 1 refers to environmental goods considered a luxury, as found by Tiezzi and Martini (2014) for air quality and partly by Tyllianakis and Skuras (2016) for the restoration of the good ecological status of water bodies. A negative income elasticity implies the inferiority of the good. While this categorization was underrepresented in the literature a few years ago, and rarely interpreted (e.g., McFadden and Leonard, 1993; McFadden, 1994; Horowitz and McConnell, 2003), empirical evidence on inferiority has recently grown (e.g., Huhtala, 2010; Onanuga, 2017; Vo and Huynh, 2017).

2.2 Categorization of environmental goods and E-P *substitutability*

Let us now focus on the sign of the income effect on the WTP:

$$\frac{\partial WTP}{\partial Y} = \frac{\partial \left(\frac{V_E}{V_Y}\right)}{\partial Y} dE = \frac{V_{YE}V_Y - V_{YY}V_E}{V_Y^2} dE, \tag{6}$$

with $dE > 0$. Our assumptions on the utility function (Assumption 1) imply $V_Y > 0$, $V_E > 0$, and $V_{YY} \leq 0$. The cross-derivative V_{YE} captures how the marginal utility of income changes when environmental quality increases and vice versa. This is the only element in eq. (6) whose sign is not determined by our assumptions.

By deriving eq. (2) with respect to income Y and environmental quality E, we can study the components of the cross-derivative of indirect utility:

$$V_{YE} = c^*_{YE}U_c + c^*_Y \left[c^*_E U_{cc} + U_{cE}\right]. \tag{7}$$

The cross-derivative of the indirect utility is related to the derivatives and cross-derivative of the utility function as well as to the response of the demand function c^* to changes in the context (Y, E). As we consider an environmental public good, E is provided in a fixed quantity for free and does not affect the budget. Consumption is not affected by a change in environmental quality, and we have $c^* = Y/p$, and thus $c^*_Y = 1/p$, $c^*_E = 0$, and $c^*_{YE} = 0$. Therefore, eq. (7) is reduced to $V_{YE} = U_{cE}/p$.[13]

The cross-derivative of a utility function gives information on the *substitutability* between goods according to the Edgeworth-Pareto (E-P) definition (Samuelson, 1974).

Definition 3 (E-P *substitutability*) *The E-P* substitutability *between goods c and E relies on the sign of the cross-partial derivative of the utility function as follows:*

$$\begin{aligned} U_{cE} &< 0 \quad \textit{c and E are substitutable;} \\ U_{cE} &> 0 \quad \textit{c and E are complementary;} \\ U_{cE} &= 0 \quad \textit{c and E are independent.} \end{aligned}$$

Goods are considered substitutes (complements) if environmental quality decreases (increases) the marginal utility of consumption. The *substitutability* between goods is inherent to consumer preferences and depends on the characteristics of the utility function. By extension, *substitutability* between income and the environment can be defined with respect to the indirect (maximized) utility as follows.

Definition 4 (Indirect *substitutability*) *The* substitutability *between income Y and environmental quality E relies on the sign of the cross-partial derivative V_{YE} of indirect utility. The income and environmental quality are substitutable when $V_{YE} < 0$, independent when $V_{YE} = 0$, and complementary when $V_{YE} > 0$.*

Thus, the sign of the cross-derivative V_{YE} of indirect utility exclusively depends on the sign of the cross-derivative U_{cE} of the utility function, leading to Proposition 1.

Proposition 1 (Indirect *substitutability* with a public good) *Whenever the environment is a public good, and there is a single consumption good, the income and environmental quality are complements (substitutes) if and only if consumption and environmental quality are complements (substitutes). Formally,*

$$\forall\, Y, E > 0 \begin{cases} V_{YE} > 0 \Leftrightarrow U_{cE}(c^*, E) > 0 \\ V_{YE} < 0 \Leftrightarrow U_{cE}(c^*, E) < 0 \\ V_{YE} = 0 \Leftrightarrow U_{cE}(c^*, E) = 0. \end{cases}$$

Therefore, indirect *substitutability* only relies on the *substitutability* between goods when environmental quality is a public good.[14]

[13] Eq. (7) makes it possible to study the more general case in which an environmental change affects the overall consumption. This could be the case when the environment affects income (e.g., through labor productivity), consumption good price (e.g., through production costs), or is framed as an environmental market-like good (e.g., through taxation or fees). In Appendix A.1, we study the interplay between indirect and between-good *substitutabilities*, as described in eq. (7), when the elasticities are not nil.

[14] We relax the assumption of a single consumption good in section 3.2, which results in a link between indirect *substitutability* and the *substitutability* between goods that is more subtle.

Now, we can discuss the link between the income effect on the WTP and indirect *substitutability*, and thus between the categorization of public goods and indirect *substitutability*. From eq. (6), as $V_Y > 0$, $V_E > 0$, and $V_{YY} \leq 0$, a positive income effect on the WTP would occur either if income and environmental quality are substitutes or complements, whereas a negative income effect on the WTP would occur only if income and environmental quality are substitutes. This result is formalized in Proposition 2 (proof in Appendix A.2).

Proposition 2 (Inferior public goods and indirect *substitutability*) *A necessary condition for a negative income effect on the WTP, that is, for an environmental public good to be inferior, is that income and environmental quality are substitutes. This condition is necessary and sufficient if marginal utility of income is constant.*

Tab. I summarizes the three possible cases and single impossible case emerging from Proposition 2.

Table I: Link between indirect *substitutability* and income effects

	Positive income effect (normality/luxury)	Negative income effect (inferiority)
Indirect substitutability	**Case (1): possible**	**Case (2):possible**
Indirect complementarity	**Case (3): possible**	Case (4): not possible

While indirect complementarity imposes positive income effect on the WTP, indirect substitutability can lead to both negative and positive income effects. When would a negative effect occur? When would an environmental public good be inferior? According to eq. (6), it occurs when $\frac{V_{EY}}{V_E} < \frac{V_{YY}}{V_Y} \leq 0$, that is, when an additional unit of income reduces relatively more the marginal utility of the environment than the marginal utility of income. In this case, one values an environmental improvement less, which leads to a negative income effect (Case **(2)**). For example, if private consumption and the quality of the local climate are substitutable enough (i.e., if V_{EY} is sufficiently negative), then an increase in income may reduce the WTP to mitigate climate change. Conversely, if an additional unit of income decreases one's marginal utility of income relatively more than it decreases the marginal utility of the environment (formally, when $\frac{V_{YY}}{V_Y} < \frac{V_{EY}}{V_E} \leq 0$), then one would value income less when compared to an improvement in environmental quality, leading to a positive income effect (Case **(1)**). The same effect occurs in the complementarity case (Case **(3)**) in which an additional unit of income increases the marginal utility of the environment (with $\frac{V_{YY}}{V_Y} \leq 0 < \frac{V_{EY}}{V_E}$). In that case, the environment is never an inferior good.

The empirical literature on demand analysis has long acknowledged the possibility that the category of a good may change with income (Lewbel and Houthakker, 2017). Likewise, with the WTP issues, Tiezzi and Martini (2014) argue that environmental goods should not be restricted to one category across all income ranges. The theoretical models studying environmental goods do not allow the categorization of the environment to vary with the context. The most commonly used utility functions, such as the CES function (Flores and Carson, 1997; Ebert, 2003; Baumgärtner et al., 2017a), even imply indirect complementarity and thus normality (Case **(3)** in Tab. I only).[15] To the best of our knowledge, there is no theoretical framework that makes it possible for an environmental good to switch among Cases **(1)**, **(2)**, and **(3)** in Tab. I with the change in context.

We propose a theoretical framework that is flexible enough to allow for the categorization of public goods to vary across the context (i.e., with the income and environmental quality), and even to cover the case discussed in the introduction in which a good would switch from normal to inferior and to normal again when income increases.

3 Context-dependent *substitutability* and needs

We consider that utility is derived from the satisfaction of different needs, or wants (Maslow, 1943).[16]

The satisfaction of every need is partially dependent on environmental quality; However, the way the environment interacts with private goods for the satisfaction of needs may differ. We show that if the environment is a substitute for private goods for the satisfaction of some needs and a complement for the satisfaction of other needs, then the categorization of an environmental public good can vary across the context. The environment may be an inferior good for some income and environmental quality levels, while it will be a normal good in other contexts.

We distinguish the case in which the overall private consumption contributes to the satisfaction of all needs (subsection 3.1) from the case in which different private goods specifically contribute to the satisfaction of different needs (subsection 3.2). The single-good case allows us to link our framework to the literature and emphasize our contribution. From an empirical perspective, this case is also relevant when considering aggregate income or consumption data,

[15] We provide an analysis of several utility functional forms in Appendix A.3. Extended CES utility functions, such as those with a subsistence requirement (Baumgärtner et al., 2017b), are also analyzed.

[16] This approach echoes some of the classical aspects of both empirical and theoretical analyses of consumer choices. In Engel's work, expenditures for private goods are classified according to the wants they serve, and the idea of a hierarchy in these wants is used to interpret the observed consumption patterns; however, without using a theoretical model (Chai and Moneta, 2010). Engel's curves are key to describing consumption patterns and categorizing inferior goods. According to Chai and Moneta (2010), "the desirability of developing a theoretical explanation for the shape of Engel curves based on a rich behavioral foundation has been duly noted in the literature, but this issue has not been properly investigated since Engel's time." Our analysis provides a basis to establish a theoretical framework to study preferences for public goods based on need satisfaction. In the consumer theory of Lancaster (1966), utility is not derived from goods directly, but from their characteristics through different activities combining the goods in different ways. Lipsey and Rosenbluth (1971) show that even if all characteristics are valuable, a good may be inferior if it shares sufficient characteristics with a "superior" good. A similar pattern occurs in our framework for environmental goods if activities are interpreted as actions aimed at satisfying needs.

that is, when no information on good-specific expenditures is available. The case of need-specific consumption goods is more realistic but requires richer data on expenditures and their purpose.

3.1 Need satisfaction with a single consumption good and the environment

We assume that the consumer derives utility from consumption and environmental quality through the satisfaction of two needs, A and B. For the sake of simplicity, we consider only two needs, but the framework can be extended to accomodate more than two needs. The satisfaction of both the needs depends on the consumption of a private aggregate good c as well as on environmental quality E. We start by considering a single (aggregate) consumption good to match the literature and conceptual framework described in the previous section and Appendix A.3 but relax this assumption in the next subsection.

Within Need A and Need B, the interaction between consumption c and environmental quality E can be different. For instance, private and environmental goods can be complements for the satisfaction of Need A, while they would act as substitutes for the satisfaction of Need B. Need satisfaction is represented by specific functions $A(c,E)$ and $B(c,E)$, encompassing the interaction between goods for each need. We assume these functions to be increasing and concave in each of their arguments, i.e, $A_c > 0$, $B_c > 0$, $A_E > 0$, $B_E > 0$, $A_{cc} \leq 0$, $B_{cc} \leq 0$, $A_{EE} \leq 0$, and $B_{EE} \leq 0$. For the sake of simplicity, we assume there are no interactions between the needs, and that need satisfaction is measured in the same unit as utility. Utility can thus be expressed as $U(c,E) = A(c,E) + B(c,E)$. This specification provides clearer results.

