Structure of preferences, decision-making and the environment: Theoretical and experimental approaches

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Executive summary

Climate change encompasses a large range of impacts such as extreme climatic events, biodiversity losses or deforestation. These impacts are very heterogenous across countries. Additionally, countries distinguish one from another according to their preferences and/or their context (income and environmental quality levels). Before any implementation, projects which entail both economic and environmental impacts are evaluated. The main tool used for projects appraisal is the cost-benefit analysis. It relies on the way (objective) quantities are accounted for and the way the environment is valued via the individual willingness to pay and over time via the discount rates. The two latter elements are based upon preferences and the context of decision.

This thesis aims at providing insights on the (objective and subjective) determinants of the heterogeneity of project evaluations. At first, I analyze how (objective) quantities are incorporated in the cost-benefit analysis. The first main chapter deals with the way cost-benefit analysis is affected by the time distribution of impacts considered. Through the example of land use change from biofuel production, I find that decisions regarding projects with non-constant environmental impacts rely on distorted net present values, which may result in the implementation of actually non-desirable projects or the non-implementation of actually desirable projects. This work is both theoretical and numerical.

Second, I investigate the role of the structure of preferences, i.e. whether private goods and environmental goods are substitutable or complementary in providing utility, on individual decision-making in an individual framework and a collective framework. At the individual level (second main chapter), we develop a single theoretical model which allows either for substitutability or complementarity depending on the context (income and environmental quality). It results that the income elasticity of willingness to pay can be negative in contexts of between-goods substitutability, which contrasts with usual frameworks which only allow for positive income elasticities (thus the environmental good can never be inferior but is always normal). Our framework also affects the way consumption and environmental quality are discounted, which is all the more relevant in the context of income shocks. At the collective level (third main chapter), we use an experimental approach to analyze the effect of the interaction between individuals with different structures of preferences on contributions to the public good. It results that perfect substitutability is associated with more free-riding than complementarity. However, an aversion to advantageous inequality also emerges from individuals whose preferences underlie perfect substitutability towards those whose preferences are based on complementarity.

These results suggest that the structure of preferences, often overlooked, plays a major role regarding the way individuals value the environment, thus more globally regarding decision-making towards the environment.

Key words : substitutability, complementarity, discounting, willingness to pay, public good game, biofuels, land use change

Résumé

Le changement climatique englobe un large éventail d'impacts tels que des événements climatiques extrêmes, des pertes de biodiversité ou la déforestation. Ces impacts sont très hétérogènes entre les pays. En outre, les pays se distinguent les uns des autres en fonction de leurs préférences et / ou de leur contexte (niveaux de revenu et de qualité de l'environnement). Avant toute mise en œuvre, les projets qui engendrent des impacts économiques et environnementaux sont évalués. Le principal outil utilisé pour l'évaluation des projets est l'analyse coûts-avantages. Il repose sur la manière dont les quantités (objectives) sont comptabilisées et sur la manière dont l'environnement est valorisé via le consentement à payer individuel et au cours du temps via les taux d'actualisation. Ces deux derniers éléments sont fondés sur les préférences et le contexte de décision.

Cette thèse vise analyser les déterminants (objectifs et subjectifs) à l'origine de l'hétérogénéité des évaluations de projets. Dans un premier temps, j'analyserai comment les quantités (objectives) sont incorporées dans l'analyse coût-bénéfice. Le premier chapitre principal traite de la manière dont l'analyse coût-bénéfice est affectée par la distribution temporelle des impacts considérée. À travers l'exemple du changement d'affectation des terres provenant de la production de biocarburants, il ressort que les décisions concernant les projets ayant des impacts environnementaux non constants dans le temps s'appuient sur des valeurs actuelles nettes biaisées, ce qui peut entraîner la mise en œuvre de projets en réalité non souhaitables ou la non-implémentation de projets réellement souhaitables. Ce travail est à la fois théorique et numérique.

Ensuite, j'étudie le rôle de la structure des préférences, c'est-à-dire si les biens privés et les biens environnementaux sont substituables ou complémentaires au sein de l'utilité, sur la prise de décision individuelle dans un cadre individuel puis un cadre collectif. Au niveau individuel (deuxième chapitre principal), nous développons un modèle théorique qui permet soit de la substituabilité, soit de la complémentarité entre les biens en fonction du contexte (revenu et qualité de l'environnement). Il en résulte que l'élasticité-revenu du consentement à payer marginal peut être négative dans un contexte de substituabilité inter-biens, ce qui contraste avec les modèles habituels qui ne permettent que des élasticités positives du revenu (le bien environnemental ne peut jamais être inférieur mais est toujours normal). Notre cadre théorique affecte également la façon dont la consommation et la qualité de l'environnement sont actualisées, ce qui est d'autant plus pertinent dans un contexte de chocs sur les revenus. Au niveau collectif (troisième chapitre principal), j'utilise une approche expérimentale pour analyser l'effet de l'interaction entre les individus ayant des structures de préférences différentes sur les contributions au bien public. Il en résulte que la substituabilité parfaite est associée à un plus grand nombre de passagers clandestins que la complémentarité. Cependant, une aversion à l'inégalité avantageuse émerge également des individus dont les préférences sont à l'origine d'une parfaite substituabilité vis-à-vis de ceux dont les préférences sont fondées sur la complémentarité. Ces résultats suggèrent que la structure des préférences, souvent négligée, joue un rôle majeur sur la façon dont les individus valorisent l'environnement, et donc sur la prise de décision relative à l'environnement.

Mots clefs: substituabilité, complémentarité, actualisation, consentement à payer, jeu du bien public, biocarburants, changement d'affectation des sols

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Chapter 1

General Introduction

As the result of a process initiated more than forty years ago, the international climate agreement entered into force on the fourth of November 2016. The text resulting from the climate conference (COP 21) held in Paris in December 2015 has been ratified by a large number of countries[1] which committed to maintaining global warming below the 2 degrees threshold. Climate change is one of the most recognized social dilemmas which challenge global society (Van Lange et al., 2013). Indeed, preventing climate change involves a conflict between (generally immediate) country self interests, *e.g.* investing in more profitable projects, and (longer-term) collective interests, *e.g.* better air quality, less extreme climatic events. Every country faces the same global challenge of reducing greenhouse gas (GHG) emissions but achieving a consensus constitutes an even greater challenge since negotiations build upon a strong heterogeneity of impacts across countries (Tiezzi and Martini, 2014). Indeed, while climate change is expected to have a net negative impact, it comes with important asymmetries (Giraudet and Guivarch, 2016). The recent study of Burke et al. (2015) which assesses the impact of temperatures on regional economies underpins this heterogeneity of impacts. While some Northern countries like Russia and Canada may be gainers to a changed climate, others like African and South American countries should expect consequent economic losses (see Figure 1.1). This heterogeneity of impacts[2] mostly concerns the economic sectors of tourism, water supply, agriculture and energy use (Arent et al., 2014). Regarding agriculture, better agricultural yields can be expected in cold regions while lower productivity is more likely in warm regions (Costinot et al., 2016). Regarding the building sector, in cold countries like Russia, climate change would result in lower energy use (thus expenditures) while in warm countries, energy use would be enhanced due to the need for more air conditioning thus more expenditures (Isaac and Vuuren, 2009). As highlighted by Schelling (1992, p.7), there is a "mismatch between those who may be vulnerable to climate change and those who can afford to do anything about it". Lower-income countries are mostly located in the (warm) regions which are expected to suffer the most from global warming whereas higher-income countries mainly located in colder regions are less likely to undergo severe damages (Sterner, 2015).

Besides the heterogeneity of impacts, it is important to consider the heterogeneity in terms of both economic (income) and environmental endowments. This results in different valuations of the environment today (Horowitz and McConnell, 2003) and over time (Hausman, 1979; Harrison et al., 2002; Tanaka et al., 2010). Put differently, relative environmental prices (or more generally marginal willingness to pay) and discount rates vary according to income levels and environmental quality levels (see for example, Rollins and Lyke (1998)), even though there is a few evidence regarding the latter (Horowitz, 2002). In turn, valuations of the environment and time accounting are crucial to the economic evaluation of projects which affect the environment.

[1]The entry into force required that 55% of the world emissions were covered by the signatory countries.

[2]Climate change encompasses a wide range of impacts: air quality degradation, extreme weather conditions like droughts, water pollution, biodiversity losses, etc.

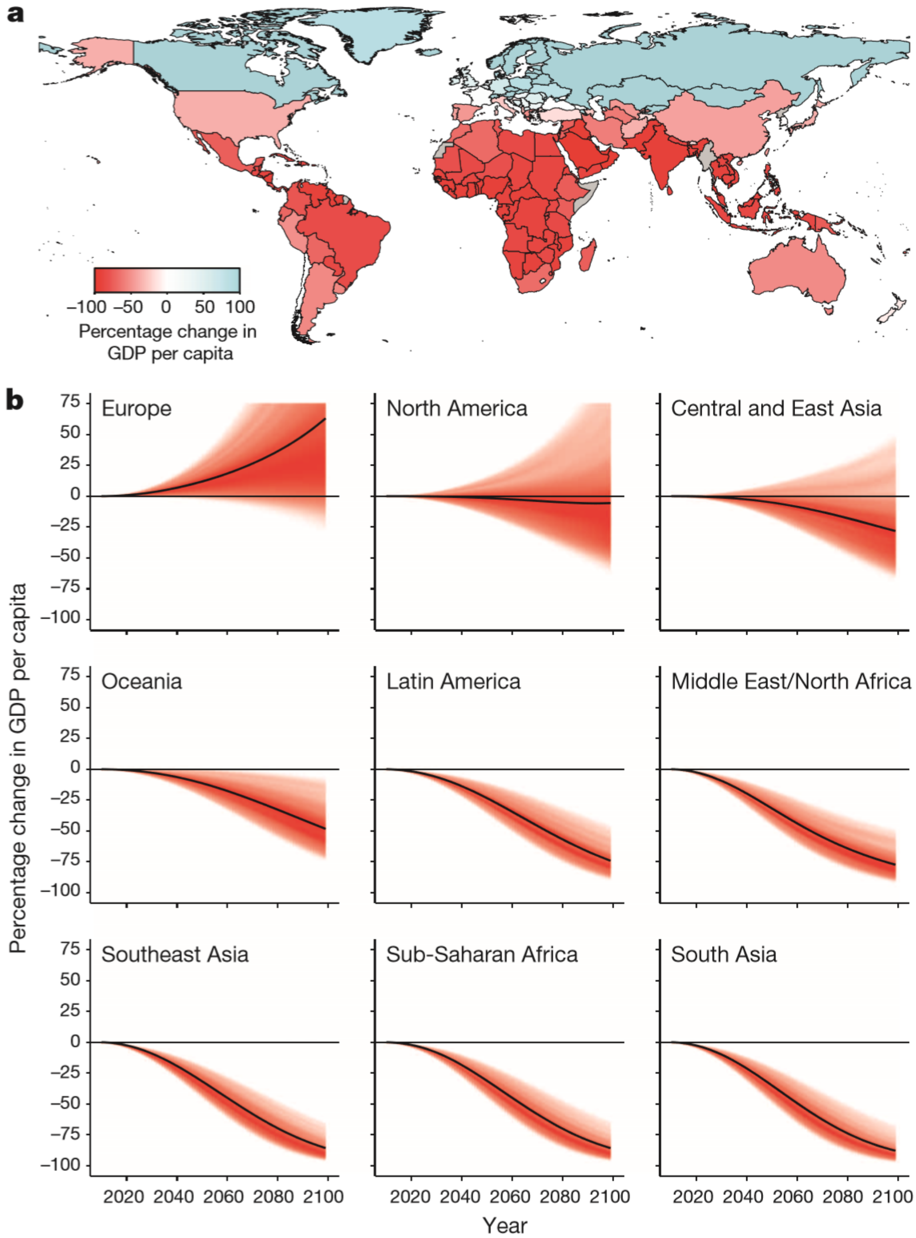

Figure 1.1: Projected effect of temperature changes on regional economies

[a, b] Change in GDP per capita (RCP8.5, SSP5) relative to projection using constant 1980–2010 average temperatures.

[a] Country-level estimates in 2100.

[b] Effects over time for nine regions. Black lines are projections using point estimates. Red shaded area is 95% confidence interval, colour saturation indicates estimated likelihood an income trajectory passes through a value. Base maps by ESRI.

* Source: Burke et al. (2015)

While impacts related to climate change are primarily evaluated upon an objective basis *i.e.* environmental quantities, the economic evaluation of these impacts builds upon preferences which are subjective. These preferences can result in different decisions either according to the context (income and environmental quality) or simply because these are specific to each individual (or country). Hence, a single project may be evaluated differently across countries.

The broad aim of this thesis is to examine how project economic appraisal is affected by (i) the accounting for (objective) environmental impacts or quantities, and (ii) (subjective) individual preferences at the individual level in different contexts, and at the collective level. This implies considering the multidimensional notion of value i.e. (i) value of the environment with vs. without time considerations, and (ii) value at the individual vs. collective level. In this thesis, I focus on three aspects related to the heterogeneity of project evaluations, namely (1) the way environmental impacts are accounted for over time, (2) the role of the structure of preferences in environmental and time preferences at the individual level and (3) the role of the structure of preferences in providing a collective good.

1.1 Challenges

Heterogenous project evaluations

In practice, cost-benefit analysis is largely employed as an economic calculation tool which provides policy-makers with a simple rule. If the net present value of a project is positive (negative), the project is (not) desirable thus should (not) be implemented. This value strongly depends on the discount rate chosen for the analysis (Stern, 2006) and on the future relative environmental prices (Sterner and Persson, 2008). Though, before the consideration of these economic concepts, it is important to examine the way quantities are taken into account, which is often overlooked. When incorporated in the cost-benefit analysis process, quantities undergo discounting and instantaneous environmental prices which themselves vary over time thus affect each point in time in a different manner. When environmental impacts are effectively constant over time *e.g.* daily/monthly/yearly GHG emissions from an industrial process, there is no reason for worrying. What if environmental impacts are not constant over time but considered as such? A striking example is the land use change (LUC) issue which is a second major source of global warming (IPCC, 2007). LUC is peculiar by its non-uniform time distribution of carbon emissions. Yet, most energy policies incorporate these emissions in a uniform way without considering the resulting distortion of project values.

Project evaluation relies on how impacts are accounted for, which are objectively determined in the sense that it is based upon physical (objectively measurable) quantities. As mentioned as well, it depends on how time is taken into account through the value assigned to the discount rate, and how quantities are "priced" over time. These two considerations are founded on preferences (subjective by definition) and have a common source which theoretically hinges around the way consumption and environmental quality combine in providing utility. As a consequence, besides economic calculation, this calls for an exploration of the structure of preferences.

The structure of preferences as a channel of heterogeneity?

The *structure of preferences* has not broadly been explored yet. By structure of preferences, I mean the way private goods and environmental goods interact within utility (as substitutes or complements). Perfect substitutability is the predominant underlying assumption in the literature. In practice first, cost-benefit analysis is by definition the discounted *sum* of costs and benefits generated by a project. Thus, large models which assess climate change impacts based on cost-benefit analysis such as the DICE model of Nordhaus (1994) are implicitly based on the perfect substitutability assumption (Neumayer, 1999). Second, in game theory related to public goods, the game structure is mostly founded on perfect substitutability between the private good and the public good as well, since the benefits from these two goods are additively separable. Eventually, theoretical works, and especially discounting models, always rely on a single assumption about the structure of preferences. Either goods are independent (*e.g.* Heal (1998)) or substitutable or complementary (see for example Weikard and Zhu (2005)). Yet, one may argue that goods may be substitutable in one context and complementary in another context. Along these lines, Baumgärtner et al. (2015b) introduce an elegant extended CES utility function with a subsistence requirement which allows goods to be more and more substitutable as the level of income grows. However, this is the introduction of the exogenous subsistence requirement which makes possible this dependence of the relationship between goods upon the levels of consumption and environmental quality. Additionally, there is an important focus on income effects in the literature but environmental effects may also have an important influence on the way the environment is valued. Wouldn't an individual with degraded environmental surroundings behave like an individual with good environmental surroundings if endowed with the same good environmental conditions? The preferences of the poor towards environmental quality may differ from those of the rich, but income and environmental quality levels are also very likely to constitute determinants of decisions. Consider the LUC issue which is in particular initiated by the fostering of biofuel production in many countries. While a biofuel project may be fostered by one country, its impacts go beyond the geographical confines of this country. Such projects may be considered as desirable in, say, Malaysia because it generates economic benefits even though at the expense of the destruction of forests. Other countries like European countries, by contrast, may dampen these projects because environmental quality is attributed more importance in their context.

Heterogenous contexts and structure of preferences

Regarding climate change impacts, countries may not have fundamentally different preferences but their own context may result in different decisions. In this thesis, the context is defined as the levels of income and environmental quality of each individual.[3] Income proved to play a major role. This is for example advocated by the environmental Kuznets curve. As income gets higher, environmental quality decreases due the country's development phase. This occurs up to a turning point at which environmental quality starts to matter and increases as income grows. It suggests that for lower-income countries, environmental quality is substituted for economic benefits whereas for higher-income countries, environmental quality is progressively considered on the same level as income. While the former situation seems to underpin a certain substitutability between consumption and environmental quality, the latter tends to indicate a certain complementarity. Mostly, preferences (and their structure) of the poor and the rich are considered as different, which translates into different exogenous parameters in models such as elasticities of substitution or weights assigned to consumption and environmental quality. Yet, one may argue that lower-income countries or individuals may behave like higher-income individuals once they reach the same level of income without fundamentally changing their preferences. In other words, behavior would be based upon their economic and environmental endowments. To the question addressed by Tiezzi and Martini (2014, p.2) "Are the preferences of the poor towards a cleaner environment really different from those of the rich?", this suggests a "no". As far as I know, only Baumgärtner et al. (2015b) proposed a theoretical model which allows for different natures of interaction between consumption and environmental quality within a single model. This is based on the definition of substitutability according to Hicks. However, there is another well-known and straightforward definition of substitutability according to Edgeworth-Pareto which may lead to different results.