For an environmental public good, the indirect utility function (eq. 2) is given by $V(Y,E,p) = U(Y/p,E) = A(Y/p,E) + B(Y/p,E)$. The associated indirect *substitutability* is given by

$$V_{YE} = \frac{1}{p}U_{cE} = \frac{1}{p}\left(A_{cE}(Y/p,E) + B_{cE}(Y/p,E)\right). \tag{8}$$

Thus, indirect *substitutability* depends on the between-good *substitutability* for satisfying both the needs. If the environment and the private good interact in a different way for satisfying the two needs and the magnitude of the two effects varies across the context, then the sign of V_{YE} may differ from one context to another, thereby making indirect *substitutability* context-dependent. We can illustrate this idea with our example on the quality of the local climate. Consider one basic need (e.g., housing) and an ancillary need (e.g., recreational activities). On the one hand, the quality of the local climate and private consumption can reasonably be perceived as substitutes to satisfy the basic need—higher total expenditures, associated with better housing, enable individuals to adapt to climate change, acting as a substitute for a good local climate. On the other hand, the quality of the local climate and private consumption can be complements for recreational activities. For example, both a good local climate and suitable outdoor equipment are necessary for enjoying outdoor activities. While increasing the overall consumption reduces the marginal utility of the quality of the local climate for satisfying the need for housing, it can increase this marginal utility through higher-order needs. Depending on the context (high or low income; high or low local climate quality), an increase in the quality of the local climate through climate change mitigation can be perceived as a complement or a substitute to income, depending on the prevalent need. Overall, in this example, low income individuals would rather perceive the local climate and income as substitutes, resulting in either normality or inferiority of the local climate (Cases (1) or (2) in Tab. I). Conversely, high income individuals would experience complementarity between income and the local climate, resulting in normality of the local climate (Case (3) in Tab. I).

To illustrate such a pattern, we provide an example of utility function with context-dependent *substitutability* (CDS).

An example of a utility function with CDS Consider a utility function with the following putative form.[17] For any $(c,E) \in \mathbb{R}_{+}^{*2}$,

$$U(c,E) = c^{\gamma}E^{\omega} - \frac{\theta}{c^{\alpha}E^{\beta}} \,, \tag{9}$$

where $\theta > 0$ and $0 < \gamma, \omega, \alpha, \beta < 1$ are given parameters. For simplicity, we call it the CDS utility function.

This function would correspond to the need-satisfaction functions $A(c,E) = c^{\gamma}E^{\omega}$ and $B(c,E) = -\frac{\theta}{c^{\alpha}E^{\beta}}$. We have $A_{cE} = \gamma\omega c^{\gamma-1}E^{\omega-1} > 0$, meaning that the private good complements the environmental quality in satisfying Need A, whereas $B_{cE} = -\theta\alpha\beta c^{-\alpha-1}E^{-\beta-1} < 0$, meaning that the private good acts as a substitute for environmental quality in satisfying Need B.

Fig. 1 shows the indifference curves associated with the CDS utility function for a specific combination of parameter values. The properties of function U are consistent with preferences satisfying completeness, continuity, transitivity, and non-satiation. The preferences represented by U are not homothetic. The cross-partial derivative of the CDS utility function is

$$U_{cE} = A_{cE} + B_{cE} = \gamma\omega c^{\gamma-1}E^{\omega-1} - \theta\alpha\beta c^{-\alpha-1}E^{-\beta-1} \,. \tag{10}$$

As the first term in the sum is positive and the second term is negative, its sign depends on the context, that is, on environmental quality and income levels. This allows us to derive the indirect *substitutability*, which, for demand $c^{*}(Y,E,p) = Y/p$, depends on the context (values

[17]Other possible functions are $U(c,E) = c^{\gamma}E^{\omega} + \theta\ln(c^{\alpha} + E^{\beta})$ and $U(c,E) = cE - e^{\theta-c-E}$.

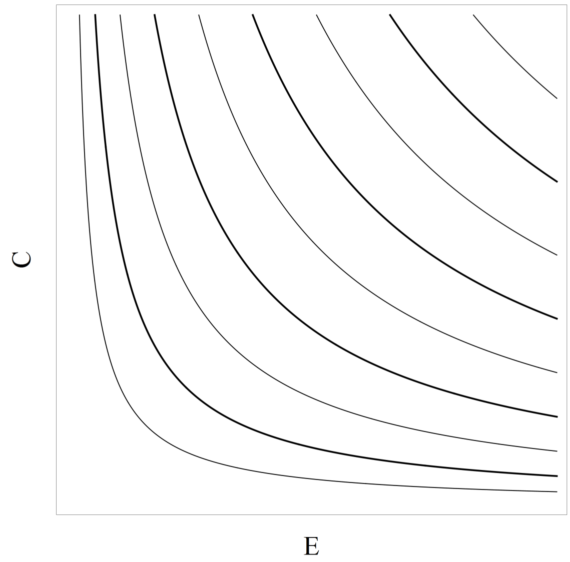

Figure 1: Indifference curves of the CDS utility function ($\alpha = \beta = \gamma = \omega = 0.5$ and $\theta = 100$)

of Y and E) as follows,

$$\begin{cases} V_{YE} < 0 \;\Leftrightarrow\; Y < K/E^{\frac{\omega+\beta}{\gamma+\alpha}} \\ V_{YE} = 0 \;\Leftrightarrow\; Y = K/E^{\frac{\omega+\beta}{\gamma+\alpha}} \\ V_{YE} > 0 \;\Leftrightarrow\; Y > K/E^{\frac{\omega+\beta}{\gamma+\alpha}} \end{cases}$$

where $K = p\left(\theta \frac{\alpha}{\gamma}\frac{\beta}{\omega}\right)^{\frac{1}{\gamma+\alpha}}$ is a constant.

Fig. 2 illustrates the indirect *substitutability* of the CDS utility function. For relatively

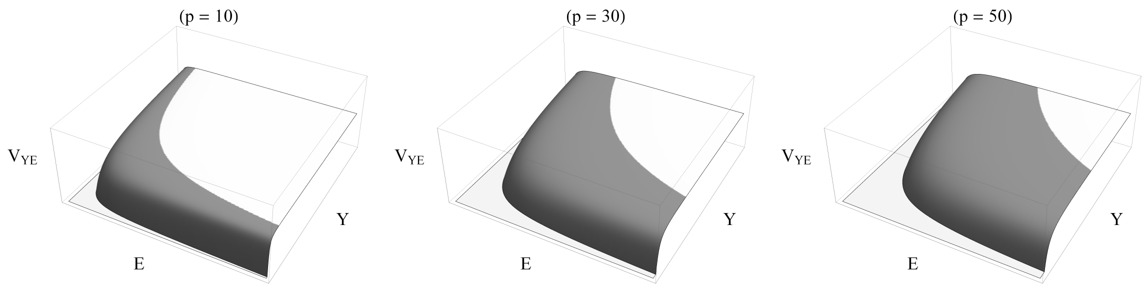

Figure 2: *Substitutability* for a CDS utility function with parameters $\alpha = \beta = \gamma = \omega = 0.5$ and $\theta = 100$, for different prices p. Y and E are substitutes in the gray area and complements in the white area.

low values of environmental quality and/or income levels, income and environmental quality are substitutable (the gray area). For higher values, income and environmental quality are complementary (the white area). This pattern is particular to the CDS utility function. We do not claim that this should be universal. The frontier between the areas covering substitutability and complementarity depends on the price p of the private good. As p increases, the purchasing power decreases, which increases the size of the domain wherein income and the environment substitute one for the other in the provision of utility.

CDS preferences exhibiting inferiority of the environment We derive the conditions under which a negative income elasticity of the WTP is possible with the CDS specification, in line with Proposition 2.

Proposition 3 (Negative income elasticity of the WTP under CDS preferences) *If* $\frac{\alpha\omega}{\beta\gamma} < \frac{(\gamma+\alpha-1)^2}{(\gamma+\alpha+1)^2}$*, then there will be contexts in which the income elasticity of the WTP will be negative (i.e.,* $\varepsilon^{WTP} < 0$*).*

The proof of Proposition 3 is in Appendix A.4. This condition is satisfied for the following set of parameters (among others): $\alpha = \beta = \gamma = 0.99$ and $\omega = 0.01$; in the case of these parameters, the range of contexts for which the environment is an inferior good is large. Fig. 3 illustrates this case.

The black curves with black labels in Fig. 3 indicate the levels of income elasticity. The light green area illustrates the contexts for which the environment is an inferior good (negative income elasticity of the WTP). The two dark green areas indicate contexts for which the environment is a normal good (positive income elasticity of the WTP). The white curve indicates the frontier between the substitutability and complementarity domains (i.e., $V(Y,E) > 0$ above the curve and $V(Y,E) < 0$ below it). The income elasticity of the WTP can be negative only when income and environmental quality are substitutes (Proposition 2). Thus, the CDS utility function allows for a categorization of environmental goods that depends on the context.[18]

Heterogeneity of contexts In the case of the parameters of the CDS utility function used in Fig. 3, different preferences toward the environment (WTP) coexist. We can interpret this heterogeneity with our climate change example. Consider different regions that differ in terms of the quality of the local climate and/or income, that is, different contexts. For simplicity, we consider that the contexts denoted by **(1)** and **(2)** have a similar, lower local-climate quality and differ only with respect to their income. Contexts **(3)**, **(4)**, and **(5)** share a similar, higher local-climate quality and also differ only with respect to their income.

In the higher local-climate quality case, for individuals with an extremely low-income level, as in context **(3)**, the satisfaction of basic needs heavily relies on the climate quality, and the environment is a normal good. An individual living in a house built with brittle materials may be willing to pay more to mitigate climate change as the individual experiences a rise in income (in this case, the climate is a normal good) rather than relying on a rise in expenditures, such as

[18] With the CES or extended CES utility function, the whole graph would be dark green. The income and environmental quality would be complements in all contexts, and the environmental good would be a normal good.

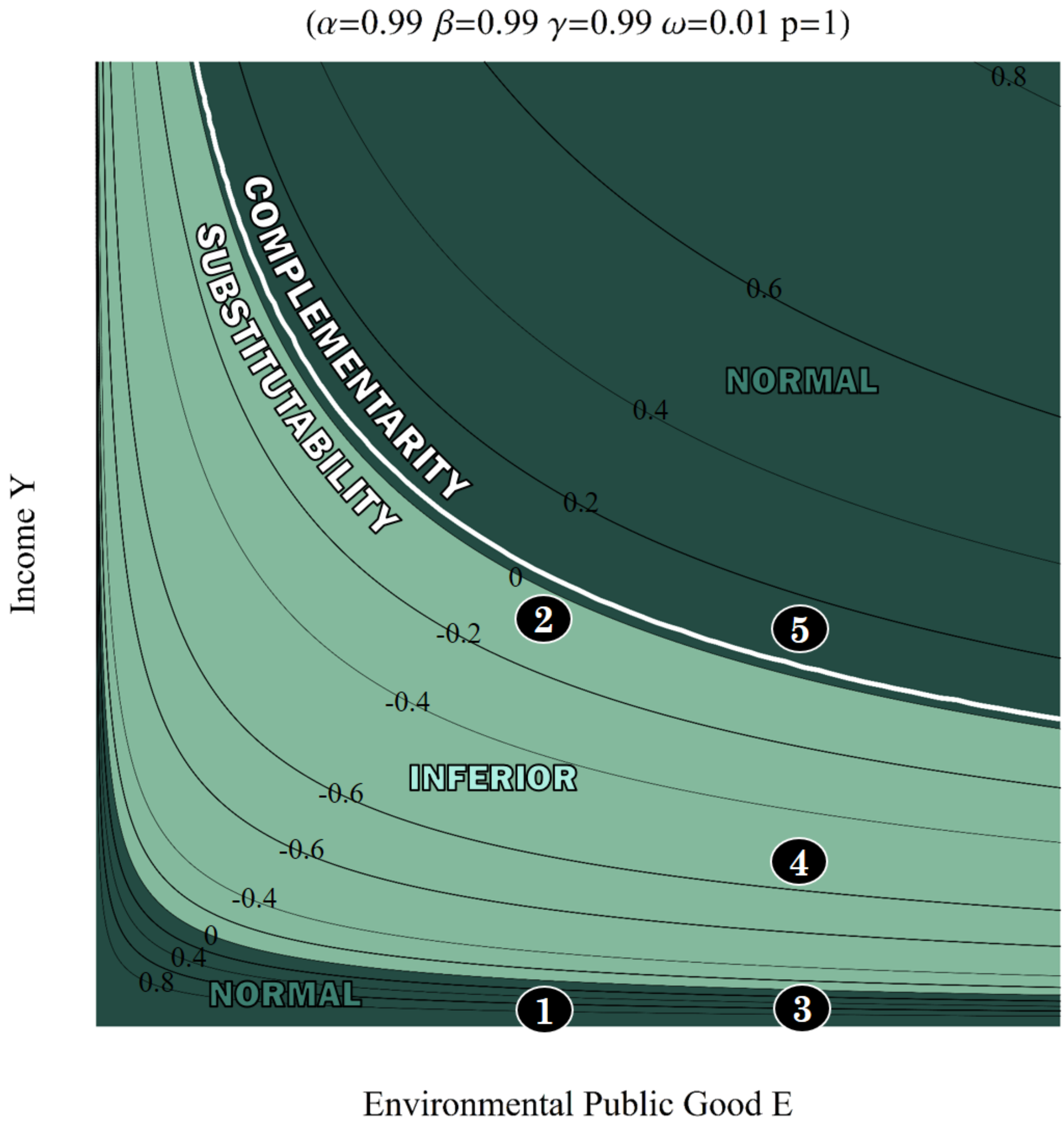

Figure 3: Income elasticity of the WTP under CDS preferences

superior quality building materials that provide an adaptation to climate change.[19] In context **(4)**, with a similar local-climate quality, but a higher income, private consumption may cover most of the basic needs, and an individual will have a low dependence on the environmental substitute. As income increases, the individual would exhibit a low WTP for the environment, and the WTP for climate-change mitigation will decrease. The environmental good is inferior. This could apply to an individual living in a strong house who may be willing to contribute less to the climate-change mitigation as income rises because higher private expenditures provide an adaptation to climate change. In context **(5)**, corresponding to a high income, ancillary needs

[19] It may seem unrealistic that very low-income individuals would be willing to pay (monetarily) for climate change mitigation. However, in tribal economies, the extremely low income of native people and their high willingness to protect the environment (see UN Environment Article) leads to a consideration of the WTP beyond its proper *monetary* definition. The non-monetary WTP can take various forms, such as spending time protecting the environment or engaging in benevolent communication in favor of environmental protection .

may prevail and income may act as a complement to the environment. Recreational activities or self-fulfillment may require a good local climate and income. As higher income allows for more private consumption of, say, outdoor equipment, the WTP for the climate-change mitigation increases as income increases (normal good).

The magnitude of the income bracket for which there is a negative income effect on the WTP varies with environmental quality. In Fig. 3, in regions characterized by lower environmental quality (contexts **(1)** and **(2)**), inferiority of the environment occurs for a larger range of income levels than in regions that have a better environmental quality (contexts **(3)**, **(4)**, and **(5)**). The lower the environmental quality, the larger will be the income bracket for which there is a negative income effect on the WTP. As environmental quality worsens, richer individuals are more likely to exhibit a negative income effect. With such preferences, countries with poor environmental conditions may enter a vicious circle, when the environmental degradation resulting from growth and increasing income induces an overall diminishing WTP for environmental preservation. Certainly, these interpretations are specific to some parameters of the CDS utility functional form. Altogether, such a utility function could represent situations in which a negative income effect on the WTP would occur more in low-income countries, and would have a higher likelihood of occurrence when environmental quality is low.

Benefit transfers Our results indicate that the benefit transfer method should be used with caution. When there are contexts in which the environment is an inferior good, applying a unit constant income elasticity to transfer environmental benefits, a widespread practice (Barbier et al., 2017; Czajkowski et al., 2017), can lead to misestimation.

When the environment is an inferior good for some range of income, the WTP is non-monotonic and decreases for that range. Fig. 4 and 5 represent the marginal environmental WTP as a function of income for the two levels of environmental quality discussed previously.[20] On both figures, the pattern is similar. The WTP first increases with income, then decreases, and, finally, rises again as income increases.

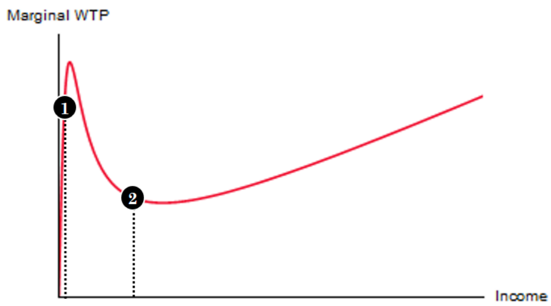

Figure 4: Marginal WTP as a function of income - Lower environmental quality

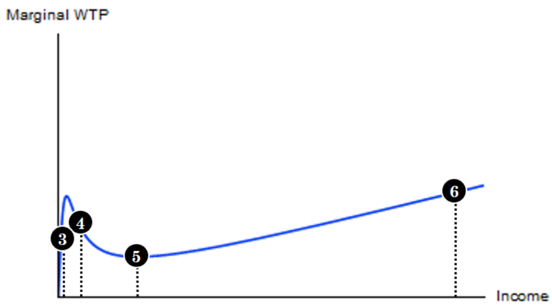

Figure 5: Marginal WTP as a function of income - Higher environmental quality

[20]The axes in Fig. 4 and 5 have the same scale and ensure that the marginal WTP can directly be compared across the two figures. Compared to Fig. 3, we extended the range of income to discuss further interesting cases.

Consider benefit transfers among different contexts tagged in Fig. 3.[21] Applying a unit income elasticity, with the underlying assumption of normality, would lead to estimating a higher WTP in richer contexts and a lower WTP in poorer contexts when compared to the reference site. For example, the WTP in context **(2)** would be estimated higher than in the poorer context **(1)**, whereas Fig. 4 illustrates that this is not the case for CDS preferences exhibiting inferiority across a range of income. A similar misestimation occurs between contexts **(4)** and **(5)** in Fig. 5. This is due to the fact that, within a range of income wherein the environment is perceived as an inferior good, poorer individuals value the environment more than richer individuals do.

Such a misestimation would occur mainly when the two sites are characterized by contexts positioned on different sides of an income-effect border (light green/dark green in Fig. 3), even when the study sites are relatively similar in terms of income and environmental quality, one of the ideal criteria for the use of benefit transfers (Richardson et al., 2015). When the difference in income of the two sites is large and covers mainly incomes for which the environment is a normal good, a standard benefit transfer may not lead to an incorrect income effect but would still result in an error of the magnitude of the effect. This is illustrated by the overall positive income effect between context **(4)** and the richer context **(6)** in Fig. 5.

Therefore, with non-monotonic WTP profiles, using the common practices of benefit transfer could result in a misestimation of the WTP, either in the direction or the magnitude. In certain cases, the direction may be right, and the magnitude distorted (e.g., between contexts **(4)** and **(6)**). In other cases, both the direction and magnitude may be distorted (e.g., between contexts **(1)** and **(2)**). The misestimation may be even stronger if the two regions are different in both income and environmental quality (e.g., between contexts **(1)** and **(5)**).

Using a context-dependent income elasticity of the WTP would make it possible to account for the possibility that the environment is an inferior good in certain contexts, and help policymakers prevent such transfer errors.

3.2 Need satisfaction with need-specific consumption goods and the environment

Assuming a single aggregate consumption good as in subsection 3.1 amounts to assuming that the consumer will purchase the same bundle of commodities, irrespective of the given income or environmental quality levels. If the interplay between private goods and the environment depends on the context, then the type of goods purchased will also depend on the context. In fact, if goods are purchased to satisfy different needs that have relative importance, then income would more likely be devoted to the purchase of goods that contribute to the satisfaction of the currently more urgent need. From this viewpoint, the assumption of a single composite consumption good is restrictive.

In this section, we relax this assumption and consider the case in which different private

[21] Context **(6)** in Fig. 5 is not in the range of income depicted in Fig. 3.

goods contribute to various needs differently. For simplicity, we consider two private goods, each contributing to the satisfaction of one (and only one) of the needs. This is a simplified case in which each private good has a single characteristic, as discussed in Lancaster (1966, p. 136–137).[22] The environment, however, is assumed to have two characteristics and contribute to both the needs.

The private consumption associated with Need A is denoted by $c_A \in \mathbb{R}^+$, and the private consumption associated with Need B is denoted by $c_B \in \mathbb{R}^+$. The corresponding prices, denoted by p_A and p_B, are given, finite, and positive (i.e., $0 < p_A < \infty$ and $0 < p_B < \infty$). Environmental quality E contributes to the satisfaction of the two needs, possibly, in different ways.

The need-satisfaction functions are, respectively, denoted by $A(c_A, E)$ and $B(c_B, E)$ and are assumed to be continuous and twice differentiable. We assume that the need-satisfaction functions satisfy the following assumptions: $A_{c_A} > 0$, $A_{c_A c_A} \leq 0$, $A_E > 0$, $A_{EE} \leq 0$, $B_{c_B} > 0$, $B_{c_B c_B} < 0$, $B_E > 0$, $B_{EE} \leq 0$.

Utility is denoted by $U(c_A, c_B, E)$. For the sake of simplicity, we assume the separability of needs and that need satisfaction is measured in the same unit as utility. This ensures that $U(c_A, c_B, E) = A(c_A, E) + B(c_B, E)$. Given the properties of A and B, the utility function $U(c_A, c_B, E)$ has the following properties:

- $U_{c_A}(c_A, c_B, E) > 0$ and $U_{c_A c_A}(c_A, c_B, E) \leq 0$;
- $U_{c_B}(c_A, c_B, E) > 0$ and $U_{c_B c_B}(c_A, c_B, E) < 0$;
- $U_E(c_A, c_B, E) > 0$; $U_{EE}(c_A, c_B, E) \leq 0$.

Our framework aims to capture consumer decisions in a given context. The objective of the consumer is to maximize own utility, which depends on the satisfaction of the two needs, by choosing the optimal consumption levels c_A and c_B, given the budget Y, prices p_A and p_B, and environmental quality E.

$$V(Y, E, p_A, p_B) = \max_{c_A, c_B} U(c_A, c_B, E) \quad (11)$$
$$s.t \begin{cases} p_A c_A + p_B c_B \leq Y , \\ c_A, c_B \geq 0 , \\ \text{given } Y, E, p_A, p_B . \end{cases}$$

V is the indirect utility function, namely the optimal level of utility obtained in a context (Y, E) and given prices (p_A, p_B).

[22] The specific goods can be thought of aggregate goods for each need, for example, a composite food basket, on the one hand, and the rest of the economic goods, on the other hand, if one considers the first need to be food consumption, as opposed to another ancillary need. The problem could also be set in terms of need-specific expenditure by suppressing prices.

Denoting the demand functions for the two private goods (which are implicitly defined by the optimization problem (11)) by $c_A^*(Y,E,p_A,p_B)$ and $c_B^*(Y,E,p_A,p_B)$, the indirect utility can be written as

$$V(Y,E,p_A,p_B) = A(c_A^*(Y,E,p_A,p_B),E) + B(c_B^*(Y,E,p_A,p_B),E)\ . \tag{12}$$

The cross-partial derivative of this expression gives us indirect *substitutability*:

$$V_{YE} = \left(A_{c_A c_A}\frac{\partial c_A^*}{\partial E} + A_{c_A E}\right)\frac{\partial c_A^*}{\partial Y} + A_{c_A}\frac{\partial c_A^{*2}}{\partial Y \partial E} + \left(B_{c_B c_B}\frac{\partial c_B^*}{\partial E} + B_{c_B E}\right)\frac{\partial c_B^*}{\partial Y} + B_{c_B}\frac{\partial c_B^{*2}}{\partial Y \partial E}. \tag{13}$$

This expression depends on the *substitutability* between private goods and the environment for both need satisfactions (i.e., $A_{c_A E}$ and $B_{c_B E}$), in interaction with the response of demands to changes in the context, particularly, with income Y. The term $\frac{\partial c_A^*}{\partial Y}$ (resp. $\frac{\partial c_B^*}{\partial Y}$) is proportional to the share of marginal income allocated to the satisfaction of Need A (resp. B), with the condition that marginal income is fully used, that is, $p_A \frac{\partial c_A^*}{\partial Y} + p_B \frac{\partial c_B^*}{\partial Y} = 1$ (from the budget constraint). If marginal income is mainly allocated to the satisfaction of one of the needs, then the *substitutability* of the associated private good with the environment for the satisfaction of that need would influence indirect *substitutability* more than the *substitutability* of the other private good with the environment for the satisfaction of the other need. The extreme case in which marginal income is allocated to a single good (e.g., $\frac{\partial c_B^*}{\partial Y} = 1/p_B$ and $\frac{\partial c_A^*}{\partial Y} = 0$) provides an intuitive discussion of eq. (13) and makes it possible to establish a direct link between indirect *substitutability* and between-good *substitutability* for that need. Such behavior prevails when there is a (partial) need hierarchy, a particular case we examine now.