Heterogenous other-regarding behaviors and structure of preferences

While individuals may differ according to their context at the individual level, they may also behave in their own way regarding others, especially when faced with a social dilemma. The study of interactions between individuals is of great interest in experimental economics. In the public good game setting, individuals are assigned to a group of several individuals. They have the choice to invest either in their private account or a public account which benefits them and all the members of their group. Various types of other-regarding behavior have been explored. Individuals may satisfy the Homo-economicus definition *i.e.* behave in a purely self-interested manner. But it is often not the case. In the most common type of public good game (the linear game), only 33% of individuals behave self-interestedly (Fischbacher et al., 2001). Behaviors which depart from the Homo-economicus definition mainly consist of reciprocity (Croson, 2008), inequality aversion (Fehr and Schmidt, 1999; Dannenberg et al., 2007), altruism and warm-glow (Andreoni, 1995). While the previous challenge tackles the issue of context differences potentially at the origin of different structures of preferences across individuals, it seems worthwhile studying the interaction between individuals with different preference structures.

[3]For example, an individual can have a high income but live in degraded environmental conditions.

Only heterogeneity in terms of endowments or marginal value of the public or the private good has been studied so far in the public good game literature. Most of these studies build upon a linear structure *e.g.* Reuben and Riedl (2013), or a non-linear but additive structure of preferences, *e.g.* Willinger and Ziegelmeyer (2001), Bracha et al. (2011), which underlies perfect substitutability between the private good and the public good. Yet, individuals may experience utility based on different interactions between goods. And these different structures of preferences may yield different (degrees of) other-regarding behaviors.

1.2 Research objectives

The general goal of this thesis is to progress understanding of the heterogeneity of project evaluations which entails both economic and environmental impacts, whether this heterogeneity is based on objective measures (quantities) or subjective measures (environmental and time preferences). This is done through three different angles namely theoretical, applied and experimental.

The first part of this thesis raises the issue of the time accounting of environmental impacts in project appraisal. While relative prices and discount rate values are largely debated within the cost-benefit analysis framework, there is no emphasis on the time profile of impacts. Some environmental impacts are not constant over time but incorporated as such in cost-benefit analysis which treats points in time differently due to the compounding effect of the discount rate and the increase of prices over time. The examination of this question in the context of the relevant example of LUC aims to provide some insights and policy recommendations for a better accounting of the temporal dimension of impacts. This is crucial in that it directly affects project net present value on which policy-makers base their decisions.

The second part of this thesis aims to shed light on the role of the structure of preferences in decision-making towards the environment. This is based on two different approaches which respectively provide insight in an individual framework and a collective framework. The first approach is exclusively theoretical and aims to isolate the effect of the context on individual environmental and time preferences through the channel of the structure of preferences. The second approach is experimental and allows me to study individual behavior in a collective setting where individuals either have the same structure of preferences or different ones. The experimental approach provides insights on how the structure of preferences translates into behavior motives.

With these two approaches, heterogeneity is addressed through the channel of the structure of preferences *(i)* at the individual level with an emphasis on the context of the choice and *(ii)* at the collective level through the elicitation of other-regarding behavior within a lab experiment.

1.3 Structure of the thesis

The thesis is structured as follows. Chapter 2 introduces, both generally and formally, the concepts employed in this research (cost-benefit analysis, willingness to pay, discounting, substitutability and complementarity, public good game) and reviews the literature to motivate the three main chapters. These following chapters are based on three different working papers.

Chapter 3 raises the importance of the temporal distribution of environmental impacts within cost-benefit analysis in the context of LUC initiated by biofuel production projects. The way the uniform time accounting for LUC-related impacts as considered by most energy policies affects cost-benefit analysis, is derived theoretically and numerically through the case of bioethanol production in France.

Chapter 4 examines heterogeneity across individuals based on the context of their choice. A model is developed to allow either for substitutability or complementarity between goods depending on the context (*i.e.* income and environmenral quality levels). This framework is applied to environmental preferences and discounting in order to study the effect of a context-dependent substitutability on willingness to pay and discount rates.

Chapter 5 examines heterogeneity across individuals in a collective setting where individuals interact one with another. This chapter takes a laboratory approach which allows for an analysis of the effect of preference structure on contributions to the public good. In one treatment, individuals interact with their peers, which means that they have the same structure of preference (either substitutability or complementarity) as their group member. In another treatment, they interact with individuals with a different structure of preferences. This dual setting provides insights on the way heterogenous individuals interact when a public good is implied. Especially, I derive the behavior motives associated to each kind of preference structure.

Chapter 6 summarizes the results and contributions of each chapter constituting the thesis and offers a general conclusion with respect to the initial research objectives. Limitations and avenues for research are also provided.

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Chapter 2

Environment, time and the structure of preferences: the multidimensionality of the notion of value

This chapter introduces both generally and formally the concepts central to this thesis.

Value of environmental impacts, value of impacts over time, value of a project with environmental and economic impacts, individual and collective value... This chapter hinges around the multidimensionality of the notion of value and its link to the structure of preferences. Evaluating a project which impacts the environment requires economic tools to convert environmental impacts (quantities) into values. In most cases, quantities are first monetized in order to be compared with economic (monetary) impacts. Second, a conversion of these current monetized impacts into present monetized impacts is necessary as environmental impacts are characterized by a scattering over long periods of time. This whole process constitutes a cost-benefit analysis. The first step often needs the estimation of *willingness to pay* (WTP) when prices are not available, and the second step relies on the choice of a *discount rate* to express future values in terms of present values.

In this chapter, I first consider the switch from quantities to values by analyzing the case of biofuels. Then, I present, both generally and formally, the marginal WTP and the economic and environmental discount rates. Besides, I propose a way to take into account heterogeneity across agents and end up by introducing the substitutability concept. This allows me to derive the links *(i)* between substitutability and discounting and *(ii)* between substitutability and willingness to pay for individuals and the collectivity. For the latter, the approach of experimental economics is introduced. Indeed, it allows for an analysis of the interaction between agents. The order of the sections follows the flow of motivations of the three chapters of the thesis.

2.1 From quantities to values

Biofuels are a noteworthy example of projects which both entail environmental and economic impacts. In this section, the necessary steps to convert quantities into values are broadly reviewed through this instance.

2.1.1 An illustration through biofuel production projects

One of the main objectives of biofuel production is to fight against climate change, the others being securing employment and energy supply. Mostly, biofuels are an alternative to oil in the transport sector. Oil combustion generates large releases of greenhouse gases (GHG) to the atmosphere. Biofuels are biomass-based fuels, which implies that the carbon captured by the biomass during plant growth is released by vehicles after combustion. This results in a carbon-neutral process contrary to oil combustion. This statement is partly true however. The production of biofuels necessitates several steps (agricultural practices, extraction of oil from the plant, drying of the plant, etc) which require energy thus involves GHG emissions. Generally, after an analysis of global warming impacts related to production and consumption, biofuels are still better than oil combustion. This incentivized policies to foster biofuel production.

The European Renewable Energy Directive (RED) adopted in 2009 particularly aims at reducing greenhouse gases (GHG) emissions by 20% vs. 1990 by 2020. This objective encapsulates a minimum incorporation of 10% of renewable energy in the transport sector for each of the European Union members including first and second generations of biofuels. Although biofuels are considered as an alternative to fossil fuels, it also constitutes a source of land use change (LUC) (IPCC, 2007) which should be accounted for in the analysis of global warming impacts.

Changes in land use are the most important environmental impact of biofuels production (Van Stappen et al., 2011). LUC results in carbon stock changes after a land is converted to a new use. The carbon balance disturbance is twofold: in the vegetation (plant) and in the soil[1] which both constitute important carbon sinks. Changes in land use affect the oxidation and formation of carbon in both plants and soils, which results in changes in carbon-CO_2 fluxes between the land and the atmosphere (Delucchi 2011). Many factors influence the magnitude of the disturbance: climate region, type of the land converted, nature of the new land, agricultural practices. Considering the two sinks together, forests accumulate and maintain carbon stocks better than grasslands and even more than croplands. Land-use intensity increases from forests to grasslands to croplands (Poeplau et al. 2011). Depending on the carbon fraction of both the land which undergoes the change and the new land, the impact can occur in both directions: either a release of carbon generating GHG emissions *e.g.* a forest is converted into a cropland, or a sequestration of carbon inducing GHG uptakes from the atmosphere *e.g.* afforestation. Therefore it is crucial to understand the impact of LUC on carbon balances in order to reduce GHG emissions since it can either be beneficial or harmful to the climate (Ben Aoun et al. 2015).

LUC can either result from the replacement of other types of lands *i.e.* direct LUC or from the displacement of existing crops *i.e.* indirect LUC (Broch et al. 2012). Direct LUC refers to the substitution of a given land for a cropland entirely dedicated to biofuel production. Indirect LUC occurs when the substitution for biofuel crops of a land dedicated to food crops reduces the availability of lands for food supply; this decrease is compensated by a switch of the demand for food in other locations where lands are converted into food crops (through market responses). For example, corn first produced for food supply purposes are turned into energy crops to be used for biofuel production. Many energy policies in different parts of the world[2] foster a switch from fossil fuels to biofuels, resulting in an expansion of lands for energy crops hence an increase of LUC. As a consequence, considerable attention has been drawn towards the potential significant emissions due to LUC up to the possibility of switching a positive[3] environmental balance into a negative one (Searchinger et al., 2008; Tyner et al., 2010). LUC from biofuel production can also help mitigate climate change. Lignocellulosic biofuels such

[1]Stock changes in the soil are commonly named SOC stock changes for Soil Organic Carbon.

[2]*e.g.* the Energy Independence and Security Act of 2007 in the United States and the EU Renewable Energy Directive of 2009.

[3]In the sense that the environmental balance of biofuels is better than the oil's.

as *Miscanthus*[4] have indeed the potential to reduce emissions specifically when replacing a cropland (Stewart et al., 2007; Poeplau and Don, 2014; Qin et al., 2015; Harris et al., 2015). Based on these findings, the main biofuel policies namely the Renewable Energy Directive (RED) in the European Union and the Renewable Fuel Standard (RFS2) in the United States, progressively incorporate these impacts in the environmental requirements for the development of a biofuel production. A recent project for an indirect LUC Directive has been presented to the European Commission in October 2012. It aims at reporting estimated iLUC emissions in order to speed up the transition to advanced biofuels production (substantial GHG savings). Especially, it focuses on decreasing the GHG emissions from iLUC when growing the first generation biofuels (agreement on a cap) as well as limiting the land and water use conflict with the food production sector. Therefore, the second generation biofuels may contribute considerably to the 10% objective of the RED. These biofuels are produced from lignocellulosic biomass, woody crops, agricultural residues or waste. They recently entered the market of biofuels with for example the French Futurol project. Their environmental balance seems promising compared with first generation biofuels.

Life cycle assessment is the common method used to quantify environmental impacts from projects (Finkbeiner et al., 2006). However, decisions are based on economic evaluation. What are the steps between environmental impacts quantities and environmental impacts values?

Evaluating a project that impacts global warming requires *(i)* giving a monetary value to GHG emissions (usually to $CO_2 eq$) at each point in time and *(ii)* aggregating costs and benefits of the project over time by discounting them to a chosen time period (De Gorter and Tsur, 2010). These two steps are fully part of the time dimension which characterizes a cost-benefit analysis, the common tool employed in economic assessments of projects.

2.1.2 Cost-benefit analysis: how projects are evaluated

Cost-benefit analysis first converts all costs and benefits to money equivalents based on willingness to pay, and second to a present value by applying the discount rate. The discount rate has a major role in determining whether a project should be accepted or not. And its role is even stronger when the project includes costs and benefits which occur over very long periods. LUC impacts are a good illustration of long-term impacts on the environment since this is directly linked to GHG emissions which remain in the atmosphere for hundreds of years.

In a cost-benefit analysis, a project which yields economic and environmental outcomes is usually evaluated by monetizing the environmental outcome at each date and applying the discount rate. A cost-benefit analysis is always carried out in comparison to a baseline or *status quo* (Pearce et al. 2006). Consider a project starting at time $t = 0$ with time horizon T,

[4] A perennial grass.

and resulting in a sequence of outcomes $\{(\Delta C_t, \Delta E_t)\}_{t=0,1,\dots,T}$ with ΔC_t the economic variation relative to the status quo and E_t the environmental-related (emissions or sequestrations of GHG) variation relative to the status quo. Put differently, ΔC and ΔE underlie variations between the status quo and the project assessed respectively in terms of economic (monetary) impacts and environmental impacts. The rate at which next period's consumption is discounted at time $t-1$ is denoted by r_t^C (with the convention $r_0^C = 0$).[5] The relative price of the greenhouse gases emissions (measured in CO_{2eq}) *i.e.* the price of carbon at time t, that is, the willingness-to-pay for mitigating one tonne of CO_2 emitted at time t, is denoted by p_t. The net present value of the project denoted by NPV is then:

$$NPV\left(\{(\Delta C_t, \Delta E_t)\}_{t=0,1,\dots,T}\right) = \sum_{t=0}^{T} \frac{\Delta C_t + p_t \Delta E_t}{\Pi_{s=0}^{t}(1 + r_s^C)} \tag{2.1}$$

In the case of biofuels, the usual baseline is the fossil fuel (gasoline for bioethanol and diesel for biodiesel) which is a substitute for biomass-based fuels. In the context of LUC only, the baseline is the land which undergoes the change *e.g.* if *Miscanthus* is planted on a former cropland then the cropland constitutes the baseline for the analysis. The decision maker thus evaluates if the project improves ($NPV > 0$) or worsens ($NPV < 0$) social welfare.

2.1.3 Willingness to pay

In the context of global warming impacts such as those from LUC, projections of carbon prices over time are available, in general from international institutions such as the International Energy Agency (in the World Energy Outlook annual reports). However, biofuels for example affect other environmental goods or services such as water quality or biodiversity which are not traded. In the absence of markets, *i.e.* when no price is available for the environmental good, the WTP can be estimated through various methods.

2.1.3.1 *Generalities*

In the context of cost-benefit analysis, WTP has a major role. WTP allows to give a monetary value to nonmarket goods to be directly compared with market goods within cost-benefit analysis. In the environmental context, this is the largest amount of money an individual is willing to pay for an environmental improvement or to avoid an environmental damage.

WTP can be estimated in various ways. Two main approaches have been developed namely revealed preferences and stated preferences. The method of benefit transfer complements these two approaches and will be described in subsection 2.2.1.

[5] The notations indicate that the discount rate can be decreasing over time. This is an important concern when dealing with the very long run. See Arrow et al. (2013) for a review.

Stated preferences collect information about respondent preferences for the environmental good which is evaluated, by asking choices in hypothetical situations presented in a survey. The two main methods of stated preferences are the contingent valuation method and more recently discrete choice experiments. In contingent valuation, respondents are asked to express their maximum WTP or minimum willingness to accept (WTA) compensation for a hypothetical change in the level of provision of the good. For a broad review about this method, see Carson (2012). In choice experiments, respondents are required to choose their most preferred option out of a set of alternative hypothetical options (see for example Birol et al. (2006)). The main limitation to the stated preferences approach is the hypothetical bias (Carlsson and Martinsson, 2001).[6]

Revealed preferences methods refer to situations where people's choices are observed in actual market situations. The travel cost method and hedonic pricing are two of the common techniques used in this approach. See Boyle (2003) for a broad review of revealed preferences methods. However, compared to stated preferences, *(i)* some environmental data are often unavailable thus not analyzable through revealed preferences and *(ii)* revealed preferences cannot account for the passive use value of goods (Carson et al., 2014).[7] Since cost-benefit analysis incorporates the total economic value of environmental goods, stated preferences seem more appropriate than revealed preferences to estimate WTP in this context. Studies progressively combine the two approaches in order to reduce their respective limitations (Atkinson and Mourato, 2008).

2.1.3.2 *Formal description*

Consider two goods $C \in \mathbb{R}^+$ and $E \in \mathbb{R}^+$ contributing to the well-being of a consumer. C is a private (composite) good whereas E represents environmental quality (a public good for which no market exists). I assume that increasing the consumption of each good increases well-being, but at a decreasing rate. Put differently, preferences over these two goods are represented by a utility function U which is increasing and concave in each of its arguments.

The indirect utility[8] derived from C and E is given by $V(Y,E) = \underset{C}{\text{Max}}\ U(C,E)\ s.t.\ pC = Y$ where Y is the available income and p is the price index of C. Then, the WTP for improving environmental quality by ΔY is defined as the solution of the following equation:

$$V(Y - WTP, E + \Delta E) = V(Y,E)\,. \tag{2.2}$$

[6] The hypothetical bias refers to the fact that choices made in surveys are not incentive-compatible. As a consequence, the stated preferences may not reflect preferences in a real situation.

[7] The total economic value is composed of the use value and the non-use or passive value. The use value relates directly or indirectly to the actual use of the good, *e.g.* visit to a national park (direct) or trees along a river which protect urban areas from flood damages (indirect). The passive value refers to the willingness to pay to maintain some good in existence even though there is no actual, planned or possible use. See Pearce et al. (2006, p.86) for an accurate description.

[8] The indirect utility function gives the optimal utility level obtainable given a set of prices and income.

Equation (2.2) states that for a given price index p, the consumer whose preferences are represented by U is indifferent between *(i)* giving up from her budget the amount $WTP (= \Delta Y)$ for improving the environmental quality by ΔE and *(ii)* remaining in the initial situation (*i.e.* no environmental improvement and no change in income).

Then, the marginal WTP (w) is defined as the marginal rate of substitution between income and environmental quality.[9] Put differently, marginal WTP is the maximum relative price the individual is willing to pay for the next unit of the (environmental) good.

$$w(Y,E,p) = \frac{V_E}{V_Y} \tag{2.3}$$

The marginal WTP may change over time (Horowitz, 2002). It has been put forward within a discrete choice experiment on water pollution for example (Meyer, 2013). As the author states "willingness to pay for an environmental improvement is a function of how long it takes to deliver the improvement". This justifies the use of discount rates which convert impacts at each point in time into a net present impact.

2.1.4 Discounting

When intertemporal decisions are involved, discounting allows for a direct comparison of future monetary impacts with present ones.

2.1.4.1 *Generalities*

The discount rate addresses the issue of the trade-off between an impact (be it economic or environmental) today and an impact in the future (see *e.g.* Martinet (2012) for further details). It determines the value of future costs and benefits relative to current ones. Usually, current impacts are given more value than future impacts, which underlies a positive discount rate. Two main reasons for discounting can be put forward and come with empirical support (Florio, 2014). First, economic agents generally prefer to receive a payment sooner than later. This is explained by *(i)* a rate of pure preference for the present based on impatience or myopia and *(ii)* the wealth effect which relies on the belief that agents in the future will be wealthier than us, thus, under the assumption of decreasing marginal utility, one euro is more valuable to us than to them (Gollier 2013). This wealth effect is even more important at the generation scale and in the long run. Second, in the context of public economics, funding a project has an opportunity cost. It means that resources could be invested in other projects which also generate returns. To trigger investment, the expected return of the project needs to be greater or equal to the expected return of an alternative investment (*i.e.* the opportunity cost of funding). This

[9] If the consumer is indifferent between two situations, then the variation of her utility is nill: $dU = U_C dC + U_E dE = 0 \Leftrightarrow -\frac{dC}{dE} = \frac{U_E}{U_C} = MRS_{C,E}$. The marginal rate of substitution is indeed often defined as the marginal willingness-to-pay for consuming an additional marginal quantity of a good.

opportunity cost justifies discounting in the sense that a euro invested in a project must produce more benefits than using this euro in an alternative project.