A case with need hierarchy Consider a hierarchical behavior in the satisfaction of needs, with Need B being of primary importance with respect to Need A. This would be the case if Need B corresponds to *basic* needs and Need A to *ancillary* needs. A hierarchy of needs is often related to quasi-lexicographic preferences in the literature, as presented in the transposition of Maslow's theory of motivation in a utility maximization framework (e.g., Seeley, 1992). However, imposing such restrictions on the optimization problem is unnecessary. Appendix B provides simple properties that utility can satisfy and that induce (endogenous) hierarchical behavior. A hierarchy simply emerges as a corner solution of a utility maximization problem when the utility function satisfies such properties. This allows us to avoid imposing *exogenous* thresholds for satiation (or for behavioral change, as in Baumgärtner et al., 2017b). Appendix B describes the way the *endogenous* thresholds for behavioral changes are derived in our framework. We refer to such thresholds below.

Let us describe a stylized hierarchical behavior in our framework. For some range of (low) income, the marginal income is exclusively allocated to the satisfaction of the basic need B.

For a higher range of income, marginal income is allocated to the satisfaction of both the needs. For the remaining range of income, marginal income is exclusively allocated to the satisfaction of the ancillary need A. The threshold below which marginal income is only allocated to Need B, with $c_B^* = \frac{Y}{p_B}$ and $c_A^* = 0$, is denoted by $\underline{Y}(E, p_A, p_B)$. The threshold above which additional income is only allocated to Need A, with $c_B^* = \bar{c}_B$ and $c_A^* = \frac{Y - \bar{c}_B p_B}{p_A}$, where $\bar{c}_B$ is the maximum private consumption devoted to the satisfaction of Need B, is denoted by $\overline{Y}(E, p_A, p_B) \geq \underline{Y}(E, p_A, p_B)$. Subsequently, the indirect utility function can be written as follows (dropping the arguments of the endogenous thresholds $\underline{Y}$ and $\overline{Y}$):

$$V(Y,E,p_A,p_B) = \begin{cases} U(0,\frac{Y}{p_B},E) = B(\frac{Y}{p_B},E) & \text{if } Y \leq \underline{Y} \\ \\ U(c_A^*(Y,E,p_A,p_B), c_B^*(Y,E,p_A,p_B), E) & \text{if } \underline{Y} < Y \leq \overline{Y} \\ \\ U(\frac{Y-\bar{c}_B p_B}{p_A}, \bar{c}_B, E) = A(\frac{Y-\bar{c}_B p_B}{p_A}, E) + B(\bar{c}_B, E) & \text{if } \overline{Y} < Y \end{cases}$$

This leads to the following result for indirect *substitutability*[23]

$$V_{YE} = \begin{cases} \frac{B_{c_B E}}{p_B} & \text{if } Y < \underline{Y} \\ \\ \text{Eq.(13)} & \text{if } \underline{Y} < Y < \overline{Y} \\ \\ \frac{A_{c_A E}}{p_A} & \text{if } \overline{Y} < Y \end{cases}$$

In this case of (partial) hierarchy, indirect *substitutability* in the two extreme cases, which correspond to the allocation of marginal income for purchasing a single good, relies on the *substitutability* between goods for the satisfaction of the relevant need only. Consequently, in a given environmental context E, two individuals with different income levels Y may exhibit different preferences for the environment because they allocate marginal income to the satisfaction of different needs.

The thresholds $\underline{\text{Y}}$ and $\overline{Y}$ depend on environmental quality E (and on prices p_A and p_B). Essentially, the income threshold at which behavior changes varies with a change in environmental quality. We discuss this effect with an example.[24]

An example of a utility function with need hierarchy and CDS for two goods To illustrate the previous results, we provide an example of a utility function based on the two needs, for

[23]The derivatives at the threshold levels $\underline{\text{Y}}$ and $\overline{Y}$ may not be well-defined. We discuss these cases in Appendix B.1.

[24]Proposition 5 in Appendix B provides a general result on the links between such thresholds and on the *substitutability* between private goods and the environment for the satisfaction of both the needs.

which there is a hierarchy with a *prevalence*[25] of the basic need B for low-income levels and a *strong non-satiety*[26] of the ancillary need A.

For any $(c_A, c_B, E) \in \mathbb{R}_+^{*3}$, consider the utility function

$$U(c_A, c_B, E) = c_A E^{\omega} - \frac{\theta}{c_B^{\alpha} E^{\beta}} \tag{14}$$

with $0 < \omega, \alpha, \beta < 1$, and $\theta > 0$.

Here, Need A is such that, for any $(c_A, E) \in \mathbb{R}_+^{*2}$, $A(c_A, E) = c_A E^{\omega}$, and Need B is such that, for any $(c_B, E) \in \mathbb{R}_+^{*2}$, $B(c_B, E) = -\frac{\theta}{c_B^{\alpha} E^{\beta}}$. The cross-derivatives of the need-satisfaction functions are $A_{c_A E} = \omega E^{\omega-1} > 0$ and $B_{c_B E} = -\theta\alpha\beta c_B^{-\alpha-1} E^{-\beta-1} < 0$. Therefore, in this example, there is complementarity between goods for the satisfaction of Need A and substitutability between goods for the satisfaction of Need B.

For a given environmental quality E, the marginal utility derived from the consumption of good c_A is constant and equal to E^{ω}. Regarding Need B, the marginal utility derived from the consumption of good c_B is $B_{c_B} = \frac{\alpha\theta}{c_B^{\alpha+1} E^{\beta}}$, which varies continuously and monotonically from $+\infty$ when the consumption of c_B is nil to 0 when the consumption is infinite. Hence, there is a consumption threshold $\hat{c}_B$ under which marginal income has a higher marginal utility when it is allocated to Need B and above which the marginal income should be allocated to Need A only. This is the case of a pure hierarchy[27] is described and resolved in Appendix B. We denote the corresponding income threshold by $\bar{Y}(E, p_A, p_B)$. This threshold is such that $U_{c_A}(0, \frac{\bar{Y}}{p_B}, E)/p_A = U_{c_B}(0, \frac{\bar{Y}}{p_B}, E)/p_B$. Given that $U_{c_A}(0, \frac{Y}{p_B}, E) = E^{\omega}$ and $U_{c_B}(0, \frac{Y}{p_B}, E) = \alpha\theta E^{-\beta} \left(\frac{p_B}{Y}\right)^{\alpha+1}$, its expression is as follows:

$$\bar{Y}(E, p_A, p_B) = p_B \left(\frac{p_A}{p_B} \frac{\alpha\theta}{E^{\omega+\beta}} \right)^{\frac{1}{\alpha+1}}. \tag{15}$$

Fig. 6 illustrates this case of a pure hierarchy for $p_A = p_B = 1$ to ease the visual interpretation.

Depending on the context (Y, E), additional income is either allocated to the satisfaction of the basic need B (increase in c_B) for low income, or the ancillary need A (increase in c_A) for a sufficiently large income. The income threshold $\bar{Y}(E, p_A, p_B)$ at which behavior changes is decreasing with environmental quality (see Proposition 5 in Appendix B). The intuition for this pattern is as follows. As the environmental quality increases, the marginal utility of consumption for the satisfaction of Need B decreases due to substitutability, whereas the marginal utility

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[25] Roughly speaking, this means that income is allocated only to the basic Need B for low-income levels. Refer to Appendix B for the formal definitions of this property.

[26] Roughly speaking, this means that marginal income is allocated only to the ancillary need A for high-income levels. This does not mean that the basic need B is fulfilled and does not require *absolute satiety* of Need B. Refer to Appendix B for the formal definition of these properties.

[27] 'Pure' in the sense that there is a complete switch in behavior regarding the allocation of marginal income to the two needs, contrary to the case of the partial hierarchy described before, wherein marginal income was allocated to both goods for a range of income. When there is a pure hierarchy, the two previously defined thresholds, $\underline{Y}$ and $\overline{Y}$, merge.

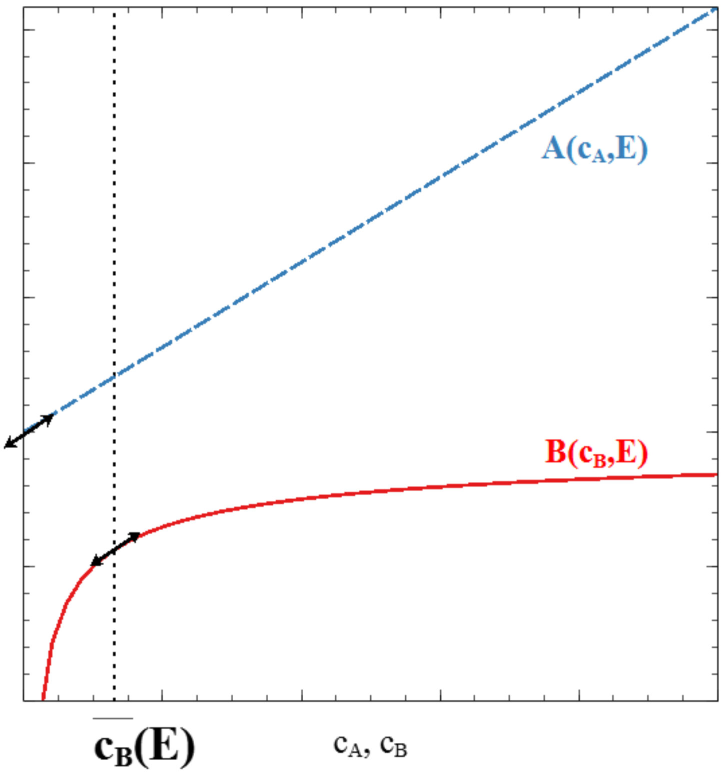

Figure 6: Utility from needs satisfaction in the case of pure hierarchy.

of consumption for the satisfaction of Need A increases due to complementarity. Expenditures for the satisfaction of Need A start at a lower income level when there is an improvement in environmental quality.

4 Discussion

The novelty of our framework lies in the conceptual link between needs and *substitutability*. Depending on one's needs, private consumption and environmental quality may act as substitutes or complements. The prevalence of a specific need in a given context of income and environmental quality leads an individual to perceive income and the environment as either substitutes or complements. This indirect *substitutability* affects individual preferences regarding the environment, that is, whether the individual is willing to pay more, or less, for environmental improvements as income rises. First, concerning the theoretical literature on the WTP, we offered a framework that endogenizes the categorization of environmental goods. This framework allows us to address the lack of consideration of inferior environmental goods in theoretical models. Second, we enriched the theoretical literature by considering an additional dimension, environmental quality, which, beside income, influences the income elasticity of the WTP. How the WTP for the environment increases with income may indeed be affected by the status quo of the environment.

We provided utility functional forms that illustrate such a framework. The CDS utility functional form we scrutinized is one of the many examples. The interpretation of the underlying preferences should not be considered universal, but rather as an illustration of the flexibility of our framework. Our aim was to show that such a model with CDS allows for a variation in the category of environmental goods depending on the income and environmental context of individuals.

In this section, we discuss i) the implications of our approach and its relevance for environmental benefit transfers, ii) suggestions for the empirical testing of our framework, and iii) avenues for future research.