As eq. (2.1) states, the higher the discount rate, the smaller the net present value. A high discount rate may be in favor of biofuel projects which entail long-term global warming damages. Indeed, the further in the future, the lower the value of the environmental damage, the higher the value of the biofuel project. On the contrary, if biofuel production is beneficial to the climate in the long run *e.g.* the development of second generation biomass, a high discount rate turns disadvantageous since it overwhelms the future benefits of the project thus reduces its net present value.

2.1.4.2 *Formal description*

Let the present value of indirect utility at time t be denoted by $U^{\delta}(C(t),E(t),t) = U(C(t),E(t))e^{-\delta t}$. The marginal utility derived from an increment of income C at time t is

$$U_C(C(t),E(t),t)^{\delta} = U_C(C(t),E(t))e^{-\delta t} \ , \tag{2.4}$$

By definition, the economic discount rate, r^C is the rate of change of marginal utility for income[10] as time changes:

$$r^C \equiv -\frac{\dot{U}_C^{\delta}(C(t),E(t),t)}{U_C^{\delta}(C(t),E(t),t)} = -\frac{1}{U_C(C(t),E(t))e^{-\delta t}} \frac{d[U_C(C(t),E(t))e^{-\delta t}]}{dt} \tag{2.5}$$

As

$$\dot{U}_C(C(t),E(t),t) = \frac{d[U_C(C(t),E(t))e^{-\delta t}]}{dt} = \left(\dot{C}U_{CC} + \dot{E}U_{CE}\right)e^{-\delta t} - U_C\delta e^{-\delta t} \ , \tag{2.6}$$

we get

$$r^C = -\frac{[\dot{C}U_{CC} + \dot{E}U_{CE}] - U_C\delta}{U_C} = \delta - \frac{\dot{C}}{C}\left(C\frac{U_{CC}}{U_C}\right) - \frac{\dot{E}}{E}\left(E\frac{U_{CE}}{U_C}\right) \tag{2.7}$$

Let $\eta_{C,C} = -C\frac{U_{CC}}{U_C} > 0$ be the elasticity of marginal utility of income with respect to income and $\eta_{C,E} = -Y\frac{U_{CE}}{U_C}$ be the elasticity of marginal utility of income with respect to environmental quality, then:

$$r^C = \delta + \frac{\dot{C}}{C}\eta_{C,C} + \frac{\dot{E}}{E}\eta_{C,E} \ . \tag{2.8}$$

Thus the discount rate is the sum of three components. The first component is the pure preference for the present which reflects the individual's impatience. The second component

[10] The negative sign is attributed to the fact that the discount rate is conventionally positive whereas the discount factor growth rate is negative (negative slope).

is a wealth effect: as consumption grows over time, the discount rate increases. This is explained by the diminishing marginal utility. Under the assumption that consumption is greater for future generations than present ones, consumption is more valuable to present than future generations, hence the positive wealth effect on the discount rate. The last component is a substitution effect. It depends on the growth of environmental quality. This term disappears when assuming that the interaction between consumption and the environment in terms of utility is null (this is the case for utility functions which are separable in their arguments). When this is not the case, it can either be interpreted as a distaste effect[11] if the cross derivative of utility is positive ($u_{CE} > 0$ or equivalently $\eta_{C,E} < 0$) or a compensation effect[12] if it is negative ($U_{CE} < 0$ or equivalently $\eta_{C,E} > 0$) (Michel and Rotillon, 1995; Ayong Le Kama and Schubert, 2004).

2.1.4.3 *Dual-rate discounting*

In the environmental context, the use of a single discount rate may not be appropriate. Weikard and Zhu (2005) point out two situations under which dual discount rates (one for consumption, the other one for environmental quality) should be used. First, when relative environmental prices are not available, dual-rate discounting is an equivalent way of evaluating projects. Indeed, the authors show that the difference between the consumption and the environmental discount rates is equal to the environmental price growth rate. Second, if consumption and environmental quality are not substitutable, relative prices cannot exist, which results in a necessary evaluation of economic and environmental impacts separately with their own discount rate. They further argue that the lowest (limiting) discount rate in this context is the one that should be used in economic evaluation.

The expression of the environmental discount rate can be similarly found for an increment of the environmental good E. The environmental or ecological discount rate, r^E is the rate of change of marginal utility for environmental quality as time changes

$$r^E \equiv -\frac{\dot{U}_E^{\delta}(C(t),E(t),t)}{U_E^{\delta}(C(t),E(t),t)} = -\frac{1}{U_E(C(t),E(t))e^{-\delta t}}\frac{d[U_E(C(t),E(t))e^{-\delta t}]}{dt} . \tag{2.9}$$

As

$$\dot{U}_E(C(t),E(t),t) = \frac{d[U_E(C(t),E(t))e^{-\delta t}]}{dt} = \left(\dot{Y}U_{EE} + \dot{C}U_{EC}\right)e^{-\delta t} - U_E \delta e^{-\delta t} , \tag{2.10}$$

we get

$$r^E = -\frac{[\dot{E}U_{EE} + \dot{C}U_{EC}] - U_E\delta}{U_E} = \delta - \frac{\dot{E}}{E}\left(E\frac{U_{EE}}{U_E}\right) - \frac{\dot{C}}{C}\left(C\frac{U_{EC}}{U_E}\right) . \tag{2.11}$$

[11] In the sense that a reduction of environmental quality diminishes the marginal utility of consumption.
[12] In the sense that a reduction of environmental quality increases the marginal utility of consumption.

Let $\eta_{E,E} = -E\frac{U_{EE}}{U_E} > 0$ be the elasticity of marginal utility of environmental quality with respect to environmental quality and $\eta_{E,C} = -C\frac{U_{EC}}{U_E}$ the elasticity of marginal utility of environmental quality with respect to income, then:

$$r^E = \delta + \frac{\dot{E}}{E}\eta_{E,E} + \frac{\dot{C}}{C}\eta_{E,C} \tag{2.12}$$

Thus more formally, Weikard and Zhu (2005) derive the crucial theoretical link between dual-rate discounting and the relative environmental prices as presented within cost-benefit analysis in eq. (2.1).

$$\frac{\dot{p}}{p} = r^C - r^E \tag{2.13}$$

with $\frac{\dot{p}}{p}$ is the growth rate of environmental prices.

Earlier, Yang (2003) put forward the importance of using different utility discount rates for consumption and the environment for GHG emissions reduction. He implements the two resulting discount rates (the environmental discount rate being smaller than the consumption discount rate) in Nordhaus' DICE model and justifies the Kyoto Protocol's constraints. Tol (2004) justifies the use of a smaller environmental discount rate in a different manner. The WTP increases over time as income increases, which makes the environmental discount rate grow at a smaller rate than the consumption discount rate. Guesnerie (2004) justifies as well the existence of an ecological discount rate smaller than the conventional discount rate by ethical considerations, in a model where the utility function underpins a constant elasticity of substitution (CES). In the long run, he shows that the ecological discount rate tends to zero. Hoel and Sterner (2007) clearly show the importance of future prices in calculating the discount rate. The scarcity of environmental resources makes the relative prices increase over time, which reduces the consumption discount rate as time passes. They also illustrate this with a CES utility function. The growth rate of environmental prices is dependent on the degree of substitutability between consumption and environmental quality. The lower the elasticity of substitution, the higher the growth rate of environmental prices and the lower the discount rate. Further, Sterner and Persson (2008) implement such a framework in Nordhaus' DICE model to justify a drastic reduction of emissions. Still with a CES utility function, Traeger (2011a) goes further by showing the evolution of the consumption discount rate under several assumptions regarding the substitutability between consumption and environmental quality. Finally, Gollier (2010) strongly justifies the use of ecological discounting in a context of uncertainty. Indeed, it avoids the computation of certainty equivalent future values of the environmental impact (Gollier, 2012, p.140).

Chapter 3 constitutes the point of departure of the thesis. It shows that a project may result in different values depending on how time and environmental impacts are accounted for and combined. In other words, a project may be evaluated differently depending on the assumptions made about future environmental prices (or willingnesses-to-pay) and the value of the discount rate. The latter is supported by Baumgärtner et al. (2015a) who estimated the difference between the consumption and the environmental discount rates[13] across five countries. In Chapter 3, plausible values of prices and discount rates are combined in the context of biofuel's impacts on land use. These values are chosen in accordance with those employed in public evaluation of projects in France. Both empirically and theoretically, the next section goes further by reviewing the potential sources of these different values of prices and discount rates.

2.2 Heterogenous values across agents

This section is a review of the literature on the variations of the two key elements of cost-benefit analysis, namely WTP and the discount rate, with income and environmental quality levels.

2.2.1 Heterogenous willingness to pay

Individual preferences mostly determine WTP (by definition), but importantly, WTP also reflects individuals' ability to pay. Therefore, WTP is sensitive to income levels. There is a broad literature on the income effects on WTP. From a theoretical perspective, Barbier et al. (2016) develop a model which results in a non-constant income elasticity of WTP (except for very restrictive conditions). They also estimate WTP for the case study of the pollution of the Baltic sea based on a multi-country dataset which confirms their model's results: WTP increases with income but the income elasticity of WTP[14] remains between 0 and 1. This result supports previous theoretical and empirical works.

Kristrom and Riera (1996) were the first to raise the question of the value of the income elasticity of environmental improvements. They estimate this value across different European datasets and find that this elasticity lies between 0 and 1. This finding opens the question of the distributional concerns, which is beyond the scope of this thesis.[15] Hökby and Söderqvist (2003) in the context of marine eutrophication effects in the Baltic Sea and Jacobsen and Hanley (2009) in the context of biodiversity conservation also find an elasticity which is less than one.

The study of income effects on WTP is particularly crucial when the method of benefit transfer is employed. How can valuation studies of an environmental good in one country be used for the valuation of the same good in another country with lower or higher income? Water

[13]Recalling that the difference between the two is equal to the rate of growth of the environmental price in a certainty framework.

[14]Formally and according to notations defined in the previous section, income effects are denoted by $\frac{\partial WTP}{\partial Y}\ \forall\, Y, E$.

[15]If the elasticity lies between 0 and 1, the environmental good is said to be distributed regressively, which benefits poorer individuals. An elasticity above one makes the environmental good distributed progressively, which benefits richer individuals.

quality is a good example of such a good. Czajkowski and Ščasný (2010) show that an income elasticity of WTP of 1 can be applied to transfer WTP for the valuation of lake water quality from Norway where incomes are relatively high, to Poland and Czech Republic, two countries in transition. This adjustment of WTP through income levels allows for an extension of (rather costly) valuation studies across countries.

In summary, the income effect on WTP has been broadly studied and is generally positive on WTP. Still, a few results suggest a negative income effect (McFadden, 1994; Horowitz and McConnell, 2003), which is not generally further interpreted. Although the income effect is mostly found positive, Huhtala (2010) finds an effect of the type of public good on the sign of the income effect. She finds a negative income effect regarding recycling which requires time and effort but a positive income effect regarding convenient incineration which is effortless in terms of pro-environmental behavior. Indeed, a negative effect on WTP means that WTP decreases as income rises. This makes the environmental good an inferior good. This instance is generally overlooked, and this may be because in theoretical works, the functional forms of utility functions on which WTP is based, underpin homothetic preferences which only allow for positive income effects *e.g.* CES functions.

Although rarely studied, impacts of the environmental quality level on WTP should be of value. Can't the same good be evaluated differently by two countries with approximately the same incomes but different environmental impacts from that good? This would be interesting to take into account the level of environmental quality in benefit transfer as it is done for income. For example, the valuation of water quality in the Baltic sea which is at the crossover of nine countries has been studied in Ahtiainen et al. (2015). These countries substantially differ in their income levels, which is of interest for the previous question. But potentially, each country may experience water pollution at different levels as well, which naturally should affect WTP. As far as I know, only Rollins and Lyke (1998) studied the effect of environmental quality level on WTP estimates. In the context of national parks, they find that the higher the number of (hypothetical) existing parks, the lower the WTP for an additional park (WTP decreases by 47%). Horowitz (2002) theoretically defines the environmental effect on WTP[16] and emphasizes the need for more studies of the effect of environmental quality level on WTP.

2.2.2 Heterogenous discount rates

Hausman (1979) is the first paper which finds that the discount rate decreases as income increases. This makes poorer individuals discount the future more than richer individuals. Regarding households from the US, Lawrance (1991) estimates discount rates and confirms this finding. The same empirical evidence, although weaker, is put forward for Chinese households

[16]Similarly to the income effect and with the same notations as in the previous section, the environmental effect is formally denoted by $\frac{\partial WTP}{\partial E}\ \forall\, Y, E$.

by Sullivan (2011). Evidence in India (Pender and Walker, 1990) and Ethiopia (Yesuf and Bluffstone, 2008) also suggest a negative income effect on the discount rate.[17] Harrison et al. (2002) and Tanaka et al. (2010)[18] experimentally elicit time preferences and also support this result in respectively Denmark and Vietnam.

To the best of my knowledge, there are no empirical studies on the effect of environmental quality on discount rates.

Further empirical research is needed in this area. The limiting point seems to be the difficulty of estimating the cross elasticities of marginal utility which enter the discount rate formula ($\eta_{C,E}$ and $\eta_{E,C}$). Estimating such cross elasticities must imply that consumption and environmental quality are not considered as independent (in the Edgeworth-Pareto sense, see definition below).

As a summary, beyond the widely studied heterogeneity in terms of income levels, there is a heterogeneity in terms of environmental quality levels which is often overlooked in the literature, yet should be taken into account. As far as both private consumption and environmental quality provide utility, which is in line with most theoretical models in the area of environmental economics, it is natural to think that the way consumption goods and environmental goods interact in giving utility has a role in this observed heterogeneity of WTP and discount rates.

2.3 The substitutability concept at the core of the values heterogeneity?

In this thesis, I focus on the substitutability in terms of utility,[19] that is, how the interaction between private consumption and environmental quality affects utility. This section presents a broad review of the links which have been put forward between substitutability and *(i)* WTP elasticities and *(ii)* discounting.

2.3.1 The different definitions of substitutability

There are different ways of defining substitutability. Samuelson (1974) gives an exhaustive overview of these various definitions. Substitutability in utility, which is the focus of interest in this thesis, is generally defined either in the Edgeworth-Pareto (E-P) sense (Edgeworth, 1925; Pareto, 1909)[20] or in the Hicks sense (Hicks, 1932). The E-P definition simply relies on the

[17] The works from Sullivan (2011), Pender and Walker (1990) and Yesuf and Bluffstone (2008) were found thanks to Haushofer et al. (2013)'s literature review.

[18] This finding is only true for exponential discounting, not for the model of hyperbolic discounting.

[19] There are other contexts in which substitutability is defined. In a market setting, substitutability can be derived from crossed-price elasticities. In game theory, substitutability is employed to describe strategies interactions, see for example Figuières (2009).

[20] In the discounting literature, the E-P definition of substitutability is often employed (Heal, 2009; Gollier, 2012). This is also used by Gangadharan et al. (2015) in a context of risk.

sign of the cross derivative of the utility function, denoted by $U_{CE} = \frac{\partial U(C,E)^2}{\partial C \partial E}$, such that for all C and E:

$$\begin{array}{ll} \text{If } \; U_{CE} < 0 & \text{then, } C \text{ and } E \text{ are substitutable} \\ \text{If } \; U_{CE} > 0 & \text{then, } C \text{ and } E \text{ are complementary} \\ \text{If } \; U_{CE} = 0 & \text{then, } C \text{ and } E \text{ are independent} \end{array}$$

Thus, the direction in which the marginal utility of consumption changes with environmental quality determines whether consumption and environmental quality are substitutable or complementary. The E-P criterion is not directly a measure of substitutability but gives the nature of the interaction between consumption and environmental quality. This is the point of interest in Chapter 4.

The general Hicks definition of the elasticity of substitution (Hicks, 1932) is the following:

$$\varepsilon_{CE} \equiv \frac{\frac{\partial (C/E)}{(C/E)}}{\frac{\partial MRS}{MRS}} \tag{2.14}$$

where $MRS = \frac{U_E}{U_C} = \frac{\frac{\partial U}{\partial E}}{\frac{\partial U}{\partial C}}$ is the marginal rate of substitution between C and E.

This elasticity measures substitutability between goods along an indifference curve (for a given level of utility). In other words how the ratio of the consumption of the two goods for a given allocation varies as the marginal rate of substitution between the two in that allocation increases (Baumgärtner et al., 2015b).

The Hicks definition, in the case of homothetic preferences[21] (Samuelson, 1974), has been derived in Hicks (1932).[22]

$$\varepsilon^h_{CE} \equiv \frac{U_C \, U_E}{U \, U_{CE}} \tag{2.15}$$

If $\varepsilon^h_{CE} \longrightarrow 0$ then C and E are perfect complements. If $\varepsilon^h_{CE} \longrightarrow \infty$ then C and E are perfect substitutes. If $\varepsilon_{CE} = 1$ then preferences over C and E are represented by a Cobb-Douglas utility function. And a CES utility function implies $\varepsilon^h_{CE} = \sigma$ where σ is the elasticity of substitution between C and E that characterizes the CES utility function:

$$U^{CES}(C,E) = ((1-\gamma)C^{1-\frac{1}{\sigma}} + \gamma E^{1-\frac{1}{\sigma}})^{\frac{\sigma}{\sigma-1}} \tag{2.16}$$

[21]Preferences are homothetic if and only if they are of the form $\Phi(C,E) = F(f(C,E))$ where F is a monotone increasing function, f is a homogeneous function of degree one, that is, $f(kC,kE) = kf(C,E)$ for any $k > 0$.