Implications for benefit transfers Benefit transfers constitute a promising tool to address the increasing demand for ecosystem service valuation (Richardson et al., 2015). The challenge is the degree of heterogeneity between the study site and the site to which the WTP is transferred (Bateman et al., 2011). The usual guidelines applied rely on a constant (unit) income elasticity of the WTP. This is supported by some research studies. For example, Czajkowski et al. (2017) examine several transfer methods and conclude that unit income elasticity adjustments lead to minimum transfer errors. Other studies continue to suggest improvements to or the sophistication of benefit transfer methods. For example, Barbier et al. (2017) recommend non-constant income elasticities of the WTP. Other studies emphasize the need to account for *substitutability* and scope effects[28] (Bishop and Boyle, 2017; Richardson et al., 2015). Our framework accounts for heterogeneity in two dimensions, income and environmental quality. Our first message is that non-constant income elasticities should be considered in benefit transfers in practice. Income elasticities may not only depend on income levels but also on environmental quality. In addition to the fact that the income effect can be bi-dimensional, two countries with the same income may not exhibit the same WTP for an environmental good if their environmental status quo differ. The WTP needs not only be adjusted for income but also for environmental quality levels. We focused on the income effect on the WTP because discussing the categorization of environmental goods constituted our primary interest. Nonetheless, our framework also offers insights on the environmental effect on the WTP.[29] Similar to the study on the income effect, our framework relates the environmental effect on the WTP with *substitutability* between income and the environment, which is in line with Amiran and Hagen (2010). We can express the environmental elasticity of the WTP[30] as $\varepsilon^E = \frac{\partial WTP}{WTP} / \frac{\partial E}{E}$ where

[28]The scope effect requires that both the status quo of environmental quality and the magnitude of the change in the environmental good be accounted for when valuing the environment. In our framework, the status quo of the environment is accounted for in the definition of the context.

[29]The environmental effect refers to the effect of a change of the environmental status quo (i.e., the current state of the environment) on the WTP.

[30]As far as we know, few studies estimate the environmental elasticity of the WTP (e.g., Rollins and Lyke, 1998).

the environmental effect is

$$\frac{\partial WTP}{\partial E} = \frac{\partial \left(\frac{V_E}{V_Y}\right)}{\partial E} dE = \frac{V_{EE}V_Y - V_{YE}V_E}{V_Y^2} dE. \tag{16}$$

Would two individuals with the same income but different environmental qualities be willing to pay the same for environmental improvements? Intuitively, one might think that their contribution might not be the same and that the WTP would decrease as environmental quality improves. Nonetheless, a positive environmental effect can occur when income and environmental quality are (sufficiently) substitutable. This would mean that individuals are willing to pay more as environmental quality improves. Our framework makes it possible to study such cases in which some individuals may be less willing to pay for environmental preservation as environmental quality increases, while others may be more willing to pay for it, depending on the context.

Importantly, and, as a second recommendation, considering all possible categorizations of environmental goods is all the more relevant if one thinks about the current selection bias toward relatively developed countries in the empirical literature (Drupp, 2018). While the categorization of environmental goods as normal seems reasonable in relatively high-income contexts, inferiority could arise from contexts depicting a conflict between development and environmental preservation. We could reasonably expect an increasing demand for ecosystem valuation in developing countries in the future. By broadening the origins of the studies on environmental valuation (i.e., by broadening the studied ranges of income as well as the environmental-quality levels), negative income effects may emerge more often than is currently observed. We showed that inferiority of the environment for some range of contexts can result in misestimation of the WTP when applying standard benefit transfer methods. Therefore, there is a need to enrich benefit transfer methods to ensure that they fit every possible context of environmental valuation and ensure a correct understanding of individual's preferences for the environment.

Experimental testing While running an experiment is beyond the scope of our study, we suggest two ways in which our conceptual framework can enrich experimental approaches to environmental valuation. One way to evaluate the WTP for environmental improvement is to decompose the environmental good into a set of attributes and assess preferences for these attributes. This reflects the purpose behind the design of the discrete choice experiments. Our framework suggests that the different attributes considered in these experiments may contribute to the satisfaction of different needs. One interesting addition to the standard choice experiments would be to explicitly account for different needs and evaluate how the different attributes of the environment contribute to their satisfaction. If different individuals value these attributes differently, it may be due to the prevalence of different needs, which can be explained by the context of each individual (income and environmental quality). The environmental attributes that stand out would change from one context in which basic needs are prevalent to another context in which higher-order needs are prevalent. Subsequently, we can relate the environmental WTP to different needs, and therefore to specific attributes. Setting up such an experiment requires the identification of two contexts in which prevalent needs are expected to be different. This would make it possible to determine whether and to what extent need-specific attributes drive the overall values of the WTP for the environment.

Another way to assess the relevance of our framework would be to design experiments that estimate whether private and environmental goods are substitutes or complements. The manner in which the marginal utility of income and the marginal utility of the environment change with income determines the sign of the income effect on the WTP, and therefore the categorization of the environmental good (see Proposition 2). The context of our research requires a cardinal measure of utility.[31] This echoes the reason behind the development of happiness studies. So far, the curvature of utility has been estimated over a single dimension—income (e.g., Layard et al., 2008). In our framework, one needs to characterize how the marginal utility of income changes with income as well as with environmental quality, given that our context is bidimensional. One way of measuring E-P *substitutability* would be to identify several contexts with the same level of income but different environmental quality levels (other aspects, such as culture, should be controlled). This would be done for different strata of income. This will facilitate the estimation of the marginal utility of income in these different study sites and determine if the estimates vary from one site to another, as predicted by our framework.

Avenues for future research Besides empirical testing, several extensions of our framework may be of interest for future research. First, we considered environmental public goods. Relaxing the non-rivalry property would allow us to discuss common pool resources and enable us to include a larger variety of environmental goods in our examples. Second, our framework could be relevant in a dynamic context. Given the evolution of income and environmental quality, how the environmental WTP varies over time and how it is affected by changes in income and environmental quality can be assessed through the following equation, where the dots refer to derivatives with respect to time:

$$\frac{\dot{WTP}}{WTP} = \frac{\frac{dWTP}{WTP}}{\frac{dY}{Y}}\frac{\dot{Y}}{Y} + \frac{\frac{dWTP}{WTP}}{\frac{dE}{E}}\frac{\dot{E}}{E},$$

in which $\frac{\dot{WTP}}{WTP}$ is the growth rate of the WTP, $\frac{\dot{Y}}{Y}$ is the income growth rate, and $\frac{\dot{E}}{E}$ is the environmental growth rate (Horowitz, 2002). In a dynamic version of our framework, *substitutability* could change over time, potentially leading to different categorization of the environment over time. A shock to the economy or the environment may lead to a significant change in the WTP. Such a dynamic model could be used to extend the literature on the environmental Kuznets

[31]E-P *substitutability* is *per se* a cardinal object (Samuelson, 1974).

curve that mostly relies on additive preferences (Figueroa and Pastén, 2015), and thus assumes normality of the environment.

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Appendices

A Proof of propositions and supplementary material

A.1 Proof of Proposition 1

The indirect utility is the maximum obtainable utility in a given context (Y,E), for a given price p:

$$V(p,Y,E) = U(c^*(Y,E,p),E)\ . \tag{17}$$

The first derivative of V with respect to Y is

$$V_Y = c_Y^*(Y,E,p)U_c(c^*(Y,E,p),E)\ . \tag{18}$$

Deriving V_Y with respect to E yields the cross-derivative of the indirect utility

$$V_{YE} = c_{YE}^*(Y,E,p)U_c(c^*(Y,E,p),E) + c_Y^*(Y,E,p)\left[c_E^*(Y,E,p)U_{cc}(c^*(Y,E,p),E) + U_{cE}(c^*(Y,E,p),E)\right]\ . \tag{19}$$

By simplifying notations, we get

$$V_{YE} = c_{YE}^* U_c + c_Y^*\left[c_E^* U_{cc} + U_{cE}\right]\ . \tag{20}$$

To prove Proposition 1, we rely on the following Corollary, which characterizes the interplay between indirect and between-good *substitutabilities* in terms of elasticities, when a change in the environmental quality influences the demand for the consumption good. The proof of Corollary 1 is provided at the end of this section, after interpretations.

Corollary 1 (Indirect and between-good *substitutabilities*) *How indirect substitutability relates to the substitutability between goods depends on the demand-related cross-elasticities and the elasticity of marginal utility for consumption as follows:*

$$\begin{cases} V_{YE} > 0 \Leftrightarrow \eta_{c,E} < \epsilon_{Y,E} - \epsilon_{c,E}\ \eta_{c,c} \\ V_{YE} < 0 \Leftrightarrow \eta_{c,E} > \epsilon_{Y,E} - \epsilon_{c,E}\ \eta_{c,c} \\ V_{YE} = 0 \Leftrightarrow \eta_{c,E} = \epsilon_{Y,E} - \epsilon_{c,E}\ \eta_{c,c}\ , \end{cases}$$

with $\epsilon_{c,E} = \frac{\partial c^*}{c^*} / \frac{\partial E}{E}$ *as the elasticity of demand with respect to the environment,*
$\epsilon_{Y,E} = \frac{\partial c_Y^*}{c_Y^*} / \frac{\partial E}{E}$ *as the elasticity of marginal consumption with respect to the environment,*
$\eta_{c,c} = \frac{\partial U_c}{U_c} / \frac{\partial c}{c} = -c\frac{U_{cc}}{U_c}$ *as the elasticity of marginal utility of consumption with respect to consumption, and*
$\eta_{c,E} = \frac{\partial U_c}{U_c} / \frac{\partial E}{E} = -E\frac{U_{cE}}{U_c}$ *as the elasticity of marginal utility of consumption with respect to the environment.*

The elasticity $\eta_{c,E}$ indicates substitutability (complementarity) between goods if it is positive (negative). Therefore, income and environmental quality are complements (substitutes) if and only if consumption and environmental quality are sufficiently complementary (substitutes).

Put differently, substitutability (complementarity) between goods does not always imply indirect substitutability (complementarity). It depends on the value of the demand-related cross-elasticities and elasticities of marginal utility. In the case of an environmental public good, however, we have $\epsilon_{Y,E}=0$ and $\epsilon_{c,E}=0$, which leads to

$$\begin{cases} V_{YE} > 0 \Leftrightarrow \eta_{c,E} < 0 \\ V_{YE} < 0 \Leftrightarrow \eta_{c,E} > 0 \\ V_{YE} = 0 \Leftrightarrow \eta_{c,E} = 0. \end{cases}$$

Therefore, as $\eta_{c,E}$ has the same sign as $U_{c,E}$, between-good substitutability (complementarity) implies indirect substitutability (complementarity), as stated in Proposition 1.

Proof of Corollary 1 The evaluation of the sign of the cross-derivative of the indirect utility gives:

$$V_{YE} > 0 \Leftrightarrow c^*_{YE} U_c + c^*_Y \left[c^*_E U_{cc} + U_{cE} \right] > 0 \tag{21}$$

$$\Leftrightarrow c^*_{YE} U_c > -c^*_Y \left[c^*_E U_{cc} + U_{cE} \right] \tag{22}$$

$$\Leftrightarrow \frac{c^*_{YE}}{c^*_Y} > -c^*_E \frac{U_{cc}}{U_c} - \frac{U_{cE}}{U_c} \tag{23}$$

$$\Leftrightarrow c^* E \frac{c^*_{YE}}{c^*_Y} > -c^* E c^*_E \frac{U_{cc}}{U_c} - c^* E \frac{U_{cE}}{U_c} \tag{24}$$

$$\Leftrightarrow c^* \left(E \frac{c^*_{YE}}{c^*_Y} \right) > E c^*_E \left(-c^* \frac{U_{cc}}{U_c} \right) + c^* \left(-E \frac{U_{cE}}{U_c} \right) \tag{25}$$

$$\Leftrightarrow \left(E \frac{c^*_{YE}}{c^*_Y} \right) > E \frac{c^*_E}{c^*} \left(-c^* \frac{U_{cc}}{U_c} \right) + \left(-E \frac{U_{cE}}{U_c} \right) \tag{26}$$

$$V_{YE} > 0 \Leftrightarrow \epsilon_{Y,E} > \epsilon_{c,E}\ \eta_{c,c} + \eta_{c,E}. \tag{27}$$

Similarly, we get

$$V_{YE} < 0 \Leftrightarrow \epsilon_{Y,E} < \epsilon_{c,E}\ \eta_{c,c} + \eta_{c,E}, \tag{28}$$

$$V_{YE} = 0 \Leftrightarrow \epsilon_{Y,E} = \epsilon_{c,E}\ \eta_{c,c} + \eta_{c,E}. \tag{29}$$

A.2 Proof of Proposition 2

We remind that $WTP = \frac{V_E}{V_Y} dE$ and that $\varepsilon^{WTP} = \frac{\partial WTP}{\partial Y} \frac{Y}{WTP}$. The WTP for a one-unit improvement in environmental quality is denoted by $w = \frac{V_E}{V_Y}$. From Eq. (6), we get

$$\varepsilon^{WTP} < 0 \Leftrightarrow \frac{\partial WTP}{\partial Y} < 0 \tag{30}$$

$$\Leftrightarrow V_{YE} V_Y - V_{YY} V_E < 0 \tag{31}$$

$$\Leftrightarrow V_{YE} < \frac{V_E}{V_Y} V_{YY} \tag{32}$$

$$\Leftrightarrow V_{YE} < w\, V_{YY}. \tag{33}$$

As $V_Y > 0$ and $V_E > 0$, one has $w > 0$. Given that $V_{YY} \leq 0$, we obtain $V_{YE} < 0$.
Conversely,

$$\varepsilon^{WTP} > 0 \Leftrightarrow V_{YE} > w\, V_{YY}. \tag{34}$$

A.3 Implicit assumptions on *substitutability* in common utility functional forms

In this section, we analyze the implications of common utility functions on the categorization of environmental goods. While empirical studies discuss whether environmental goods are normal or luxury goods, the theoretical literature is based on strong (often implicit) assumptions about indirect *substitutability* and therefore on the categorization of environmental goods.

The CES utility function The CES utility function is widely used in microeconomic models to deal with the income elasticity of the WTP (Flores and Carson, 1997; Ebert, 2003; Baumgärtner et al., 2017a). Formally, this utility function is expressed as follows:

$$U^{CES}(c, E) = \left(a\, c^{1-\frac{1}{\sigma}} + b\, E^{1-\frac{1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}}, \tag{35}$$

where $0 < a < 1$ is the weight given to consumption, $0 < b < 1$ (generally equal to $1 - a$) is the weight given to environmental quality, and $\sigma > 0$ is the Hicks elasticity of substitution between c and E. Solving the consumer problem (Eq. (1)) with the CES function (max $U^{CES}(c, E)$ $s.t.$ $pc = Y$ and E fixed) leads to the following indirect utility function:

$$V^{CES}(Y, E, p) = \left(a \left(\frac{Y}{p} \right)^{1-\frac{1}{\sigma}} + b\, E^{1-\frac{1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}}, \tag{36}$$

whose cross-derivative is always positive,

$$V_{YE}^{CES}(Y,E,p) = \frac{ab\left(\frac{Y}{p}\right)^{\frac{1}{\sigma}} E^{\frac{1}{\sigma}} \left(a\left(\frac{Y}{p}\right)^{1-\frac{1}{\sigma}} + bE^{1-\frac{1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}}{\left(a\frac{Y}{p}E^{\frac{1}{\sigma}} + b\left(\frac{Y}{p}\right)^{\frac{1}{\sigma}} E\right)^2 \sigma} > 0. \tag{37}$$

While the CES utility function is a good choice to assess (i) benefit incidence, that is, whether the distribution of environmental benefits is pro-poor or pro-rich (Ebert, 2003) and (ii) income inequality (Baumgärtner et al., 2017a), it fails to encompass the negative income effects that allow for inferior goods. Ebert (2003) shows that the income elasticity of the WTP is equal to the inverse of the elasticity of substitution. Thus, if the elasticity of substitution is greater (smaller) than one, then the environmental good would be considered a normal (luxury) good. Since the elasticity of substitution is always positive, there is no possibility of inferiority of environmental goods with the CES utility function.

The extended CES utility function The following extension of the CES utility function, with a subsistence requirement, which is described by Heal (2009), has been studied by Baumgärtner et al. (2017b).

$$U^{extCES}(c,E) = \begin{cases} U^l(E) & \text{for } E \leq \overline{E} \\ U^h(c,E) & \text{else} \end{cases}$$

where

$$U^h(c,E) = \left(a\, c^{1-\frac{1}{\sigma}} + b\,(E-\overline{E})^{1-\frac{1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}. \tag{38}$$

$\overline{E}$ is the subsistence level under which preferences are lexicographic ($U^l(E)$ increases with E only and not c). In a market setting, Baumgärtner et al. (2017b) show that the elasticity of substitution monotonically increases with income and decreases with the subsistence level. While Baumgärtner et al. (2017b) focus on the Hicks elasticity of substitution, we focus on the E-P definition of *substitutability* since this concept matters in the categorization of environmental goods. Solving the consumer problem (Eq. 1) with the extended CES function and considering E to be an environmental public good (as in our framework or in Baumgärtner et al., 2017a), the indirect utility above the subsistence threshold is given as follows:

$$V^h(Y,E,p) = \left(a\left(\frac{Y}{p}\right)^{1-\frac{1}{\sigma}} + b\,(E-\overline{E})^{1-\frac{1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}. \tag{39}$$

By deriving eq. (39) with respect to income and environmental quality, we obtain the following expression of indirect *substitutability* for the extended CES function:

$$V_{Y,E}^h(Y,E,p) = \frac{a\, b(E-\overline{E})^{\frac{1}{\sigma}} \left(\frac{Y}{p}\right)^{\frac{1}{\sigma}} \left(b(E-\overline{E})^{1-\frac{1}{\sigma}} + a\left(\frac{Y}{p}\right)^{1-\frac{1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}}{\sigma\left(a(E-\overline{E})^{\frac{1}{\sigma}}\frac{Y}{p} + b(E-\overline{E})\left(\frac{Y}{p}\right)^{\frac{1}{\sigma}}\right)^2} > 0. \tag{40}$$

Therefore, the extended CES function only allows for complementarity between goods since $E > \overline{E}$. The environment cannot be an inferior good in this framework.

Linear and quasi-linear utility functions Both linear and quasi-linear utility functions, denoted here by U^{lin} and $U^{quasilin}$, imply the separability of private consumption and environmental quality. This means that there is an independence, in the sense of E-P, between these two goods (refer to Definition 3), that is, $U_{Y,E}^{lin}(Y,E) = U_{Y,E}^{quasilin}(Y,E) = 0$ and therefore $V_{Y,E}^{lin}(Y,E,p) = V_{Y,E}^{quasilin}(Y,E,p) = 0$. According to Eq (6), then the income elasticity of the WTP is necessarily positive, resulting in normal or luxury environmental goods.

From a theoretical standpoint, the most common utility functions rely on the assumption of complementarity or independence between income and the environment. This means that the environmental public good is bound to be either a normal or a luxury good. Thus, most (microeconomic) models do not allow the consumer to consider the environmental good to be inferior and to switch back and forth from one category to the other when the consumer's income (or the environment) changes.

A.4 Proof of Proposition 3

We remind that $WTP = \frac{V_E}{V_Y}dE$ and that $\varepsilon^{WTP} = \frac{\partial WTP}{\partial Y}\frac{Y}{WTP}$. Then, the sign of ε^{WTP} is the same as the sign of $\frac{\partial WTP}{\partial Y}$.

$$\varepsilon^{WTP} > 0 \Leftrightarrow \frac{\partial WTP}{\partial Y} > 0 \tag{41}$$

$$\Leftrightarrow V_{YE}V_Y - V_{YY}V_E > 0 \tag{42}$$

$$\Leftrightarrow \frac{V_{YE}}{V_E} > \frac{V_{YY}}{V_Y} \tag{43}$$

$$\Leftrightarrow -Y\frac{V_{YE}}{V_E} < -Y\frac{V_{YY}}{V_Y} \tag{44}$$

$$\Leftrightarrow \eta_{E,Y} < \eta_{Y,Y} \tag{45}$$

where the elasticity $\eta_{Y,E}$ measures the impact of a change in income on the marginal satisfaction derived from environmental quality.

We also have

$$\varepsilon^{WTP} < 0 \Leftrightarrow \eta_{E,Y} > \eta_{Y,Y}\ . \tag{46}$$

The sign of the income elasticity of the WTP is opposite to the sign of the difference between $\eta_{E,Y}$ and $\eta_{Y,Y}$. For our CDS utility function, it leads to the following conditions:

$$\eta_{E,Y}-\eta_{Y,Y}>0 \Leftrightarrow \frac{\theta\alpha\beta-\gamma\omega\left(\frac{Y}{p}\right)^{\gamma+\alpha}E^{\omega+\beta}}{\omega\left(\frac{Y}{p}\right)^{\gamma+\alpha}E^{\omega+\beta}+\theta\beta}-\frac{\gamma(1-\gamma)\left(\frac{Y}{p}\right)^{\gamma+\alpha}E^{\omega+\beta}+\theta\alpha(\alpha+1)}{\gamma\left(\frac{Y}{p}\right)^{\gamma+\alpha}E^{\omega+\beta}+\theta\alpha}>0 \tag{47}$$

$$\Leftrightarrow Z^2(-\gamma\omega)+Z(\theta\alpha\beta\gamma-\theta\gamma\omega\alpha-\theta\gamma(1-\gamma)\beta-\theta\alpha\omega(\alpha+1))-\theta^2\alpha\beta>0 \tag{48}$$

$$\Leftrightarrow DZ^2+FZ+C>0\,, \tag{49}$$

with

$$\begin{cases} Z=\left(\frac{Y}{p}\right)^{\gamma+\alpha}E^{\omega+\beta} \\ D=-\gamma\omega<0 \\ F=\theta(\beta\gamma(\alpha+\gamma-1)-\alpha\omega(\alpha+\gamma+1))\lesseqgtr 0 \\ C=-\theta^2\alpha\beta<0 \end{cases}$$

The discriminant of the polynomial $P(Z)=DZ^2+FZ+C$ is

$$\Delta=\theta^2(\beta\gamma-\alpha\omega)[\beta\gamma(\gamma+\alpha-1)^2-\alpha\omega(\gamma+\alpha+1)^2)]\,, \tag{50}$$

which is positive if and only if

$$\textit{Condition 1}\begin{cases} \beta\gamma-\alpha\omega>0 \\ \beta\gamma(\gamma+\alpha-1)^2-\alpha\omega(\gamma+\alpha+1)^2>0\,, \end{cases}$$

or

$$\textit{Condition 2}\begin{cases} \beta\gamma-\alpha\omega<0 \\ \beta\gamma(\gamma+\alpha-1)^2-\alpha\omega(\gamma+\alpha+1)^2<0\,. \end{cases}$$

When $\Delta>0$, the two resulting real roots $Z_1=\frac{-F+\sqrt{\Delta}}{2D}$ and $Z_2=\frac{-F-\sqrt{\Delta}}{2D}$ are :

$$Z_1=\frac{4\theta\beta\gamma\alpha\omega}{\gamma\omega[\beta\gamma(\gamma+\alpha-1)-\alpha\omega(\gamma+\alpha+1)+\sqrt{(\beta\gamma-\alpha\omega)(\beta\gamma(\gamma+\alpha-1)^2-\alpha\omega(\gamma+\alpha+1)^2)}]} \tag{51}$$

$$Z_2=\frac{-4\theta\beta\gamma\alpha\omega}{\gamma\omega[\alpha\omega(\gamma+\alpha+1)-\beta\gamma(\gamma+\alpha-1)+\sqrt{(\beta\gamma-\alpha\omega)(\beta\gamma(\gamma+\alpha-1)^2-\alpha\omega(\gamma+\alpha+1)^2)}]} \tag{52}$$

The sign of the two roots depends on whether condition (1) or condition (2) holds:

- if Condition 1 holds, as $\frac{\alpha\omega}{\beta\gamma}<\frac{(\gamma+\alpha-1)^2}{(\gamma+\alpha+1)^2}\Rightarrow\frac{\alpha\omega}{\beta\gamma}<\frac{\gamma+\alpha-1}{\gamma+\alpha+1}$ because $\frac{\gamma+\alpha-1}{\gamma+\alpha+1}<1$, then $F>0$ and

$$\begin{cases} Z_1>0 \text{ since } \frac{\alpha\omega}{\beta\gamma}<\frac{\gamma+\alpha-1}{\gamma+\alpha+1} \\ Z_2>0 \end{cases}$$

- if Condition 2 holds then, as $F < 0$,

$$\begin{cases} Z_1 < 0 \\ Z_2 < 0 \text{ since } \frac{\alpha\omega}{\beta\gamma} > \frac{\gamma+\alpha-1}{\gamma+\alpha+1} \end{cases}$$

Negative income elasticity can effectively be obtained only under condition (1). Then, the income elasticity is negative between the curves of equation $Z = Z_1$ and $Z = Z_2$. Everywhere else, the income elasticity of the WTP is positive.