[22]The Hicks elasticity of complementarity is defined as: $\frac{1}{\varepsilon_{CE}} = \frac{d\ln(\frac{U_C}{U_E})}{d\ln(\frac{E}{C})} = \frac{U_{CE}C}{U_E} + \frac{U_{CE}E}{U_C} = \frac{U \, U_{CE}}{U_C U_E}$, under the assumption that U is homogeneous of degree one *i.e.* $U = CU_C + EU_E$. The inverse of the Hicksian elasticity of complementarity results in the Hicks elasticity of substitution $\varepsilon_{CE} = \frac{U_C U_E}{U \, U_{CE}}$.

with γ the value share for consumption.

The latter Hicks definition is very often employed in the literature as a measure of substitutability. Most utility functions are homogenous of degree 1: this is the case of the CES utility function and its particular cases namely the Cobb-Douglas function, the linear function and the Leontieff function. The Edgeworth-Pareto substitutability covers a broader domain. ε^h_{CE} as employed in a CES function is a positive number (σ).[23] Hicks perfect substitutability ($\sigma \to \infty$) occurs when $U_{CE} = 0$, thus when there is Edgeworth-Pareto independence between the two goods. Hicks perfect complementarity ($\sigma \to 0$) occurs when $U_{CE} \to \infty$, thus when there is Edgeworth-Pareto complementarity. Thus the whole domain of the Hicks substitutability is only a part of the Edgeworth-Pareto measure of substitutability. The fact that an increase of E decreases the marginal utility of C is excluded from the cases covered by the CES function.

In Chapter 4, I use the Edgeworth-Pareto definition of substitutability. The latter is very simple to interpret[24] and easily implementable when it comes to the construction of a model.[25] The Hicksian elasticity of substitution can merely be applied to assumed utility functions as done in Baumgärtner et al. (2015b) for an extended CES function. However, when it comes to constructing a framework with specific substitutability properties, the Edgeworth-Pareto definition seems more appropriate. Notice that, regarding homothetic preferences, the two definitions are directly linked (see the cross derivative in the denominator of Eq. (2.15)).

In Chapter 5, a CES function is employed for the sake of simplicity. Indeed, the need for existing functions which either reflects substitutability or complementarity makes the CES utility function a readily implementable function with good properties, in the sense that it elegantly fills the continuum between perfect substitutability and perfect complementarity.

2.3.2 Substitutability and WTP

We saw in the previous section that the absence of market makes the use of WTP useful. However, the notion of willingness to accept (WTA) may as well be appropriate or more convenient in some situations.[26]

$$V(Y + WTA, E + \Delta E) = V(Y, E) \ . \tag{2.17}$$

This is the least amount of money an individual would accept to endure an environmental decrement.

The divergence between these two measures has attracted a lot of attention in the literature (see *e.g.* Horowitz et al. (2013) for a broad review) and has been explained in different ways.

[23] Otherwise, preferences are concave.

[24] A positive (negative) cross derivative involves that increasing E enhances (reduces) the marginal utility of C.

[25] Making an assumption about the cross derivative of the utility function is easier than making an assumption about the general Hicksian elasticity of substitution (Eq. (2.14)).

[26] Here, it is defined as the compensating variation, as the WTP previously.

Sugden (1999) approximated the WTP/WTA ratio with the following relationship which is in line with the definitions of WTA and WTP in Eq. (2.2) and (2.17) (Horowitz and McConnell, 2003):

$$\frac{WTP}{WTA} = 1 - \frac{\partial WTP}{\partial Y} \tag{2.18}$$

$\frac{\partial WTP}{\partial Y}$ is the income effect on WTP or equivalently the rate at which WTP increases with respect to increases in the endowment of the good (Sugden, 1999). A ratio $\frac{WTP}{WTA} > 1$ indicates a negative income effect on WTP (Horowitz and McConnell, 2003) whereas a ratio $\frac{WTP}{WTA} < 1$ indicates by a positive income effect on WTP.

Therefore, any concept at the origin of the difference between WTA and WTP is as well at the origin of heterogenous WTP across income levels. This is the case of the degree of substitutability between goods as reviewed below.

In a theoretical framework, Hanemann (1991) links the substitutability between private and public goods with the difference between WTA and WTP. His intuition starts with the extreme cases of a CES function. When two goods (one private and one public) are perfect complements (*i.e.* the elasticity of substitution tends to zero), the CES function reduces to a Leontieff function. For the intuition, imagine you are in a café and you consume two goods, tea (cups) c which you can buy at the price p_c and lemon l which is free but rationed (as public goods) by the waiter *i.e.* $l \leq \bar{l}\ \forall l$. Tea and lemon are perfect complements according to you, so you consume as many cups of tea as pieces of lemon available to you (here $\bar{l}$). Formally, this means that the utility function is of the form $u(c,l) = min\{c,l\}$. Imagine you spend all your income in buying cups of tea, which corresponds to the amount of pieces of lemon you can consume, *i.e.* $p_c\bar{l} = Y$ with Y your income, you cannot increase your utility by buying an additional cup of tea since there is no piece of lemon more to go with it and conversely, you cannot afford any additional cup of tea. This means that your WTP for an additional piece of lemon is zero. However, your WTA the loss of one piece of lemon is infinite since no cup of tea can compensate for the loss of a piece of lemon under perfect complementarity. Thus, perfect complements are associated with a low WTP and a high WTA.

Now if there is perfect substitutability between the two goods you consume (*i.e.* the constant elasticity of substitution tends to infinity) such as tea and coffee, then when your entire income is spent in tea and there is no more coffee (considering this is the rationed good), your WTA the loss of a cup of coffee equals your WTP for an additional cup of coffee since coffee and tea are perfect substitutes. WTP and WTA should in this case equal the price of a cup of tea if a one-to-one form of substitutability is considered *i.e.* if the same weight is attributed to tea and coffee in the utility function.

Hanemann (1991) shows in a general manner that the difference between WTA and WTP depends on the degree of substitutability between the two goods. The observation of high WTA/WTP ratios concerns goods with a few substitutes.

Later, Shogren et al. (1994) test and confirm Hanemann's theory in an experimental framework. In their auctions experiments, they consider a first good with many substitutes namely candy bars and a second good with a few substitutes namely the risk of infection from food-borne pathogens. After a series of repetitions, they find that the WTA/WTP ratio is high for the risk of infections whereas it is approximately 1 for candy bars. This supports the relationship between substitutability and the WTA/WTP ratio or difference.

Ebert (2003) uses a CES utility function to show the inverse relationship between the income elasticity of WTP and the elasticity of substitution. The former is smaller (greater) than one if and only if consumption and environmental quality are substitutable (complementary). As noticed by Baumgartner et al. (2016), this means that all the studies reviewed in subsection2.2.1 focused on substitutable private and environmental goods.

2.3.3 Substitutability and discounting

Substitutability also affects discount rate values. This is broadly analyzed within the dual-rate discounting literature through the case of a CES-CRRA (Constant Relative Risk Aversion) utility function. For the sake of clarity, consider an intertemporal utility function W such that:

$$W = \int_0^{+\infty} U(C(t),E(t))e^{-\delta t} \tag{2.19}$$

where $C(t)$ and $E(t)$ respectively stand for consumption and environmental quality at time t. At the individual level, W represents the individual's preferences regarding consumption and environmental quality profiles across time. Suppose

$$U(C(t),E(t)) = \frac{\mu}{1-\mu}\left[(1-\gamma)C^{1-\frac{1}{\sigma}} + \gamma E^{1-\frac{1}{\sigma}}\right]^{\frac{(\mu-1)\sigma}{\mu(\sigma-1)}} \tag{2.20}$$

with σ the (intratemporal) elasticity of substitution and μ the intertemporal elasticity of substitution.

Recall that:

$$r^C = \delta + g_C\eta_{C,C} + g_E\eta_{C,E}\ . \tag{2.21}$$

with $g_C = \frac{\dot{C}}{C}$ and $g_E = \frac{\dot{E}}{E}$ the respective growth rates of consumption and environmental quality over time.

Following Horowitz (2002), Hoel and Sterner (2007) show with a CES utility function that the assumption about the substitutability between consumption and environmental quality is fundamental to the value of the discount rate that is used in an intertemporal setting. In particular, they show that the relative price of environmental quality denoted by p_E is such that:

$$p_E = \frac{1}{\sigma}(g_C - g_E) \tag{2.22}$$

Thus, the price change is larger the smaller is the elasticity of substitution. This directly affects discount rates as eq. (2.13) puts forward. Sterner and Persson (2008) go a step further by introducing this CES utility function in Nordhaus' DICE model, which allows them to compute optimal GHG mitigation paths under different parameters. Their results differ from those of Nordhaus in that it calls for more drastic mitigation. Kögel (2009) uses the Edgeworth-Pareto definition of substitutability and relates it in a general manner to the discount rate values in a framework with intratemporal substitutability σ and intertemporal substitutability μ. Traeger (2011a) derives in a very clear manner the evolution of discount rates over time across the three cases. When the intratemporal elasticity of substitution is greater/equal/smaller than the intertemporal elasticity of substitution, the social discount rate increases/is constant/decreases over time. Generally, these results rely on the sign of the difference between the intratemporal elasticity of substitution and the intertemporal elasticity of substitution $\mu - \sigma$.

This heterogeneity of values and its link with the substitutability between goods motivate the theoretical approach that I undertake in Chapter 5. Whether private consumption and environmental quality are complementary or substitutable has an impact on the way individuals discount future consumption and environmental quality levels. However, the assumption on substitutability or complementarity is generally exogenous whereas it should depend on the context of the choice of the individual. Therefore, it should impact environmental and temporal preferences.

While Chapter 4 deals with heterogenous agents (different contexts) at the individual level, Chapter 5 introduces a collective dimension to this heterogeneity.

2.4 Substitutability and heterogenous agents: from the individual to the collective value

Many environmental problems have the structure of social dilemmas. A social dilemma occurs when self-interested objectives are at odds with collective objectives. Put differently, even though everybody is better off by acting in the collective interest (*i.e.* cooperating), acting in one's immediate self-interest is tempting to every individual involved. Overharvesting of fish, overgrazing of common property, destruction of forests and overreleasing greenhouse gases to the atmosphere are some examples of social dilemmas in the environmental context. One of the goals of economic experiments is to question the need of formal government intervention in the environmental domain. To what extent is self-regulation possible? Does everybody stick to the *homo-economicus* definition given by neoclassical economic theory? The homo economicus is purely self-interested *i.e.* only cares about her personal bundle of goods. Her only objective is to maximize her utility no matter how others are affected. In the environmental context, if individuals satisfy this definition, then they would not incur any additional cost to protect the environment (Noussair and Soest, 2014). Gintis (2000) provides a literature review on the failures of neoclassical economic theory to capture such a behavior in economic experiments. Experimental laboratories allow for testing alternative models of behavior in a relatively controlled environment.

There are many games which allow for behavior analysis in the lab. The Prisoner's dilemma game is the widespread one, in which two players decide whether to cooperate or to defect. Defection is the Nash (self-interested) strategy whereas the social optimum lies in cooperation. This game is particular in that the Nash strategy is dominant *i.e.* does not depend on the other player's strategy. By contrast, in the Chicken dilemma, the Nash strategy is non-dominant. In other words, the best strategy of an individual depends on the other player's strategy, so on the belief of what the other player will do. If both players decide not to cooperate, this results in the worst outcome (death). If the player believes the other player will cooperate, then her best response is not to cooperate. However if she believes the other player will not cooperate, then it is better to cooperate because losing the game is better than dying.

These are discrete games but continuous games also allow for behavior analysis in a social dilemma context. This is the case of public good games[27] which divide into two sorts of games. In the first game namely voluntary contributions mechanism (VCM), cooperation means giving or contributing to the group activity. In the second game namely common resource pool game, cooperation means not taking from a resource shared by a group of individuals (Van Lange et al., 2013). Fischbacher et al. (2001) find that only one third of the participants to their public good experiment had a purely self-interested behavior. Other regarding preferences play a major role in the deviation of behavior from Nash. Andreoni (1995) finds evidence of altruism (whether pure or impure *i.e.* warm-glow). In his experiment, about half of cooperation is due to kindness in general. Croson (2008) raises the importance of reciprocal behavior or equivalently conditional cooperation. About 80% of the subjects display reciprocity during the experiment. Inequality effects have also been analyzed (Fehr and Schmidt, 1999). Applying Fehr and Schmidt (1999)'s model, Dannenberg et al. (2007) find that inequality aversion is the main influencing factor for behavior in their public good experiment.

The literature on public good games largely relies on the linear structure, or more generally the additive structure. This means that the payoff function is the sum of the benefits from the private good and the benefits from the public good. Therefore, these benefits are additively separable. From another angle, public good games mostly rely on the assumption of perfect substitutability between private and public goods. Giving is thus assumed to be perfectly compensated by consuming private goods and reciprocally.

The latter statement can be questioned. May giving be complementary to one's own consumption rather than substitutable? Beyond other-than-self-interested behavior motives, the usual pattern of overcontributions compared to the Nash (see Ostrom (2000) for example) may be due to the structure of payoffs which does not reflect subjects preferences. Additionally,

[27] Public good games involving a dominant Nash strategy are merely iterated prisoner's dilemmas.

some subjects may think that private and public goods are substitutable while others may think they are complementary. What happens when these different types of subjects interact to provide a public good? This is what Chapter 5 deals with.

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Chapter 3

From quantities to values: the land use change time-accounting failure

This chapter is an extended version of the FAERE Working paper N°2016.25 which has been submitted to the journal Environmental and Resource Economics.

Abstract

Land use change (LUC) is the second largest human-induced source of greenhouse gases. While LUC impacts are mostly immediate, policy makers consider it to be evenly spread over time. In the context of public evaluation of projects, I theoretically show that, as long as the discounting process perfectly offsets the rise of carbon prices, cost-benefit analysis outcomes are not affected. When this condition does not hold, which is particular to the global warming issue, the *uniform* time-accounting of LUC distorts present values by emphasizing both the discounting process and the increase in the carbon price over time. This induced bias is quantified in a case study of bioethanol in France. Depending on the type of impact and discounting and carbon pricing assumptions, a downward/upward bias between ±15% and ±30% of the LUC value is found. Two simple decision tools are provided to improve accounting of LUC impacts.

Keywords: cost-benefit analysis, public evaluation of projects, land use change, discounting, relative carbon price, non-constant impacts, bioethanol

JEL Classification: D61, H43, Q15, Q16, Q48, Q54

3.1 Introduction

It is common knowledge that the relative prices of environmental resources are important to prevent climate change. These prices are now progressively incorporated in the estimation of the value of the discount rate (Guesnerie 2004; Weikard and Zhu 2005; Hoel and Sterner 2007; Sterner and Persson 2008). As put forward by Hotelling (1931), the price of a resource changes at the discount rate. This was first established in the context of exhaustible resources and more recently applied to carbon prices (Aaheim, 2010). However, determining the change of carbon prices over time using the same methods employed for exhaustible resources is problematic for at least two reasons. First, the capacity of the atmosphere to store greenhouse gas (GHG) emissions is not fixed but limited, which makes it a renewable resource rather than exhaustible (Tol, 2013). Indeed, there is a natural carbon absorption which tends to raise the carbon price growth rate above the discount rate (Bowen, 2011). Second, climate change is surrounded by a large degree of uncertainty (Pindyck, 2012) which tends to decrease the carbon price growth rate compared to the discount rate (Gollier and Baumstark, 2009). Considering these two deviations from the Hotelling rule, the carbon price growth rate and the discount rate should differ unless the two effects perfectly offset each other. As a consequence, carbon pricing and discounting have different effects at each point in time. This is fundamental when evaluating projects which impact global warming, particularly when using cost-benefit analysis.[1]

This leads to the central question of the paper: when GHG impacts are not constant over time but considered as such, what are the effects on cost-benefit analysis outcomes? This question is important as it directly affects the public evaluation of GHG-related projects.[2]

I examine this question in the context of land use change (LUC). LUC, which constitutes the second largest source of human-induced GHG emissions (IPCC, 2007), is particular in that its impacts mostly occur immediately (De Gorter and Tsur, 2010; Broch et al., 2013). Put differently, its impacts are not constant over time. Despite this, many energy policies[3] such as the European Renewable Energy Directive (RED) and the U.S. Renewable Fuel Standard 2 (RFS2), examine LUC impacts over time in a *uniform* way *i.e.* under the assumption they are spread evenly over time[4] (Martin et al., 2010; Broch et al., 2012; Broch et al., 2013; Kløverpris and Mueller, 2013).

By connecting the literature on the time distribution of LUC impacts and the literature on relative carbon prices, this paper raises and overcomes the bias that policy makers may overlook when evaluating projects with non-constant GHG impacts. The paper also suggests two tools to improve accounting of LUC impacts over time within the cost-benefit analysis process.

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[1]Atkinson and Mourato (2008) put forward that "even if policies are not solely formulated on the basis of [cost-benefit analysis], decisions at least should be informed by this tool".

[2]In practice, before their implementation, GHG-related projects go through an evaluation by policy makers which grant licenses whenever the project is welfare-improving. Otherwise, the application is rejected.

[3]Usually underpinned by life cycle assessment models, the most common approach to assess environmental impacts.

[4]*I.e.* regardless of the effective time profile of LUC impacts in both soils and vegetation.

In this paper, I compare the *uniform* and the *differentiated* annualization approaches. Contrary to the uniform annualization, the differentiated[5] approach accounts for the non-constant temporal profile of carbon in both soils and plants after a change in land use. To compare these approaches, I develop a simple theoretical model to first assess the direction of the bias induced by the uniform approach within a cost-benefit analysis framework. The results only rely on the assumption of diminishing impacts of LUC over time, which is supported by the biology literature (see Poeplau et al. (2011) and Qin et al. (2015) for recent studies).

It follows that the direction of the bias depends on the interplay between the discount rate and the growth rate of the carbon price. I find that, when the carbon price grows faster than the discount rate, the uniform approach induces a downward (upward) bias of the project value when GHG are emitted to (sequestered from) the atmosphere. A carbon price growth rate smaller than the discount rate generates the reverse. More generally, the uniform annualization emphasizes both the discounting overwhelming effect and the carbon price hike compared to what should be accounted for *i.e.* carbon (hence CO_2) changes as incorporated in the differentiated approach. This combined effect of the discount rate and relative carbon prices ties up with the literature on dual-rate discounting (Guesnerie, 2004; Weikard and Zhu, 2005; Hoel and Sterner, 2007; Gollier, 2010).