B A theoretical framework with an endogenous hierarchical behavior

In this appendix, we describe some properties of a utility function that may be satisfied, and how they can result in a hierarchical behavior when an individual allocates income for the satisfaction of different needs. When assumed, these properties eliminate degenerate solutions or provide an interesting structure to our problem.

B.1 Utility properties and hierarchical behavior

We consider two needs, A and B. Utility is denoted by $U(c_A, c_B, E)$, and it depends on (i) the consumption of two (groups of) goods c_A and c_B (with the corresponding prices p_A and p_B) that individually contribute to the satisfaction of the corresponding need, A or B, and (ii) the environmental good E that contributes to the satisfaction of both the needs. The concavity and separability assumptions made on U in subsection 3.2 are assumed to hold (in particular, we recall that $U_{c_Ac_B} = 0$). In addition, we introduce the following properties.

The two needs may be of different importance, and a *basic* need B will have a lower rank than an *ancillary* need A if there is a prevalence of Need B.

Property 1 (Prevalence of Need B) $\frac{U_{c_B}(0,0,E)}{p_B} > \frac{U_{c_A}(0,0,E)}{p_A} > 0$ *for all p_B, p_A and $E \geq 0$.*

When Need B prevails over Need A, the first unit of income is spent to satisfy Need B (hence in consumption c_B). A *prevalence of Need B* implies that the marginal utility from the consumption of Need A-related goods is finite (i.e., $U_{c_A}(0,0,E) < \infty$) and that the marginal utility from the consumption of Need B-related goods is sufficiently high (depending on the price ratio) and possibly infinite. In next subsection, we prove that this condition alone generates (partial) hierarchical behavior for low levels of income.

A basic need could also be satiable in the sense that the marginal utility from its satisfaction vanishes at some point.

Property 2 (Satiety of Need B) *Utility U is satiable on Need B if* $\lim_{c_B\to\infty} U_{c_B}(c_A, c_B, E) = 0$ *for all E.*

If marginal utility vanishes for a finite consumption level, then we would have *absolute satiety*.

Property 3 (Absolute satiety of Need B) *Absolute satiety occurs whenever there is a threshold $\check{c}_B(E)$ such that $U_{c_B}(c_A, c_B, E) = 0$ for all $c_B > \check{c}_B(E)$.*

To avoid overall satiety, which may induce an incomplete allocation of the budget over the two categories of expenditure if no higher-ranked need is considered, one can assume that there is no absolute satiety of Need A.

Property 4 (Non-absolute satiety of Need A) $U_{c_A}(c_B, c_A, E) > 0$ *for all* $c_A, E \geq 0$.

This represents the fact that there will always be a desire to allocate budget to the highest-ranked need. The lower bound of marginal utility from the satisfaction of Need A in a given environmental context E is denoted by $\mu(E) = \inf_{c_A} U_{c_A}(c_A, c_B, E) \geq 0$. Satiety occurs when $\mu(E) = 0$.

We also define the *strong non-satiety* of needs as follows.

Property 5 (Strong non-satiety of Need A) *Need A is strongly non-satiable if there is a threshold $\hat{c}_A(E) < \infty$ such that $U_{c_A}(c_A, c_B, E) = \mu(E) > 0$ for all $c_A \geq \hat{c}_A(E)$.*

In next subsection, we prove that this property, when combined with the satiety of Need B, induces hierarchical behavior, with the full allocation of marginal income for satisfying the ancillary need A for high-income levels. This behavior occurs without imposing the absolute satiety of Need B. The marginal utility from the consumption of c_B would still be positive (the consumer would still derive satisfaction from the additional consumption aimed at satisfying this need); however, allocating income to the consumption of good c_A is preferred. In the literature (particularly, post-Keynesian consumer choice theory), hierarchical behaviors are usually imposed through exogenous thresholds, representing the absolute satiety of lower-ranked needs (Roy, 1943; Kaufman, 1990; Seeley, 1992; Lavoie, 2004). This property is strong and corresponds to the existence of an exogenous threshold (potentially depending on environmental quality) above which the consumption of good c_B does not generate additional utility (the absolute satiety defined in Property 3). After such a level, Need B is fulfilled and income is allocated to satisfy Need A only. To avoid relying on such exogenous thresholds, we provide examples based on the assumption of *strong non-satiety* of Need A.

Strong non-satiety of Need A (Property 5) is illustrated in Fig. 7 and compared with the hierarchy that would result from the absolute satiety of Need B illustrated in Fig. 8 (for $p_A = p_B = 1$ to ease the visual interpretation).

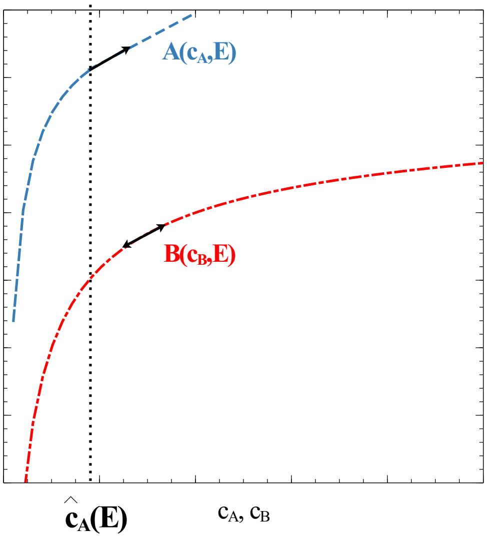

Figure 7: Strong non-satiety of Need A

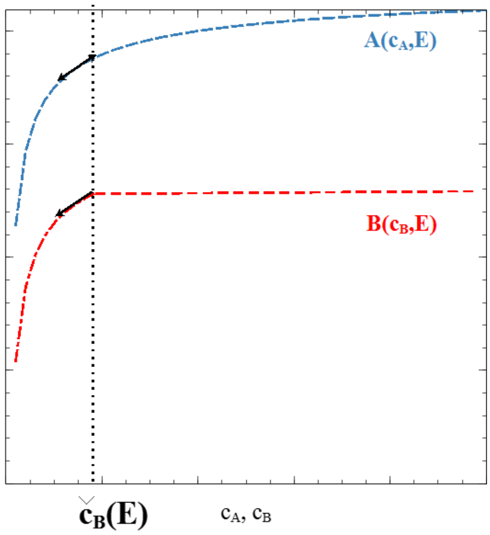

Figure 8: Absolute satiety of Need B, with a kink in $\check{c}_B$

B.2 Consumers' utility maximization under an endogenous hierarchy

The consumer's problem is to allocate own budget between the two consumption categories such that

$$V(Y,E,p_A,p_B) \equiv \max_{c_A,c_B} U(c_A,c_B,E) \tag{53}$$

$$s.t. \quad Y - p_A c_A - p_B c_B \geq 0\,, \tag{54}$$

$$c_A, c_B \geq 0\,, \tag{55}$$

where V is the indirect utility function, namely the optimal level of utility obtained in a context (Y,E) and given prices (p_A, p_B).

The Lagrangian associated with the optimization problem is

$$\mathscr{L} = U(c_A,c_B,E) + \lambda(Y - p_A c_A - p_B c_B) + \mu_A c_A + \mu_B c_B, \tag{56}$$

where

- $\lambda \geq 0$ is the adjoint variable of the budget constraint $Y - (p_A c_A + p_B c_B) \geq 0$, with the complementary slackness condition:

$$\lambda(Y - p_A c_A - p_B c_B) = 0\,. \tag{57}$$

  The variable $\lambda = \frac{\partial \mathscr{L}}{\partial Y}$ can be interpreted as the marginal value of income.

- $\mu_A \geq 0$ and $\mu_B \geq 0$ are the adjoint variables of the positivity constraints of consumption levels $c_A \geq 0$ and $c_B \geq 0$, which satisfy the complementary slackness conditions

$$\mu_A c_A = 0\,, \tag{58}$$

$$\mu_B c_B = 0\,. \tag{59}$$

Deriving the first-order conditions, we obtain

$$\begin{cases} \frac{\partial \mathscr{L}}{\partial c_A} = U_{c_A} - \lambda p_A + \mu_A = 0 \\ \frac{\partial \mathscr{L}}{\partial c_B} = U_{c_B} - \lambda p_B + \mu_B = 0 \end{cases}$$

Then, equalizing the two expressions of λ,[32] we obtain

$$\frac{U_{c_A} + \mu_A}{p_A} = \frac{U_{c_B} + \mu_B}{p_B}. \tag{60}$$

In an interior solution, both consumption levels are positive ($c_A > 0$ and $c_B > 0$), and $\mu_A = \mu_B = 0$. Marginal utilities satisfy

$$\frac{U_{c_A}}{p_A} = \frac{U_{c_B}}{p_B}\,. \tag{61}$$

In such a case, indirect *substitutability* is given by the expression in Eq. (13).

The corner solution $c_A > 0$ and $c_B = 0$, implying $\mu_A = 0$ and $\mu_B \geq 0$, would lead to $\frac{U_{c_A}}{p_A} = \frac{U_{c_B}+\mu_B}{p_B} \Rightarrow \frac{U_{c_A}(c_A,0,E)}{p_A} \geq \frac{U_{c_B}(c_A,0,E)}{p_B}$, which is excluded under the *prevalence of Need B* (Property 1) and the marginal decreasing utility of c_A.

The corner solution $c_A = 0$ and $c_B > 0$ implies that $\mu_A \geq 0$ and $\mu_B = 0$, and thus $\frac{U_{c_A}+\mu_A}{p_A} = \frac{U_{c_B}}{p_B} \Rightarrow \frac{U_{c_A}(0,c_B,E)}{p_A} \leq \frac{U_{c_B}(0,c_B,E)}{p_B}$. This is possible under the *prevalence of Need B* (Property 1), at least for sufficiently low levels of income. In such a case, total income is allocated to the satisfaction of Need B, a case of hierarchical behavior characterized by Proposition 4.[33]

Proposition 4 (Hierarchy: Lower-ranked need satisfaction) *If there is a prevalence of Need B over Need A (Property 1), then there will be a budget threshold $\underline{Y}(E, p_A, p_B)$ under which the entire budget is allocated to the satisfaction of Need B, that is,*

$$\forall Y \leq \underline{Y}(E, p_A, p_B)\ : c_B^*(Y, E, p_A, p_B) = \tfrac{Y}{p_B} \text{ and } c_A^*(Y, E, p_A, p_B) = 0.$$

If this threshold is finite, then it will satisfy $U_{c_B}(0, \frac{\underline{Y}}{p_B}, E) = \frac{p_B}{p_A} U_{c_A}(0, \frac{\underline{Y}}{p_B}, E)$.