To underpin my theoretical framework, I quantitatively measure the magnitude of the bias through the case of bioethanol production in France. Only direct LUC is considered but the reasoning and conclusions can be extrapolated to indirect LUC, since the same physical mechanisms underlie these impacts. A quantification of the bias is made in the case of a conversion of an annual cropland into a second-generation biofuel feedstock, *Miscanthus*, generating sequestrations of GHG. As an example, combining discounting (3%) and relative carbon prices (1% growth rate), a 16.14% upward bias of the LUC value due to the uniform time-accounting is found, the discounting effect dominating the carbon price effect. In the case where data are only available in the form of constant annual flows, I suggest the use of a simple tool, namely the compensatory discount rate, which informs decision makers about the direction of the misestimation.

Additionally, I introduce a second tool, the *carbon profitability* payback period. It is defined as the point at which a biofuel project starts to generate net carbon gains in monetary terms compared to conventional fuels. In this framework, LUC can be thought of as a *monetized carbon investment* since the initial impact constitutes a social cost in order to get future GHG savings[6] which are expected to counterbalance the initial impact (hence the payback period concept). Such a payback period can constitute an interesting decision tool or at least inform policy makers in the context of evaluation of LUC-related projects. I provide numerical evidence that this payback period is shorter (higher) in the differentiated than in the uniform approach when discounting applies stronger (weaker) to impact flows than the increase of the

[5]Differentiated because the accounting for carbon dynamics makes LUC impact flows different across years.
[6]Compared with conventional fuels.

carbon price. The use of the uniform approach particularly in biofuel policies may be substantial and even reverse a decision about implementing or not a project depending on the decision criterion chosen by policies. This supports the importance of using the right data *i.e.* considering real CO_2 dynamics, before proceeding to the economic evaluation of any project with LUC impacts.

The remainder of the paper is organized as follows: Section 2 describes the peculiar time distribution of LUC and explains why a deviation from the Hotelling rule is required when it comes to impacts on global warming. Section 3 presents the model and the results. Section 4 offers numerical evidence with the case of bioethanol in France. Section 5 concludes.

3.2 Background

This section reports the two crucial elements whose interaction is at the origin of skewed economic evaluation of LUC-related projects, namely the time distribution of LUC impacts and the carbon price path considered within cost-benefit analysis.

3.2.1 Land use change time distribution: effective vs. accounted for in policies

LUC results in carbon stock changes after a land is converted to a new use, both in the vegetation and in the soil[7] which both constitute important carbon sinks. Many factors influence the magnitude of the disturbance: climate region, type of land converted, nature of the new land, agricultural practices. Depending on the carbon fraction of both the land which undergoes the change and the new land, the impact can occur in both directions: either a release of carbon generating GHG emissions[8], or a sequestration of carbon inducing GHG uptakes from the atmosphere.[9] Therefore it is crucial to understand the impact of LUC on carbon balances in order to reduce GHG emissions since it can either be beneficial or harmful to the climate.

Biofuels can constitute both an alternative to fossil fuels and a source of LUC. Changes in land use are the most important environmental impact of biofuels production (Feng and Babcock, 2010). They can either result from the replacement of other types of lands *i.e.* direct LUC[10] or from the displacement of existing crops *i.e.* indirect LUC[11] (Broch et al., 2012).

[7] Carbon in the soil is commonly named SOC, for Soil Organic Carbon.

[8] *E.g.* a forestland is converted into a cropland.

[9] *E.g.* afforestation.

[10] Direct LUC refers to the substitution of a given land for a cropland entirely dedicated to other uses such as energy crops.

[11] A cropland initially used for food supply purposes can be deviated from its original purpose for, say, energy purposes in a context of biofuel production. Since the initial food demand remains, the associated production may be partly displaced to previously non-cropland.

Many energy policies in different parts of the world[12] foster a switch from fossil fuels to biofuels, resulting in an expansion of lands for energy crops hence an increase of LUC. As a consequence, considerable attention has been drawn towards the potential significant emissions due to LUC up to the possibility of switching a positive[13] environmental balance into a negative one (Searchinger et al., 2008; Tyner et al., 2010).

LUC from biofuel production can also help mitigate climate change. Lignocellulosic biofuels such as *Miscanthus*[14] have indeed the potential to increase carbon storage in soils specifically when replacing a cropland (Qin et al., 2015). Based on these findings, the main biofuel policies namely the Renewable Energy Directive (RED) in the European Union and the Renewable Fuel Standard (RFS2) in the United States, progressively include these impacts in the environmental requirements for the development of biofuel production.

Despite this gradual consideration, LUC is characterized by a particular time profile which is not usually dealt with in the models on which policies are based.[15] Land conversion occurs just once as a shock, involving a decreasing temporal distribution of the impact by contrast to the steady time profile of emissions from *e.g.* feedstock cultivation or biofuel conversion. While the change in vegetation carbon stocks is in most cases instantaneous, the stock changes in the soil spread out over several years till the carbon stock reaches a new equilibrium (Marshall, 2009; Delucchi, 2011; Poeplau et al., 2011).[16]

The quantification of LUC impacts and their associated temporal dynamics is a difficult task. In life cyle assessments (LCAs) of biofuels, global warming impacts are totalled over a chosen period and divided equally across years (Martin et al., 2010; Broch et al., 2012; Kløverpris and Mueller, 2013). This straight line amortization method (henceforth *uniform* annualization) constitutes the basis of most biofuel policies, specifically the European RED.[17] Those take advantage of the simplicity and consistency of this approach but fail to account for the real dynamics of each carbon sink, henceforth *differentiated* annualization. The two different time distributions are illustrated in Figure 3.1 where the areas under the two curves are equal. This confusion is not an issue when only accounting for impact: as far as LCAs are founded on the summation of physical GHG flows and as long as no temporal parameter affect

[12] *E.g.* the Energy Independence and Security Act of 2007 in the United States and the EU Renewable Energy Directive of 2009.

[13] In the sense that the environmental balance of biofuels is better than the oil's.

[14] A perennial grass.

[15] A formal categorization of the American and the European energy policies regarding the time-accounting of LUC they employ is provided in Appendix D in Definition 3.

[16] In the case of emissions, LUC impacts divide into *(i)* a large upfront release of carbon to the atmosphere especially due to the above-ground biomass and *(ii)* smaller ongoing releases of carbon from the soil during a specific period of time (De Gorter and Tsur, 2010; Broch et al., 2013). In the case of sequestrations, which mainly refers to a land conversion from an annual cropland to a lignocellulosic feedstock such as *Miscanthus*, research still goes on regarding the dynamic of SOC. The general trend is though a decreasing profile of sequestrations in the soil over time (Qin et al., 2015).

[17] The U.S. policy (RFS2) goes forward by distinguishing vegetation and soil time horizons: emissions from vegetation are fully accounted for at time zero whereas soil emissions are equally scattered over 30 years. Nonetheless, there is no carbon dynamic.

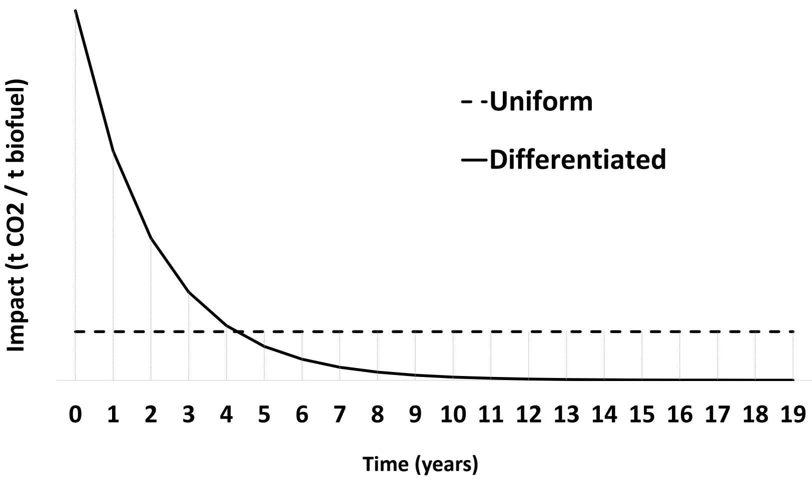


Figure 3.1: Time distributions of LUC impact flows: uniform annualization *vs.* differentiated annualization

differently points in time, the two time allocations are strictly equivalent (De Gorter and Tsur, 2010). Beyond LCA though, the process of decision-making about whether or not to develop a biofuel production requires economic tools implemented to evaluate the social net benefit of the project in monetary terms. De Gorter and Tsur (2010) emphasize that the economic outcomes of under-policy GHG impacts must be assessed through cost-benefit analysis, beyond LCA methods.

3.2.2 Carbon prices and the Hotelling rule

Evaluating a project that impacts global warming requires *(i)* giving a monetary value to GHG emissions (usually to CO_2eq) at each point in time and *(ii)* aggregating costs and benefits of the project over time by discounting them to a chosen time period. These two steps are fully part of the time dimension which characterizes a cost-benefit analysis, the common tool employed in economic assessments of projects.

A fundamental question in a context of public evaluation of GHG impacts is how does the carbon price grows over time? Most climate-economy models (hence policies) are run as if climate change were an exhaustible resource to which the Hotelling rule applies (Aaheim, 2010). It means that relative carbon prices follow from a standard Hotelling rule which results in a carbon price growing at the discount rate.[18]

However, it is crucial to depart from the well-known context of the theory to fully account for the global warming framework. Indeed, the Hotelling rule may not apply unless the two following reasons thoroughly offset each other. First, emissions of GHG can be absorbed nat-

[18]The capacity of the atmosphere to manage a certain concentration of GHG is treated as an exhaustible resource. The emissions cap (quotas) determines the amount of allowed emissions within a given period and this margin depletes over time as one emits GHG. Consuming the entire quota implies an equivalence between emitting one tonne of CO_2 today or in a year, which underlies that the carbon price increases at the discount rate.

urally, which partially corrects the context by switching it into a renewable resource problem (Tol, 2013). Following this, the carbon price grows at a rate equal to the sum of the discount rate and the natural carbon absorption rate.[19] Indeed, a positive natural absorption generates additional decay thus encourages emissions today rather than in the future (Ulph and Ulph, 1994). This makes the carbon price rise over time at a faster pace than the discount rate (Greaker et al., 2009; Quinet, 2009; Becker et al., 2010). Second, the consequences of global warming are largely uncertain (Pindyck, 2012). Uncertainty particularly applies to damages in the future, technological progress and the efforts and cooperation necessary to the emissions reduction (Gollier and Baumstark, 2009). By accounting for uncertainty, economic agents[20] prefer to diminish the risk of climate change *e.g.* by making more efforts upfront (Stern, 2008). As a consequence, the carbon price is emphasized today, which counterbalances its slow growth (slower than the discount rate) further after (Philibert, 1999; Gollier and Baumstark, 2009; Anthoff et al., 2011).

Therefore these two features of global warming induce a potential deviation from the Hotelling rule that is, a growth rate of the carbon price which is not the same as the discount rate.

3.3 Theoretical framework

This section develops a simple two-period model to assess the direction of the bias induced by the uniform approach on cost-benefit analysis outcomes, depending on the involved temporal effect (discounting *vs.* relative carbon prices).

3.3.1 The model

Consider two periods $t = \{0,1\}$ and denote by z_t the effective impact flow occuring at time t. The model aims to compare the LUC-related net present value[21] (NPV) under the uniform (index u) and the differentiated (index d) annualization approaches. It also allows me to disentangle the effects of the two main parameters of the cost-benefit analysis namely the discount rate and the carbon price over time. The differentiated annualization preserves the effective flows at their respective time. By contrast, the uniform annualization which averages emissions over a chosen period of time (here 2 years) , modifies the effective flows z_0 and z_1 into $\frac{z_0+z_1}{2}$ $\forall t = \{0,1\}$.

Consider a project which generates LUC impacts from time $t = 0$ to time $t = 1$. The price of carbon grows at the carbon price growth rate denoted by $r_p \in [0;1]$ such that $p_0 \geq 0$ and $p_1 = p_0(1+r_p) \geq 0$. Denoting by $0 \leq r \leq 1$ the discount rate, the NPVs respectively associated to the differentiated and uniform approaches are as follows:

[19] In the DICE model (Nordhaus, 2007), this rate is referred to as the "net carbon interest rate".

[20] Supposed risk-averse.

[21] Which is a component of the more global NPV which accounts for both economic and environmental impacts.

$$\forall z_0, z_1 \in \mathbb{R} \begin{cases} NPV_d = p_0 z_0 + p_0(1+r_p)\frac{z_1}{1+r} \\ \\ NPV_u = p_0 \frac{z_0+z_1}{2} + p_0(1+r_p)\frac{z_0+z_1}{2(1+r)} \end{cases} \tag{3.1}$$

So far, I did not specify the nature of the impact z_t. Henceforth, based on the literature about the dynamic profiles of emissions and sequestrations put forward in Section 3.2, I rely on the following assumption.[22]

Assumption 1 (Emissions and sequestrations time monotonicity) *Emissions are considered as a social cost ($z_t < 0\ \forall t$) whereas sequestrations are considered as a social benefit ($z_t > 0\ \forall t$). Both impacts in the conversion year are greater than impacts at the next time i.e. formally $|z_0| > |z_1|$.*

In the following subsections, Equation (3.1) is divided into specific cases which correspond to particular values of the discount rate and the carbon price growth rate. Considering the differentiated annualization as the baseline, I assess the bias induced by the uniform approach.

3.3.2 Discounting effect ($r_p = 0$ and $0 < r \leq 1$)

To isolate the discounting effect, I assume in this subsection that the carbon price is constant such that $p_0 = p_1 = p$. Denoting by $\Delta NPV = NPV_u - NPV_d$ the NPV difference between the two kinds of annualization, the resulting sign of ΔNPV gives information about the downward or upward bias generated by the use of the uniform annualization. Deriving the NPV difference relatively to the discount rate allows me to determine how the bias varies when the discount rate value changes. In other words, it indicates whether the bias is emphasized or reduced when the discount rate increases. I get:

$$\Delta NPV = \frac{p\, r(z_1 - z_0)}{2(1+r)} \qquad \& \qquad \frac{\partial \Delta NPV}{\partial r} = \frac{p(z_1 - z_0)}{2(1+r)^2} \tag{3.2}$$

The results are summarized in Proposition 1 whose proof is in Appendix A.

Proposition 1 (Discounting effect) *The uniform annualization emphasizes the process of discounting, which results in:*

- *an overestimation of the project value in the net emissions case;*
- *an underestimation of the project in the net sequestrations case.*

The higher the discount rate, the larger the bias for both cases.

[22] To keep the model general, I do not specify the functional form of the carbon dynamics but only the time monotonicity. Indeed, as highlighed in Poeplau et al. (2011), the functional form for one conversion (*e.g.* linear, exponential or polynomial) does not necessarily hold for other conversion types.

Indeed, from Eq. (3.2), ΔNPV is positive (negative) in the case of net emissions (sequestrations) and the misestimation increases as the discount rate grows for both impacts.[23]

Emissions interpretation: Since emissions are equally scattered over time in the uniform approach, the emissions at $t = 1$ are overwhelmed by the discounting effect which softens the monetary cost of the impact and thus underestimates the costs of the project or equivalently overestimates the project value. On the contrary, in the differentiated approach, the emissions are mostly gathered at $t = 0$ hence not subject to discounting; therefore, the costs associated with these upfront emissions are fully accounted for.

Sequestrations interpretation: The dynamic of sequestration being taken into account in the differentiated approach, the sequestered quantities are higher at $t = 0$ than $t = 1$ (Assumption 1) thus less subject to the discounting pressure than in the uniform approach. In the latter though, sequestrations are relatively more accounted for at the end of the project when discounting applies, leading to the downward bias on the project value.

Generally, the discount rate exercises an increasing weight on GHG impacts in the future. Since *(i)* sequestrations are benefits to the society and mostly occur in the years following land conversion and *(ii)* emissions are costs to the society and mainly upfront, the scattering of impacts equally over time, stipulated by the uniform approach, induces an upward (downward) knock-on effect on the NPV when GHG are emitted (sequestered) to (from) the atmosphere.

3.3.3 Carbon price effect ($r = 0$ and $0 < r_p \leq 1$)

To isolate the carbon price effect, I apply in this subsection a discount rate equal to zero. Denoting by $\Delta p = p_1 - p_0 = p_0 r_p > 0$ the carbon price difference between the two periods, the NPV difference between the two approaches and its derivative with respect to Δp are:

$$\Delta NPV = \frac{1}{2}\Delta p(z_0 - z_1) \qquad \& \qquad \frac{\partial \Delta NPV}{\partial \Delta p} = \frac{1}{2}(z_0 - z_1) \tag{3.3}$$

which leads to Proposition 2 proved in Appendix B.

Proposition 2 (Carbon price effects) *The uniform annualization enhances the increase of the carbon price over time, which results in:*

- *an underestimation of the project value in the net emissions case;*
- *an overestimation of the project in the net sequestrations case.*

[23]Regarding emissions, since $\Delta NPV > 0$, $\frac{\partial \Delta NPV}{\partial r} > 0$ implies an increasing bias. Regarding sequestrations, since $\Delta NPV < 0$, $\frac{\partial \Delta NPV}{\partial r} < 0$ means a more and more negative ΔNPV as r increases, hence an increasing bias as well.

The higher the carbon price growth, the larger the bias for both cases.

Indeed, ΔNPV is negative (positive) in the case of net emissions (sequestrations) and the bias increases for both emissions as the carbon price grows faster.[24]

Emissions interpretation: Because the carbon price is increasing over time, the earlier the emission the lower its social cost. In the differentiated approach, emissions mostly occur up-front when the carbon price is lower. By contrast, the uniform approach entails emissions equally spread out over time thus more emissions are priced higher at time $t = 1$. Higher priced emissions constituting an emphasized cost leads to an understated NPV under the uniform approach.

Sequestrations interpretation: Sequestrations are mostly accounted for at $t = 0$ in the differentiated approach hence given a smaller value than in the uniform approach. This overestimates the project value under the uniform approach and all the more the carbon price scenario is constraining.

The scattering of GHG impacts over time in the uniform approach emphasizes the carbon price effect compared with the differentiated approach *i.e.* flows are given more value regardless the sign. However, as sequestrations are environmental benefits and emissions are environmental costs, the former has an upward knock-on effect on the NPV whereas the latter induces a downward knock-on effect.

3.3.4 Combined discounting and carbon price effects

As showed in the two previous subsections, the uniform annualization enhances both the discounting overwhelming effect and the carbon price increase. Those have opposite impacts on the NPV. Here, the two effect are combined as to determine the dominant one. Evaluating the NPV difference between the two approaches results in opposite conditions for the net emissions case and the net sequestrations case. Propositions 3 and 4 are based upon the results in Table 3.1 and proved in Appendix C.

Table 3.1: Results of the combined discounting and carbon price effects

Emissions	Sequestrations
$\Delta NPV = 0 \Leftrightarrow r_p = r \quad (a)$	
$\Delta NPV > 0 \Leftrightarrow r_p < r \quad (b_{emi})$	$\Delta NPV > 0 \Leftrightarrow r_p > r \quad (b_{seq})$
$\Delta NPV < 0 \Leftrightarrow r_p > r \quad (c_{emi})$	$\Delta NPV < 0 \Leftrightarrow r_p < r \quad (c_{seq})$

[24] Since $\Delta NPV < 0$ in the case of emissions, $\frac{\partial \Delta NPV}{\partial r} < 0$ means that ΔNPV is more and more negative involving an increasing bias. Regarding sequestrations, since $\Delta NPV > 0$, $\frac{\partial \Delta NPV}{\partial r} > 0$ also implies an increasing bias as well.

Proposition 3 (Combined effect under the Hotelling rule) *Under the Hotelling rule, no bias is induced by the uniform approach: the uniform and differentiated annualizations result in the same value of the project whether greenhouse gases are emitted to or sequestered from the atmosphere.*

There is no bias induced by the uniform annualization (case (a)) when discounting and carbon price effects perfectly offset one another. Distributing the impacts uniformly or differentiately gives the same NPV of the project since the temporal parameters at stake thoroughly balance out each other. This situation underlies that the construction of the carbon price trajectory either stricly follows the Hotelling rule or involves a perfect compensation between *(i)* the uncertainty surrounding climate change which tends to diminish the growth rate of the carbon price and *(ii)* the natural absorption of CO_2 emissions which on the contrary tends to elevate it. The latter is one of the conclusions drawn out of the shadow value of carbon report in France (Quinet, 2009).

Proposition 4 (Combined effect out of the Hotelling rule) *When the carbon price time evolution deviates from the Hotelling rule, the uniform annualization approach induces :*

- *an upward bias of the project value if and only if the carbon price grows slower (faster) than the discount rate, in the case of net emissions (sequestrations);*
- *a downward bias of the project value if and only if the carbon price grows faster (slower) than the discount rate, in the case of net emissions (sequestrations).*

Emissions interpretation: The upward bias (case (b_{emi})) comes from the discounting effect which outweighs the carbon price effect. In other words, the discounting effect overwhelms the global warming impacts of the project faster than the carbon price raises. This effect is partly avoided in the differentiated approach since most emissions are immediate when no discounting applies. The uniform distribution of the total impact over time though suffers more from this outcome. In monetary terms, it means that the cost of upfront emissions is given relatively more value in the differentiated approach, leading to an overestimation of the project. A lower growth rate of the carbon price than the discount rate puts forward the uncertainty about the magnitude of the damages of climate change. This view calls for a strong price signal today to incentivize the reduction of emissions immediately.

By contrast, the uniform approach understates the project value when the carbon price effect dominates the discounting effect (case (c_{emi})), which allows GHG impacts to gain (monetary) value over time even after discounting: the undiscounted initial emission in the differentiated approach is then counterbalanced by the increasing price of carbon which applies to the ongoing impacts over time in the uniform approach. The differentiated approach benefits virtually nothing from increasing the price, since emissions are mainly upfront. Such a situation where the annual growth rate of the carbon price is greater than the discount rate is likely to occur when the natural absorption of CO_2 is not negligible.

Sequestrations interpretation: The upward bias (case (b_{seq})) comes here from the carbon price effect which outweighs the discounting effect. The same logic as emissions applies since most sequestrations occur right after land conversion. Nevertheless, in monetary terms, sequestrations are benefits. Those are raised by the carbon price increase in the uniform approach leading to such an overestimation of the project value. On the contrary, the downward bias (case (c_{seq})) comes from the dominant discounting pressure which overwhelms the monetary flows of sequestration in the uniform approach, resulting in an undervaluation of the project.

3.4 Numerical illustration

Bioethanol constitutes an alternative to gasoline. It can be produced from a variety of feedstocks such as wheat, corn, sugarbeet (first generation biofuels), switchgrass, *Miscanthus* (second generation biofuels). The production of first generation bioethanol is well-established at the commercial scale in contrast with the second generation which is more recent. However, the Futurol project[25] initiated by French stakeholders will be launched in 2016 to produce second generation bioethanol. France is the first bioethanol producer in Europe and the second consumer after Germany. It is located in a temperate region where the increasing demand in bioenergy currently leads to more and more LUC (Poeplau et al., 2011). The lands which are likely to be converted for both first and second generations are: croplands, grasslands and less likely forestlands (Chakir and Vermont, 2013).[26] The two types of biomass I consider in the analysis are wheat for the first generation and *Miscanthus* for the second generation of biofuel, which is representative of the feedstocks used in France.[27]

3.4.1 Scope and assumptions

As a locally assessed change, direct LUC is easier to estimate than the global-scale issue of indirect LUC which involves market responses (Feng and Babcock, 2010). Estimating indirect LUC is more complex since it can occur in a different location from the one where biofuels are produced. It particularly involves various market mechanisms (Broch et al., 2013; Zilberman et al., 2013) (see for example Keeney and Hertel (2009)). Thus, to avoid controversy about how to measure indirect LUC, I only focus on direct LUC. Still, as shown below, the impact

[25]Futurol is one of the top five international second generation bioethanol projects in the world.

[26]Indeed, despite the regulations which prohibit the conversion of high carbon land types, grasslands and some forestlands are still respectively ploughed and cleared because the incentive to develop energy crops is considerable.

[27]To get an idea of the scale of LUC impacts due to French bioethanol compared to the other emission types, wheat-based ethanol generates LUC emissions which account for 23% of the environmental balance: 46.2 gCO_{2eq}/MJ for the overall process and 14 gCO_{2eq}/MJ for LUC. These data come from Chakir and Vermont (2013) and the IFPRI report Laborde (2011).

of direct LUC is remarkable. Nonetheless, all the results in this section extend to the issue of indirect LUC.

I argue it is reasonable to use a 20 year time horizon[28] for a number of reasons. First this is the time horizon considered in the Renewable Energy Directive in Europe (The European Commission, 2009). Second, the lifetime of an industry producing ethanol is often about 20 years (Humbird et al., 2011). Third, the second generation crop considered in this paper *i.e. Miscanthus* has a producing life of around 20 years (Khanna et al., 2008). Fourth, the temporal dynamics of SOC changes are assumed to occur over 20 years (IPCC, 2006). Fifth, uncertainty increases the longer the time horizon (see Stern (2008)). Finally, I assume that biofuels are more often considered a transition technology rather than a long run technology as in Searchinger et al. (2008, supplementary material).

Regarding emissions (*i.e.* conversions of both grasslands and forests into a cropland in this section), I suppose that *(i)* SOC dynamics follow an exponential decrease based on Poeplau et al. (2011) and *(ii)* biomass-related impacts are instantaneous[29] (*i.e.* only accounted for at t_0) as put forward by De Gorter and Tsur (2010). Regarding sequestrations (*i.e.* when replacing an annual cropland by *Miscanthus* in this section), *(i)* I also consider an exponential decrease of sequestrations in the soil which can fit the description of Qin et al. (2015) while awaiting further research and *(ii)* I do not consider any carbon dynamic for the biomass since *Miscanthus* biomass is harvested every year for bioethanol production.

The discount rates I employ are constant and range from 0 to 5% in the analysis, which is in line with the estimated values of the social discount rate found in Europe for cost-benefit analyses of projects and policies (Florio, 2014, p.187).

Finally, I construct trajectories of the price of carbon from 2020 as follows, characterized by the values pair $\{p_{2020},\ r_p\}$ with p_{2020} the initial price and r_p the carbon price growth rate:

- O Constant price of carbon $\{40, 0\%\}$
- A Low initial price and high growth rate $\{40, 5\%\}$
- B Low initial price and medium growth rate $\{40, 3\%\}$
- C High initial price and low growth rate $\{80, 1\%\}$

By constructing my own pathways, I avoid the complex assumptions which underpin carbon price scenarios in the literature. For example, it is not clear in the World Energy Outlook scenarios which assumptions are made about the discount rate value (which I make vary in my analysis). Scenario *O* is the baseline *i.e.* no carbon price growth. Scenarios A, B and C illustrate different situations: in Scenario A, the price of carbon grows fast; in Scenario B,

[28]Time $t = 0$ refers to the land conversion. The production starts at $t = 1$ once the biomass is mature, ready to be used and time $t = 20$ refers to the end of the biofuel production. Note that I consider the project always starts in 2020. Additionally, I hypothesize that, as an annual crop such as wheat, *Miscanthus* is mature within a year instead of two or three in reality for the sake of simplicity.

[29]Nonetheless, the rate of decay of the initial biomass depends on how it is managed afterwards *e.g.* left to decompose, burned, buried, converted into long lived products such as furnitures (Delucchi, 2011). This is taken into account through the variables ω_s and ω_v described in Appendix D.

it grows slower from the same initial price; Scenario C, characterized by a high initial price, represents a strong value signal to reduce emissions hence to avoid abrupt climate change. Roughly, Scenario A is more in line with Nordhaus' idea of *climate policy ramp* (Nordhaus, 2007) which promotes a progressive cut in emissions, hence larger cuts in the future, whereas Scenario C calls for more aggressive emissions reductions today as Stern puts forward in his review (Stern, 2006; Stern, 2008).

3.4.2 Data and computation

The computation of LUC impacts relies on the formal definitions of the uniform and the differentiated annualizations as described in Appendix D. An overview of the necessary data to the study is provided in Appendix E.

Agronomic data: To determine carbon stocks in soil and vegetation, I rely on the guidelines provided by The European Commission (2010) which are based on the IPCC (2006). Such a calculation requires the following information: climatic region, soil type, agricultural management, agricultural practices (inputs level) and crop yields.

Environmental data: Regarding the shares of carbon which are translated into CO_2 impacts, I assume that 30% of the carbon stock in soil is translated into CO_2, which is in the range given by the Winrock database (see Table 1 in Broch et al. 2013) and very close to Tyner et al. 2010's assumption of 25%. I assume that the reverse is symmetric (same coefficients from carbon to CO_2 (emissions), and from CO_2 to stored carbon (sequestrations). Regarding the carbon stored in vegetation, I hypothesize that 90% is translated into global warming impacts as the CARB policy in the United States assumes.[30] I suppose that the sequestration implies 100% of sequestrations of CO_2 transformed into carbon in biomass.

Computation tool: I develop a Python program to calculate the NPV of the GHG impacts of bioethanol projects. Once land use change impacts on SOC and biomass as well as their dynamic over time are determined, they are converted into CO_2 emissions or sequestrations according to Appendix D, and finally priced with one of the scenarios listed above.[31] Regarding price scenarios, an algorithm which exponentially extrapolates prices allows me to generate a complete trajectory of carbon prices over the time horizon considered, from one-time carbon prices as provided in most scenarios such as those from the Quinet report or the World Energy Outlook. The program essentially returns all the NPV types necessary to the analysis *i.e.* LUC impacts, non-LUC impacts and total global warming impact (*i.e.* LUC + non-LUC).

[30]Tyner et al. 2010 assume that 75% is lost and Searchinger et al. 2008 suppose that 100% goes to the atmosphere.

[31]Referring to Appendix D regarding the differentiated annualization (Definition 2), the program determines the coefficient a of the carbon response function as mentioned before, while taking into account the associated time horizon (for soil or vegetation).

3.4.3 Results

The results on the discounting, carbon price and combined effects exclusively refer to the net CO_2 sequestration case (conversion from an annual cropland to *Miscanthus*). Other land cover results (forestland/grassland into cropland) are provided in Appendix F and complement the illustration of Propositions 3 and 4. Only the last part regarding the borrowing effect, in which an emission is necessary for the analysis, deals with a conversion from a grassland to an annual cropland. Since there are no scale effects regarding emissions or sequestrations in terms of LUC from the production of one unit of bioethanol, I consider a trajectory of one tonne of bioethanol per year for 20 years for simplicity.

Discounting effects: To study the discounting effect, the price of carbon is set constant and equal to 40€ in 2020 ($t = 0$) *i.e.* Scenario O. As a consequence, all the differences in the NPVs

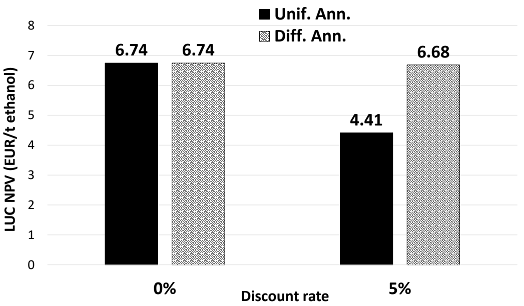


Figure 3.2: Discounting effects

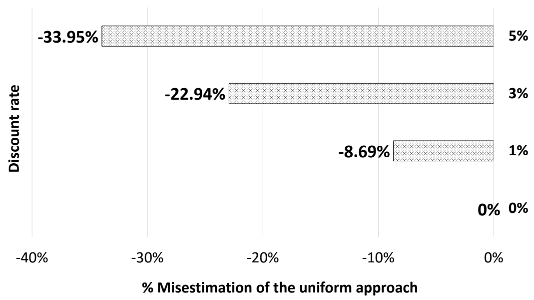


Figure 3.3: Relative downward bias induced by the uniform approch across different discount rate values

across the two time distributions are exclusively attributed to the discounting effect. An underestimation induced by the uniform approach compared to the differentiated one is clearly put forward in Figure 3.2.[32] The underestimation raises from the lower sequestrations accounted for in the beginning of the project which are not subject to the discounting process. With only a 1% discount rate, there is almost a 9% downward bias of the LUC value because of the uniform approach, as pointed out in Figure 3.3. It increases till around 34% with a 5% discount rate, which is not negligible.

Carbon price effects: The discount rate is set to 0% in order to isolate the carbon price effect. An overestimation induced by the uniform approach compared to the differentiated one is clearly noted in Figure 3.4. Figure 3.5 quantifies in relative terms the errors induced by the uniform annualization on the LUC value. The overestimation comes from the higher sequestrations occuring at the end of the project in the uniform approach when higher prices of carbon are applied. As also shown in Figure 3.5, the higher (*i.e.* more constraining) the carbon price scenario, the larger the overestimation. There is a consequent bias especially with Scenario A

[32] Since a net sequestration of CO_2 from the atmosphere is considered here, the NPVs are positive.

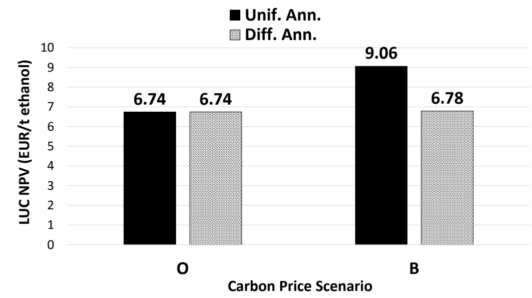


Figure 3.4: Carbon price effects

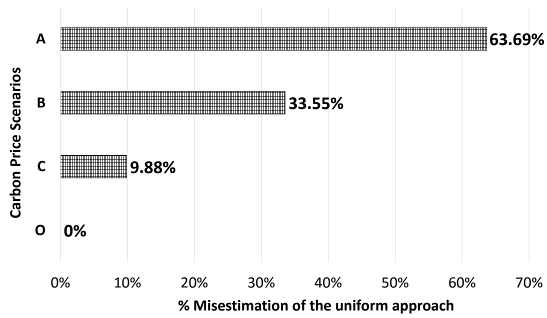


Figure 3.5: Relative upward bias induced by the uniform approach across different carbon price scenarios

(overvaluation of around 64%).

Combined effects: Here, I consider a 3% discount rate and an increasing price of carbon. As a result, the uniform annualization induces either an underestimation of the LUC value if the discounting effect dominates the carbon price effect or an overestimation if the reverse holds.

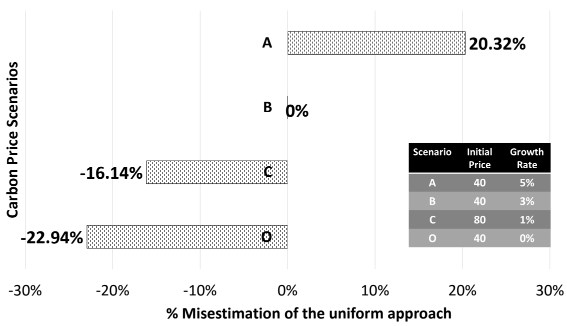


Figure 3.6: Combined dicounting and carbon price effects: bias induced by the uniform approach

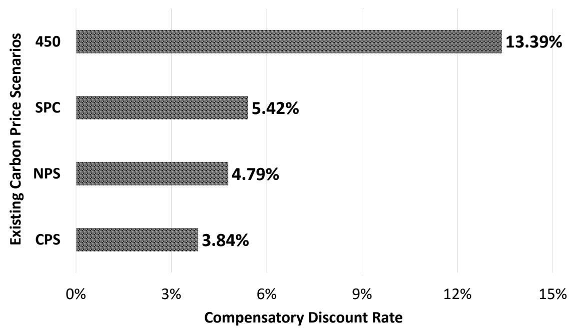


Figure 3.7: Compensatory discount rate for carbon price reference scenarios

Fixing the discount rate at 3% and varying the scenarios of the carbon price give Figure 3.6. It echoes Proposition 4 since in Scenario A, the carbon price (5%) grows faster than the discount rate, which results in an overestimation. In Scenarios O and C, the discount rate is greater than the carbon price growth rate hence the illustrated underestimation. Scenario B underlies a carbon price which grows at 3% thus perfectly offsets the discounting effect and implies an equivalence between the uniform and the differentiated approaches as stated in Proposition 3. On average, a fifth of the LUC value is either over- or underestimated because of the uniform way of accounting for LUC, which is considerable and calls for a correction of this bias.

Calculating the compensatory discount rate necessary to cancel the bias induced by the uniform annualization brings some interesting information when studying existing reference scenarios such as the French shadow price of carbon[33] (SPC) from Quinet (2009) and the World Energy Outlook scenarios (IEA, 2015) as put forward in Figure 3.7. This is the implicit discount rate that should be used in cost-benefit analysis to reach equal outcomes from both the uniform and the differentiated approaches. It particularly depends on the emissions or sequestrations flows generated by the LUC and the chosen time horizon. The calculation of such a discount rate can constitute a decision tool for policymakers. Indeed, for a given impact (net emission or sequestration) and a given carbon price scenario, if *(i)* policy makers are provided evenly spread over time LUC impacts data, as usually done by LCA models, and *(ii)* they choose a different discount rate than the compensatory discount rate while evaluating submitted projects, then according to Proposition 4, they have the information about the direction of their estimation bias.