Proof of Proposition 4 Assume that $\frac{U_{c_B}(0,0,E)}{p_B} > \frac{U_{c_A}(0,0,E)}{p_A}$ (prevalence of Need B). This is equivalent to $\frac{B_{c_B}(0,E)}{p_B} > \frac{A_{c_A}(0,E)}{p_A}$, as the two needs are independent. Given that the function $B(c_B, E)$ is continuous and differentiable, there exists $\varepsilon > 0$ such that $\frac{B_{c_B}(\frac{\varepsilon}{p_B},E)}{p_B} > \frac{A_{c_A}(0,E)}{p_A}$. As

[32] Under *Non-absolute satiety of Need A* (Property 4), $\lambda > 0$.

[33] In what follows, we may drop (some of) the arguments of functions to ease reading whenever no doubt arises.

$B_{c_B c_B} < 0$, this condition is satisfied for any Y such that $\frac{B_{c_B}(\frac{Y}{p_B},E)}{p_B} > \frac{A_{c_A}(0,E)}{p_A}$. This proves existence. If for some sufficiently large Y, one has $\frac{B_{c_B}(\frac{Y}{p_B},E)}{p_B} \leq \frac{A_{c_A}(0,E)}{p_A}$ (which requires B to be sufficiently concave in consumption), then the threshold $\underline{Y}(E,p_A,p_B)$ will be finite and it will satisfy $\frac{B_{c_B}(\frac{\underline{Y}}{p_B},E)}{p_B} = \frac{A_{c_A}(0,E)}{p_A}$, which is equivalent to $U_{c_B}(0,\frac{\underline{Y}}{p_B},E) = \frac{p_B}{p_A} U_{c_A}(0,\frac{\underline{Y}}{p_B},E)$. This completes the proof.

Fig. 9 illustrates such a proposition.

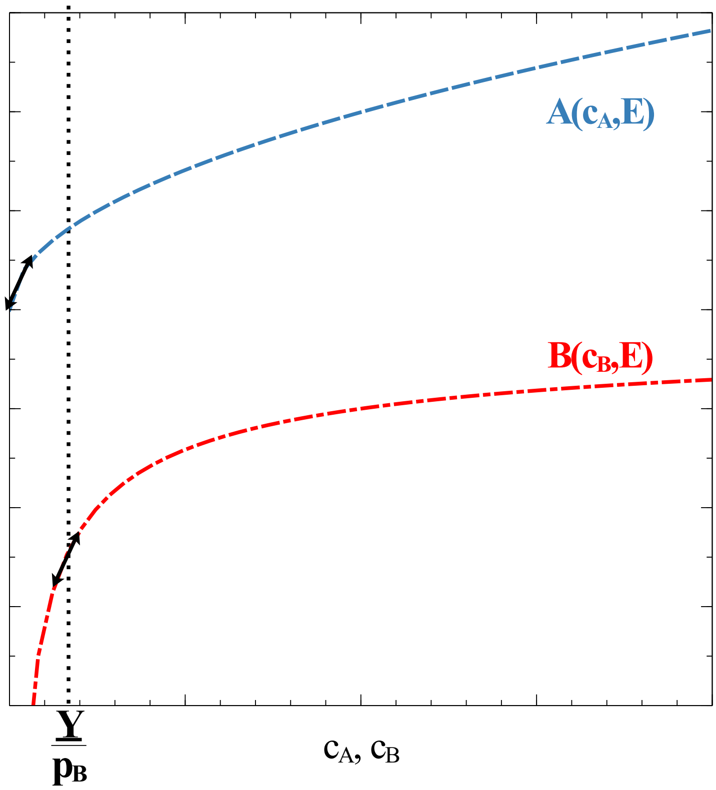

Figure 9: Hierarchy $B \succ A$ (with $p_A = p_B = 1$ to ease visual interpretation)

Under the *prevalence of Need B*, for relatively low-income levels (i.e., $Y \leq \underline{Y}$), preferences are such that all income is allocated for satisfying the basic need B. In the case of higher income, marginal income is allocated jointly for the satisfaction of both the needs according to the trade-off encompassed in Eq. (61). As the satisfaction of both the needs depends on environmental quality, the income threshold $\underline{Y}$ depends on the environmental quality too.

Proposition 5 (Sensitivity of threshold $\underline{Y}$ to environmental quality) *The income threshold $\underline{Y}$ decreases (increases) when environmental quality increases if and only if private goods are relatively more (less) substitutable with environmental quality for satisfying the basic need B than for satisfying the ancillary need A, with the specific condition $\underline{Y}'(E) < (>) 0 \Leftrightarrow \frac{U_{c_B E}}{p_B} < (>) \frac{U_{c_A E}}{p_A}$.*

Proof of Proposition 5 The threshold $\underline{Y}(E)$ is defined, for any E, through the equality $U_{c_B}(0,\frac{\underline{Y}}{p_B},E) = \frac{p_B}{p_A} U_{c_A}(0,\frac{\underline{Y}}{p_B},E)$. From the definition of the utility function, this equality is equivalent to $B_{c_B}(\frac{\underline{Y}}{p_B},E) = \frac{p_B}{p_A}U_{c_A}(0,E)$. The left- and right-hand sides of this equality are functions of E, and the equality must be satisfied for all E. Differentiating the two sides with respect to E, and isolating $\underline{Y}'(E)$, yields $\underline{Y}'(E) = \frac{p_B^2}{B_{c_Bc_B}}\left(\frac{A_{c_AE}}{p_A} - \frac{B_{c_BE}}{p_B}\right)$. As $U_{c_Bc_B} < 0$ by assumption, the sign of $\underline{Y}'(E)$ is the same as the sign of the difference $\frac{B_{c_BE}}{p_B} - \frac{A_{c_AE}}{p_A}$, which is equal to $\frac{U_{c_BE}}{p_B} - \frac{U_{c_AE}}{p_A}$. This completes the proof.

In particular, according to Proposition 5, $\underline{Y}(E)$ decreases with environmental quality when there is substitutability between private consumption and the environment for satisfying Need B (i.e., $B_{c_BE} < 0$) and complementarity between the goods for satisfying Need A (i.e., $A_{c_AE} > 0$). The mechanism for this case is intuitive and discussed in the main text.

Further, if there is satiety in the satisfaction of the basic need B, then there would be another income threshold above which marginal income is allocated for satisfying the ancillary need A only if Need A is strongly non-satiable.[34]

Proposition 6 (Hierarchy: Higher-ranked need satisfaction) *If Need B is satiable (Property 2) and Need A is strongly non-satiable (Property 5), then there will be an income threshold* $\overline{Y}(E)$ *above which all additional income will be allocated for satisfying Need A, that is,*

$$\forall Y > \overline{Y}(E) \ : \frac{dc_B^*}{dY} = 0 \quad and \quad \frac{dc_A^*}{dY} = \frac{1}{p_A}.$$

Proof of Proposition 6 Assume that Need A is strongly non-satiable. Then, there is a $\hat{c}_A(E)$ such that $U_{c_A} = \mu(E)$ for all $c_A \geq \hat{c}_A(E)$ (Property 5). As U_{c_B} is continuous and decreasing toward zero if Need B is satiable (Property 2), there is[35] a consumption level $\bar{c}_B$, implicitly defined by the condition $U_{c_B}(\hat{c}_A(E),\bar{c}_B,E) = \frac{p_B}{p_A}\mu(E)$ and such that $U_{c_B}(\hat{c}_A(E),c_B,E) < \frac{p_B}{p_A}\mu(E)$ for all $c_B > \bar{c}_B$. Define the income level $\overline{Y}(E) = p_A\hat{c}_A(E) + p_B\bar{c}_B$. For this income level, consumption levels $c_A = \hat{c}_A(E)$ and $c_B = \bar{c}_B$ satisfy the optimality condition (61) as well as the budget constraint (57). For any $Y > \overline{Y}(E)$, marginal income is allocated exclusively to consumption c_A to satisfy the optimality condition (61). Thus, we obtain $c_A^*(Y,E,p_A,p_B) = \frac{Y - p_B\bar{c}_B(E)}{p_A}$ for all $Y > \overline{Y}(E)$. This completes the proof.

According to Proposition 6, $p_B\bar{c}_B(E)$ is the largest income allocated for satisfying Need B (which is effective for incomes above $\overline{Y}(E)$).

Propositions 4 and 6 allow us to divide individual behavior into three categories that depend on the context of the choice. Indirect utility under a hierarchy is of the form:

[34]This hierarchical result can also be obtained by assuming the *absolute satiety* of Need B (see Property 3), along with a kink in the derivative of U with respect to c_B, as illustrated in Fig. 8.

[35]Formally, this level may not be defined. It will, however, be well-defined and strictly positive under the prevalence of Need B.

$$V(Y,E,p_A,p_B)=\begin{cases}U\left(0,\frac{Y}{p_B},E\right) & \text{if } Y\leq \underline{Y}(E)\\ U(c_A^*(Y,E,p_A,p_B),c_B^*(Y,E,p_A,p_B),E) & \text{if } \underline{Y}(E)<Y\leq \overline{Y}(E)\\ U\left(\frac{Y-p_B\bar{c}_B(E)}{p_A},\bar{c}_B(E),E\right) & \text{if } Y>\overline{Y}(E).\end{cases}$$

This expression characterizes behavior with a partial hierarchy of needs, which is endogenous and depends on the context. It determines three contextual cases in which consumer preferences are stated differently. When $Y \leq \underline{Y}(E)$, all income is allocated to Need B and environmental preferences are driven by the *substitutability* of private consumption and the environment for satisfying that need. For incomes above $\underline{Y}(E)$, a trade-off between the marginal satisfaction of needs A and B becomes possible, and environmental preferences depend on the interactions between private goods and the environment for satisfying both the needs (possibly with opposite effects). For high-income levels (above $\overline{Y}(E)$), expenditure for satisfying Need B no longer depends on Y (but may be influenced by the environment E) and all marginal income is allocated for satisfying Need A. Environmental preferences are driven by the *substitutability* of private consumption and the environment for satisfying that need only.

Finally, let us emphasize that in our endogenous hierarchy framework, for low-income levels ($Y \leq \underline{Y}(E)$), some satisfaction of higher-ranked needs can be derived from the environment only. This would be the case if $A_E(0,E) \neq 0$. Environmental quality E may contribute to ancillary needs. For example, children can enjoy leisure activities, such as bathing in a river or climbing trees in a forest, without using any income. Subsequently, their utility can be increased by improving environmental quality—even if they have no private consumption related to this category of needs. The traditional representation of the hierarchy of needs in the post-Keynesian literature does not allow for such a situation, as it usually assumes that primary needs must be fulfilled prior to the fulfillment of any other need.

B.3 Particular case with a pure hierarchy

We now provide the derivation of the results for the particular example of the utility function introduced in Eq. (14):

$$U(c_A,c_B,E)=c_AE^{\omega}-\frac{\theta}{c_B^{\alpha}E^{\beta}}.$$

We have $U_{cA}=E^{\omega}$ and $U_{cB}=\frac{\theta\beta}{c_B^{\alpha}E^{\beta-1}}$, and thus, for all E, $U_{cA}(0,0,E)=E^{\omega}<U_{cB}(0,0,E)=\infty$. Therefore, there is a prevalence of Need B (Property 1). Moreover, for all $c_A\geq 0$, $U_{cA}=E^{\omega}>0$, which means that there is a strong non-satiety of Need A (Property 5). Either Proposition 4 or Proposition 6 can be used to derive the income threshold $\bar{Y}(E,p_A,p_B)=p_B\left(\frac{p_A}{p_B}\frac{\alpha\theta}{E^{\omega+\beta}}\right)^{\frac{1}{\alpha+1}}$ provided in the text.