Referring to Figure 3.7, Scenarios CPS, NPS and SPC result in average discount rates of the magnitude 4-5%, which is close to market rates (Greaker et al., 2009) as would probably support Nordhaus in contrast to Stern.[34] In particular, the 450ppm scenario underlies a very high discount rate of 13.39% compared to the usual discount rates employed in public project evaluation (Florio, 2014). The latter could either be interpreted as an unfeasible path or call for a necessary deviation from the Hotelling rule hence a real carbon dynamic accounting in cost-benefit analysis. Overall, as long as decision makers depart from these discount rates while using the respective scenarios, the uniform approach distorts a project value. And even if one *imagines* that these discount rates were used for any project assessment by policies, the best alternative, in order to avoid such calculations, remains the accounting for effective impact flows as described in the biology literature and summarized in the differentiated annualization.

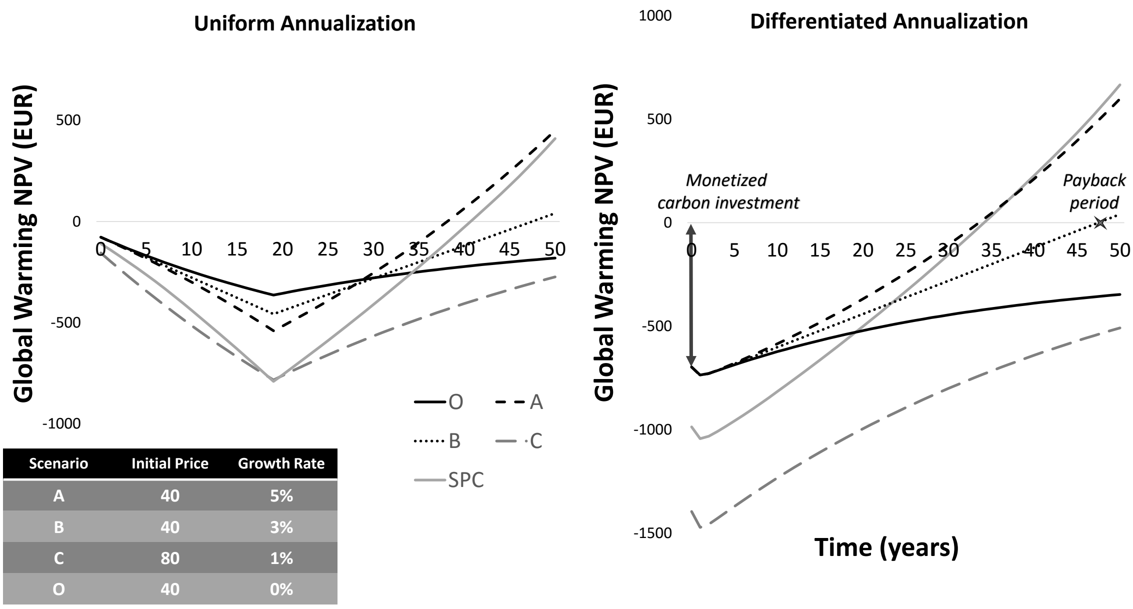
Borrowing effects: In contrast to the previous effects, the borrowing effect is studied in the context of the entire global warming impacts value *i.e.* both LUC and non-LUC emissions are accounted for in the NPV. The land conversion considered is from a grassland to wheat (emission). Ethanol projects are compared to oil production projects based on equivalent produced energy. In this study, GHG savings are allowed because aside from LUC emissions, the amount of GHG emitted from the production and consumption of oil is greater than the energy-equivalent GHG amount from ethanol production and consumption. I introduce the concept of *monetized carbon investment* which is illustrated in Figure 3.8.[35] LUC looks like a (shadow) carbon investment since the initial emission constitutes a social cost in order to get future GHG savings (hence relative carbon benefits) which are expected to counterbalance the initial impact hence generate carbon-related profits. The monetized carbon investment could also be considered as a borrowed (monetized) amount of carbon from the atmosphere which

[33] In the Quinet report, the shadow value of carbon is supposed to be 32 EUR in 2010 and 100 EUR in 2030. From 2030, the price increases at the public discount rate fixed at 4%.

[34] Who argues for a 1.4% discount rate in his report.

[35] Note that in the differentiated approach, the initial kink on every curve is due to the one-year delay of biofuel production. LUC occurs at $t = 0$ and the process of production which allows for "GHG refunding" starts at $t = 1$.

is "refunded" later in the future. The cross in Figure 3.8 illustrates the payback period of this carbon investment for Scenario B. The differentiated annualization provides clear information about the carbon investment initially made compared to the uniform annualization.



Scenario	Initial Price	Growth Rate
A	40	5%
B	40	3%
C	80	1%
O	40	0%

Figure 3.8: Monetized carbon investment payback periods across different carbon price scenarios and time distributions

Table 3.2 reports these *carbon profitability* payback periods under different carbon price scenarios and across the two time distributions.[36] Carbon profitability becomes positive (at the payback period) when a biofuel project starts to be environmentally profitable, that is when net GHG savings start to be effective in monetary terms. Such a payback period is important in that it can be compared to a payback period threshold defined either on a political or economic ground.[37] In scenarios A and SPC, the payback period is greater in the uniform than in the differentiated approach. The higher the growth rate of the carbon price, the shorter the payback period. In other words, the faster the price of carbon grows, the stronger the value signal and the more stakeholders are likely to invest in clean projects. Scenario B illustrates an equality between the uniform and the differentiated payback periods because of the underlying Hotelling approach (both the discount rate and the carbon price growth rate are equal to 3%). Scenario C is particular because the initial carbon price is very high: the value signal being strong immediately, projects which involve a large amount of emissions cannot reach a carbon profitability within a reasonable period of time. Note that the payback period is this time greater in the differentiated than the uniform annualization. This is due to the discounting effect which dominates the carbon price effect in contrast to Scenarios A and SPC. This situation is in favor

[36] A discount rate of 3% is again assumed.

[37] Nowadays, the usual concept is the carbon debt which is exclusively physical. A payback period, as introduced in this paper, which is linked to monetary terms could constitute an additional signal, possibly more incentive-compatible, for firms to reduce emissions.

Table 3.2: Payback Periods across Carbon Price Scenarios and Time Distributions

	Scenario	Unif. Annu.	Diff. Annu.	% Misestimation
A	$\{40, 5\%\}$	39	34	14.71%
B	$\{40, 3\%\}$	48	48	0%
C	$\{80, 1\%\}$	80	>100	-
O	$\{40, 0\%\}$	>100	>100	-
SPC	Quinet (2009)	41	35	17.14%

of the prevention of abrupt climate change (Stern, 2008): the stronger the initial carbon value signal, the higher the potential to prevent catastrophes due to climate change.

Some policy implications can be derived from the borrowing effect. Considering Scenario A, the project may pass the cost-benefit analysis test under the differentiated approach whereas it would not under the uniform annualization[38], which would penalize projects. Now considering Scenario C which accounts for uncertainty of climate change damages, a project assessed through the uniform approach in this case could pass while it would not under the differentiated approach. This is an important issue as it may be potentially harmful to the primary objective of cutting emissions.

A limit to the borrowing effect as studied here though is that potential scale effects regarding biofuel production are not considered. Indeed, the borrowing effect also involves non-LUC emissions from the process of production, thus it is subject to economies of scale. Intuitively, taking those into account should shorten the estimated payback periods for both time distributions since economies of scale would induce more energy efficiency in producing biofuels thus faster net GHG savings on the whole project time horizon. Nevertheless, nothing would change regarding the comparison between the uniform and the differentiated annualizations (over- *vs.* underestimation).

3.5 Conclusions

At the very least, this paper warns about the LUC time-accounting failure in internalizing GHG impacts in economic appraisal of projects by policy makers. I put forward two arguments from two different literatures. First, when dealing with global warming, a departure from the widespread Hotelling rule regarding carbon prices is necessary. Indeed, the natural absorption of carbon tends to raise the carbon price growth rate above the discount rate whereas the uncertainty surrounding climate change tends to the reverse. Second, LUC impacts decrease over time by contrast to the uniform time-accounting employed by policy makers. This is largely supported by the biology literature.

[38]This would imply that a political or economic threshold is fixed at, say, 35 years.

These two arguments are strongly intertwined. Studying the crossover between these two considerations, I provide evidence that the uniform annualization has knock-on effects on cost-benefit analysis outcomes: either an upward or downward bias of projects' NPV depending on *(i)* whether the project entails net emissions or sequestrations and *(ii)* whether the carbon price grows slower or faster than the discount rate. This is all the more important when the project entails net emissions thus can be harmful to the climate. It may lead to the implementation of a project which does not complete the environmental criteria initially imposed by policy makers (case of a slower carbon price increase than the discount rate), or the non-implementation of projects which actually satisfy these criteria (case of a faster carbon price increase). To deal with such a situation, I suggest policy makers use two very simple tools. First, in the case of an unavoidable use of the uniform approach, policy makers should estimate the compensatory discount rate which allows one to determine whether an outcome is upward or downward estimated. The second is the carbon profitability payback period. This may constitute a criterion for decision making regarding the implementation of a project. Also, in the future when carbon pricing will be completely part of private decision making, it may create an interesting means to incentivize firms to reduce emissions or increase sequestrations since it is a monetary-based concept. The general message for policy makers in this area is to substitute the uniform annualization method for the differentiated one since most GHG impacts occur right after land conversion. Therefore, it is necessary to change this accounting method within the LCA models which support (upstream) policies.

Regarding the case of bioethanol in France, only direct LUC has been treated so far in this paper but the philosophy behind the model can apply to any phenomenon which entails carbon dynamics. It is worth emphasizing that the magnitude of the bias must increase with the accounting of indirect LUC which is currently a central issue. It may even be greater if one considers time lags of indirect LUC materialization as stated by Zilberman et al. (2013) and empirically put forward by Andrade De Sá et al. (2013).

So far, the results of this paper are founded on a very simple model which in particular entails constant discount rates and growths of the carbon price. It would be interesting for future research to estimate these biases under hyperbolic discounting which is currently the trend in the climate change debate around discounting (Arrow et al., 2013).

A Proof of Proposition 1

$$\Delta NPV = p\left(\frac{z_0+z_1}{2}+\frac{z_0+z_1}{2(1+r)}-z_0-\frac{z_1}{1+r}\right) \tag{A.1}$$

$$= p\frac{(z_0+z_1)(1+r)+z_0+z_1-2z_0(1+r)-2z_1}{2(1+r)} \tag{A.2}$$

$$= p\frac{z_0(-r)+z_1 r}{2(1+r)} \tag{A.3}$$

$$\Delta NPV = \frac{p\, r(z_1-z_0)}{2(1+r)} \tag{A.4}$$

$$\frac{\partial \Delta NPV}{\partial r} = \frac{p(z_1-z_0)}{2}\frac{1+r-r}{(1+r)^2} = \frac{p(z_1-z_0)}{2(1+r)^2} \tag{A.5}$$

Assumption 1 leads to $\Delta NPV > 0$ hence $NPV_u > NPV_d$ and $\frac{\partial \Delta NPV}{\partial r} > 0$ for emissions and $\Delta NPV < 0$ hence $NPV_u < NPV_d$ and $\frac{\partial \Delta NPV}{\partial r} < 0$ for sequestrations.

B Proof of Proposition 2

$$\Delta NPV = p_0\frac{z_0+z_1}{2}+p_1\frac{z_0+z_1}{2}-p_0z_0-p_1z_1 \tag{B.1}$$

$$= \frac{p_0z_1+p_1z_0-p_0z_0-p_1z_1}{2} \tag{B.2}$$

$$\Delta NPV = \frac{\Delta p(z_0-z_1)}{2} \tag{B.3}$$

$$\frac{\partial \Delta NPV}{\partial \Delta p} = \frac{z_0-z_1}{2} \tag{B.4}$$

Assumption 1 leads to $\Delta NPV < 0$ hence $NPV_u < NPV_d$ and $\frac{\partial \Delta NPV}{\partial r} < 0$ for emissions and $\Delta NPV > 0$ hence $NPV_u > NPV_d$ and $\frac{\partial \Delta NPV}{\partial r} > 0$ for sequestrations.

C Proof of Propositions 3 and 4

$$\Delta NPV = NPV_u - NPV_d \tag{C.1}$$
$$= p_0 \frac{z_0 + z_1}{2} + p_1 \frac{z_0 + z_1}{2(1+r)} - p_0 z_0 - p_1 \frac{z_1}{1+r} \tag{C.2}$$
$$= \frac{p_0(z_0+z_1)(1+r) + p_0(1+r_p)(z_0+z_1) - 2p_0 z_0(1+r) - 2p_0(1+r_p z_1)}{2(1+r)} \tag{C.3}$$
$$= \frac{p_0}{2(1+r)} \left(z_0(r_p - r) + z_1(r - r_p)\right) \tag{C.4}$$
$$\Delta NPV = \frac{p_0}{2(1+r)}(z_0 - z_1)(r_p - r) \tag{C.5}$$

Relying on Assumption 1, the sign of ΔNPV only depends on the sign of $r_p - r$.

D Land use change impacts time profile: formal description

The following formal definitions of the uniform and the differentiated approaches are implemented in the Python program to generate the numerical results provided in Section 3.4.

Let's denote by SOC and VGC the carbon stocks respectively in soil and vegetation expressed in tonnes of carbon per hectare. $\Delta SOC = SOC_F - SOC_I$ and $\Delta VGC = VGC_F - VGC_I$ are then the carbon stock differences between land conversion and equilibrium achievement where the indices I and F respectively refer to initial (before conversion) and final (after conversion) lands. z_t is expressed in tonnes of CO_2 per unit *e.g.* hectare or tonne of ethanol, per year. It is decomposed into z_t^s and z_t^v the respective annual LUC impact from soil and vegetation which are spread out over T^s and T^v, their respective time horizons. ω_s and ω_v are introduced as the respective shares of soil and vegetation carbon which are converted into CO_2 impacts.[39] A is a constant which at least includes the coefficient of conversion of carbon into CO_2.[40]

Definition 1 (Uniform annualization) *LUC impact flows are uniformly annualized when $T^v \leq T^s$ and impacts on soil and vegetation are respectively constant over time i.e. $z_t^s = z_{t+1}^s \ \forall t \leq T^s$ and $z_t^v = z_{t+1}^v \ \forall t \leq T^v$. The total annualized LUC impact is then:*

$$\forall t = \{0, 1, ..., T^s\}, \quad z_t = z_t^s + z_t^v = A \left[\omega_s \frac{\Delta SOC}{T^s} + \omega_v \frac{\Delta VGC}{T^v} \right]$$
$$\text{with } z_t^v = 0 \ \forall t \geq T^v.$$

Definition 2 (Differentiated annualization) *LUC impact flows are differentiately annualized when $T^v \leq T^s$, $z_t^s \neq z_{t+1}^s \ \forall t \leq T^s$ and $z_t^v \neq z_{t+1}^v \ \forall t \leq T^v$. The total annualized LUC impact is*

[39] Carbon losses may be deferred when carbon vegetation is stored in wood products such as furnitures or buildings (Marshall, 2009; Tyner et al., 2010).

[40] Typically, $A = \frac{44}{12}$ (IPCC, 2006). In the case of biofuel production, $A = \frac{44}{12k}$ where the constant k refers to the biofuel yield in tonnes of biofuel per hectare.

then:

$$\forall\, t = \{0,1,...,T^s\}, \quad z_t = z_t^s + z_t^v = A\left(\omega_s\, \Delta SOC.f_s(t)\; + \omega_v\, \Delta VGC.f_v(t)\right)$$

$$with\ z_t^v = 0\ \forall t \geq T^v.$$

f^s and f^v are continuous and monotonic functions of time which underlie the carbon response of respectively soil and vegetation to LUC.

For a grassland or a forestland converted into a cropland, the SOC dynamic follows an exponential decrease according to the meta-analysis of Poeplau et al. (2011).[41]

Definition 3 (Declension in weak and strong definitions of LUC time distributions) *The uniform and differentiated annualizations are respectively characterized by the exclusion and inclusion of a carbon stock dynamic. The declension relies on whether $T^v < T^s$ or $T^v = T^s$ as Table 3.3 states.*

Table 3.3: Declension in Weak and Strong Definitions

		Time Horizons	
		$\mathbf{T^v < T^s}$	$\mathbf{T^v = T^s}$
Carbon Dynamic	**No**	Weak Uniform	Strong Uniform
	Yes	Strong Differentiated	Weak Differentiated

Definition 3 allows to categorize energy policies according to the time distribution they consider for LUC impacts. The uniform annualization definition is strong in the sense that it is the extreme case of uniformization: impact flows (from both soil and vegetation) are equal over the same time period. This is the case which is at most a far cry from the real dynamic of LUC. By contrast, the differentiated annualization is strong in the sense that soil and vegetation LUC impacts are distinguished in both their time horizon and their dynamic. The latter case is as close as possible to reality.
The European RED is based on the strong uniform annualization with the assumption that $T^v = T^s = 20$ and the U.S. RFS2 policy is based on the weak uniform approach with $T^v = 1$ and $T^s = 30$. Both though do not account for carbon (hence CO_2) dynamics either in soil or biomass.

E Data

[41] Such that $f^s(t) = e^{-\frac{t-1}{a}} - e^{-\frac{t}{a}}$ where a is a constant. Poeplau et al. (2011) estimate a stock dynamic such that $\forall t$, $SOC_t = \Delta SOC(1 - \exp(-\frac{t}{a}))$. My focus lies on flows, hence the flow from the soil at time t is $z_t^s = SOC_t - SOC_{t-1}$. Note that regarding vegetation carbon stocks, if $T^v = 1$ *e.g.* clearing a forest, no dynamic of carbon is considered since only one flow is effective at $t = 0$.

Table 3.4: Data Used for the Bioethanol Case Study in France

About	Choice/Value	Reference
Region	France	-
Biofuel	Bioethanol	-
Biomass 1^{st} generation	Wheat	Chakir and Vermont (2013)
Biomass 2^{nd} generation	*Miscanthus*	Chakir and Vermont (2013)
Project Starting Year	2020	-
Inflation rates	Historical rates till 2014	Worldwide Inflation Data
Conversion rates	Historical rates till 2014	Oanda Conversion Data
Discount rates	From 0% to 5%	Florio (2014)
Project Time Horizon	20, $t = 0$ land conversion Period of production: 20 yrs from $t = 1$ to $t = 20$	See justifications in the last section of the paper
Carbon Price Projections	"Home made" Shadow value of carbon in France	See the last section of the paper Quinet (2009)
Crop Yields	Wheat: 7.5 t DM/ha *Miscanthus*:16.5 t DM/ha	Agreste IFP energies nouvelles
Process Yields	Wheat: 0.28 t eth/t DM *Miscanthus*: 0.32 t eth/t DM	IFP energies nouvelles
Climatic Region	$\frac{1}{3}$ warm temperate dry $\frac{2}{3}$ warm temperate moist	See Map in The European Commission (2010)
Soil Type	High Activity Clay Soil	The European Commission (2010)
Land Cover	Cropland, *Miscanthus*, Improved Grassland, Degraded Grassland, Forest	-
Agricultural Management	Wheat: 60% Full tillage & 40% No till *Miscanthus*: No till	Agreste

Agricultural Practices	Wheat: 70% High input without manure 30% with manure *Miscanthus*: Medium Input	Agreste
Coefficient shares carbon to CO_2	Emi: $\omega_s = 30\%$ and $\omega_v = 90\%$ Seq: $\omega_s = 30\%$ and $\omega_v = 100\%$	See the last section of the paper
Non-LUC emissions	Wheat *Miscanthus*	Biograce Hoefnagels et al. (2010)
Gasoline emissions	87.1 g CO_2/MJ	Joint Research Centre (JRC WTT report Appendix 2 version 4a, April 2014)

F Land cover effects

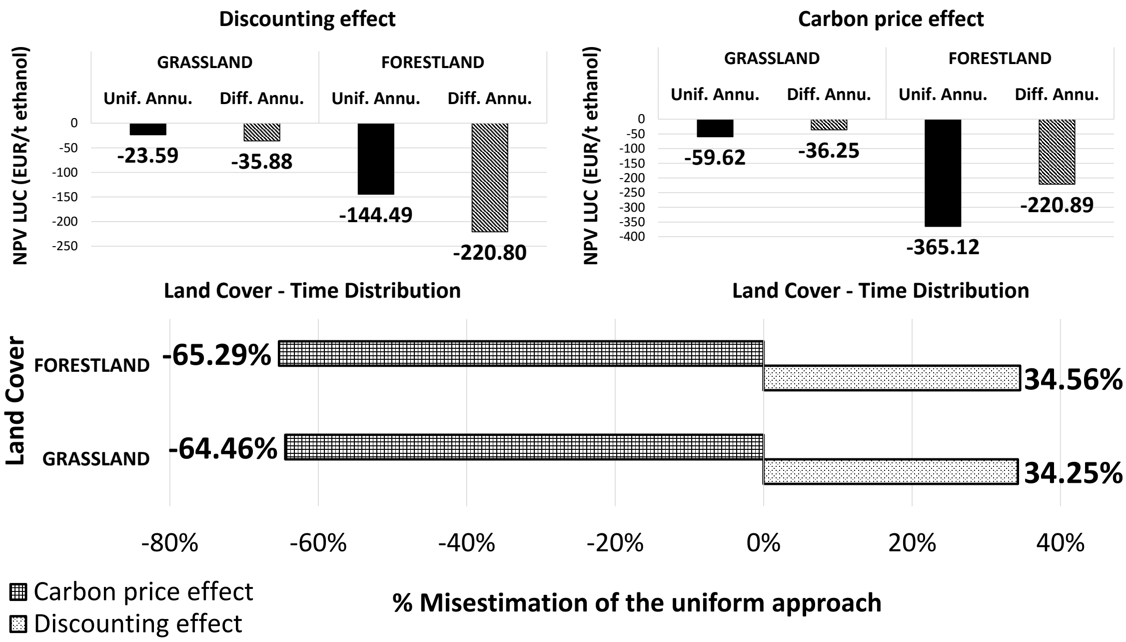


Figure 3.9: Discounting effects and carbon price effects across land conversions

The conversion either of a grassland or a forestland into an annual cropland is associated with an overestimation of the NPV regarding the discounting effect and an underestimation regarding the carbon price effect. Indeed, since emissions are considered as costs here, the NPVs are negative as shown in Figure 3.9. However, the negative NPV under the uniform annualization is greater (less negative) than the one under the differentiated approach in the discounting effect case (hence the overestimation). Similarly, the NPV under the uniform annualization is smaller (more negative) than the one under the differentiated approach in the carbon price effect effect case (hence underestimation). The combined effect results in around 30% for the two land conversions so the bias is even greater than in the net sequestration case illustrated in the last section of the paper.

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Chapter 4

Context-dependent substitutability: impacts on environmental preferences and discounting

This chapter is an extended version of a working paper co-authored with Vincent Martinet.

Abstract

Willingness-to-pay (WTP) for environmental quality as well as discounting are two crucial concepts in environmental economics. Both are linked to the substitutability between consumption and environmental quality. In classical economic models, two goods are exogenously defined as complements or as substitutes. In this paper, we develop a theoretical framework in which goods can be either complements or substitutes depending on the context, *i.e.*, on income and environmental quality. Individuals are endowed with the same preferences but differ according to their context. We analyze the impacts of a context-dependent substitutability on *(i)* environmental preferences and *(ii)* the rates at which consumption and environmental quality are discounted. We show that, in a context of substitutability, an individual's WTP can decrease as her income grows, which allows the environmental good to be characterized as an inferior good. This is an overlooked classification, yet of interest as regards lower-income individuals. In contrast with the discounting literature, our model also allows the sign of the so-called *substitution effect* in discounting to change whether the goods are substitutable or not. This impacts the values of the consumption and environmental discount rates. It is particularly well-illustrated by income shocks, which may induce a sudden change in the individual's behavior toward consumption and the environment.

Keywords: substitutability, complementarity, contextual preferences, willingness-to-pay for environmental quality, discounting

JEL Classification: Q50, D90, D91

4.1 Introduction

Are consumption and environmental goods complementary or substitutable? The question is crucial to decision-making. Whether an individual's satisfaction relies on a complementarity or a substitutability between goods affects the way the environment is valued at a given time and over time. Yet, most models which consider a two-argument utility function in the environmental economics literature build upon an exogenous assumption on the way consumption and environmental quality interact. This means that models rely on a single nature of interaction between the two goods. Either goods are considered as independent (*e.g.* Heal (1998)) or substitutable (*e.g.* Nordhaus (2008)) or complementary (*e.g.* Weikard and Zhu (2005)). It seems restrictive to consider that the way consumption and environmental quality interact to provide utility is unique and does not depend on the context *i.e.* income and environmental quality.

Empirical results suggest that people substitute consumption of produced goods and environmental quality in a different way according to their income[1]. Indeed, both empirical literatures on environmental preferences and on time preferences point out such an income effect. Willingness to pay (WTP) for improving environmental quality varies with income. So does the rate at which people discount the future. Income effects on WTP are mainly found positive and, more accurately, the income elasticity of WTP is often found between 0 and 1 (Kristrom and Riera 1996; Flores and Carson 1997; Jacobsen and Hanley 2009). This suggests that environmental goods are normal goods.[2] Some studies, however, report negative income effects (McFadden and Leonard 1993; McFadden 1994; Horowitz 2002; Huhtala 2010), which means that in some contexts, WTP for the environment decreases as income rises. This classifies environmental goods as inferior goods. Though, this case is overlooked and generally not interpreted in the literature. Income effects on the discount rate are mostly reported as negative (Hausman 1979; Lawrance 1991; Harrison et al. 2002; Tanaka et al. 2010). At a macroeconomic level, developing and developed countries also exhibit different patterns in terms of WTP for the environment and discount rate.

The usual interpretation of such empirical evidence is that low-income people and high-income people have "different preferences", either in terms of environmental preferences or in terms of time preferences. Does it mean that goods are considered as substitutes by a part of a population and complements by another? In that case, the preferences of the two groups would be fundamentally different, and the utility models of the two behaviors would require significantly different parameters. One may argue, however, that the difference in WTP (evaluated with revealed or stated preferences methods) is contingent on the endowment of the individuals, and is not driven by fundamentally different preferences. Would an individual from the

[1] Shogren et al. 1994 experimentally show the existence of a relation between the impact of income on WTP and the substitutability between a market good and a nonmarket good.

[2] Sometimes, the elasticity is found greater than 1 which classifies environmental goods as luxury goods. Regarding climate change, this is in line with the Sterner Conjecture according to which the impacts from climate change are akin to something people care more about, the wealthier they get (Tiezzi and Martini, 2014).

"low-income group" behave like a poor if given the endowments of a rich? At countries level, won't preferences of developing countries change once developed? In this case, it would be helpful to have a model which represents both preferences associated with complementarity between goods and preferences associated with substitutability, depending on the context of the choice. This could provide a theoretical explanation on why low-income and high-income people have different stated WTP and different revealed discount rates. As far as we know, no single theoretical framework allows for both substitutability and complementarity in the Edgeworth-Pareto sense without changing exogenous parameters in preference representation.[3]

In a framework with no specification of the utility function, we investigate the theoretical link between substitutability and separately, WTP and discounting. We consider the definition of between-goods substitutability within utility in the Edgeworth-Pareto (E-P) sense which relies on the sign of the cross derivative of utility. Then we develop a theoretical model which allows between-goods substitutability to vary across contexts (current income and environmental quality). Roughly speaking, if applied to high-income and low-income people, all individuals would behave according to the same preferences but the expression of these preferences (decisions) would differ depending on the context. This means that, depending on the context, utility builds upon either complementarity or substitutability between goods.

We analyze the impacts of a context-dependent substitutability on WTP changes with income and environmental quality. We show that, by contrast to classical models such as those employing a Constant Elasticity of Substitution (CES) utility function, negative income effects are possible only in a context where income and environmental quality are substitutable. Little interest has been given to such a classification of environmental goods as inferior goods. An environmental good is qualified as inferior if the income elasticity of marginal WTP is negative.[4] Environmental quality may become an inferior good when a relatively poor individual gets wealthier thus substitutes environmental goods for more convenient market substitutes for example. We also show that positive income effects are possible both when the goods are substitutes and complements.

Besides we examine the impacts of a context-dependent substitutability on discounting and especially on the approach of dual-rate discounting. Our framework does not change the way goods are discounted but the values of the discount rates. We show that the substitution effect (within the discount rate) has opposite impacts on the two discount rates (economic and environmental) whether goods are substitutes or complements. In such a framework, it is worthwhile studying income shocks. This may radically change the context of an individual, changing in turn her structure of preferences. Put differently, an individual may initially consider the two goods as complements and, once the shock occurred, as substitutes.

[3]This is done by Baumgärtner et al. (2015b) and further studied by Drupp (2016). in the context of the Hicks definition of substitutability.

[4]This is linked to a pro-poor distribution of benefits (Ebert, 2003).

Providing an empirical support for our theory is beyond the scope of the present work.[5] However, we illustrate our model with a utility function which satisfies the required properties namely the Context-Dependent Substitutability (CDS) utility function. Compared with more usual functions such as CES functions, the CDS function allows for three interesting properties. First, both substitutability and complementarity between goods can be modeled depending on the context. Second, environmental goods can be classified as inferior goods as well as normal goods. Third, in an intertemporal framework, substitutability can affect differently the way individuals discount the future.

The paper is organized as follows. Section 4.2 introduces the different concepts of substitutability and puts forward the links which exist *(i)* between willingness-to-pay and substitutability and *(ii)* between discounting and substitutability. Section 4.3 presents our general theoretical framework and introduces a particular utility function that matches our assumptions. Section 4.4 derives the impacts of a context-dependent substitutability on the income elasticity of WTP. Section 4.5 examines the impacts of a context-dependent substitutability on discounting. In Section 5.5, we conclude and suggest future research directions.

4.2 Conceptual background: the link between substitutability, WTP and discounting

4.2.1 Substitutability

Consider a consumer whose utility U is derived from *(i)* a composite consumption good denoted by C and *(ii)* environmental quality E which can be a composite good as well. We assume that increasing the "quantity" of each good strictly increases well-being, but at a decreasing rate.

Assumption 2 *The utility function $U(\cdot,\cdot) : \mathbb{R}_+^{*2} \longmapsto \mathbb{R}$ is continuously and twice differentiable, strictly increasing and concave in each of its arguments.*

$\mathbb{R}_+^{*2}$ is defined as the bi-dimensional set of real strict positive numbers, with $\mathbb{R}_+^{*} =]0,+\infty[$. Further, we use the following notations for the derivatives of the utility function:

$$U_i \equiv \frac{\partial U}{\partial i} \ , \ U_{ii} \equiv \frac{\partial^2 U}{\partial i^2} \ , \ U_{ij} \equiv \frac{\partial^2 U}{\partial i \partial j} \ , \ \dot{U} \equiv \frac{dU}{dt} \ ,$$

where $i \neq j$ are either the variable C or E and t represents time.

There are various definitions of substitutability. Samuelson (1974) provides a comprehensive overview of these definitions. We consider substitutability in terms of utility in the Edgeworth-Pareto (E-P) sense.

[5] Interestingly, Drupp (2016) provides an estimation of the elasticity of substitution for the extended CES utility function developed in Baumgärtner et al. (2015b) and analyzes its implications for social discounting.

Definition 4 (E-P substitutability) *Substitutability between goods C and E in the sense of Edgeworth-Pareto relies on the sign of the cross derivative of the utility function as follows.*

$$\begin{array}{ll} U_{CE} < 0 & \textit{C and E are substitutable} \\ U_{CE} > 0 & \textit{C and E are complementary} \\ U_{CE} = 0 & \textit{C and E are independent} \end{array}$$

The E-P criterion of substitutability is widespread in the literature and straightforward. It indicates the nature of the interaction between goods within utility. Two goods are substitutes (complements) when an increase of the first good decreases (increases) the marginal utility of the second good (Heal, 2009; Gollier, 2012). We use this definition because this is a simple concept on which an assumption is usually made in environmental economics models.

The E-P criterion characterizes the substitutability between the two goods but does not differentiate the effect of consumption C on the utility derived from environmental quality E from the effect of environmental quality on consumption's marginal utility.[6] As Neumayer (2013, p.67) highlights, if we consider two products A and B, then "for some production purposes A and B are almost near-perfect substitutes with almost linear isoquants. But for other purposes, A has some desirable properties that B does not have. Hence, A can substitute for the totality of B, but not vice-versa."

Considering substitutability in utility, this reasoning can be related to Lancaster's theory of consumption: "The good, *per se*, does not give utility to the consumer; it possesses characteristics, and these characteristics give rise to utility. In general, a good will possess more than one characteristic, and many characteristics will be shared by more than one good" (Lancaster 1966). For instance, C could be a perfect substitute for E because it possesses all the characteristics of E, but E might not replace totally C because it lacks some of the characteristics of C. Therefore, in order to measure the degree of substitutability between the two goods and to distinguish the effect of environmental quality on marginal utility for consumption and vice-versa, we use the concepts of cross elasticities of marginal utility.

Definition 5 *The elasticity of marginal utility for good A with respect to good B, denoted by $\eta_{A,B}$, is the variation of marginal utility for good A resulting from a change of good B:*

$$\eta_{A,B} \equiv -\frac{\frac{\partial U_A}{U_A}}{\frac{\partial B}{B}} = -B\frac{U_{AB}}{U_A} \tag{4.2.1}$$

The elasticity $\eta_{C,E}$ ($\eta_{E,C}$) measures the impact of a change in environmental quality (consumption) on the marginal satisfaction derived from consumption (environmental quality).

Both elasticities $\eta_{C,E}$ and $\eta_{E,C}$ have the same sign (which is the opposite of the sign of U_{CE}). This means that if C is a substitute (complement) for E, then E is also a substitute (complement) for C. The degree of substitutability between C and E is not the same as the degree of substitutability between E and C however, since $\eta_{C,E} \neq \eta_{E,C}$.

[6] As $U_{CE} = U_{EC}$ (Schwarz theorem).

4.2.2 Substitutability and WTP

When dealing with public goods, one can determine the value attributed to this good by measuring the willingness-to-pay (WTP) of an individual for increased non-market good supply.

WTP for improving environmental quality by ΔE is defined as the solution of the following equation:

$$V(Y,E) = V(Y - WTP, E + \Delta E) \tag{4.2.2}$$

Equation (4.2.2) states that the consumer whose preferences are represented by U is indifferent between *(i)* giving up from her budget the amount $WTP(=\Delta Y)$ for improving the environmental quality by ΔE and *(ii)* remaining in the initial situation (*i.e.* no environmental improvement and no change in income). In this paper, we use the definition of WTP at the margin. In this case, marginal WTP (w) is defined as the marginal rate of substitution between income and environmental quality. The indirect utility[7] derived from Y and E is given by $V(Y,E,p) = \max U(C,E)\ s.t.\ pC = Y$.[8] Formally, at the margin:

$$w(Y,E,p) = \frac{V_E}{V_Y} \tag{4.2.3}$$

Note that $WTP = w(Y,E,p) \times E$. It is common to study how WTP varies as income grows (McFadden, 1994; Kristrom and Riera, 1996; Flores and Carson, 1997; Horowitz, 2002; Jacobsen and Hanley, 2009), which is formally measured by:

$$\frac{\partial WTP}{\partial Y} = \frac{V_{YE}V_Y - V_{YY}V_E}{V_Y^2}E \tag{4.2.4}$$

with $V_Y > 0$ and $V_E > 0$.

In the empirical literature, reference is often made to the income elasticity of WTP, which is formally defined as:

$$\varepsilon^Y_{WTP} = \frac{\frac{\partial WTP}{WTP}}{\frac{\partial Y}{Y}} = \frac{\partial WTP}{\partial Y}\frac{Y}{WTP} \tag{4.2.5}$$

As $Y > 0$ and $WTP > 0$, ε^Y_{WTP} is of the same sign as $\frac{\partial WTP}{\partial Y}$. The E-P criterion can be applied to the indirect utility function such that V_{YE} indicates the nature of interaction between income and environmental quality.

Mostly, it is found that $0 < \varepsilon^Y_{WTP} < 1$ (Kristrom and Riera, 1996; Flores and Carson, 1997; Jacobsen and Hanley, 2009; Barbier et al., 2016), which means that WTP increases less than proportionally with income. This means that the environmental good is a normal (necessity) good. The case of a negative income elasticity (McFadden and Leonard, 1993; McFadden, 1994; Horowitz, 2002; Huhtala, 2010) , i.e., $\varepsilon^Y_{WTP} < 0$, can also occur, even if it is underrepresented in empirical results and not often interpreted. This means that the environmental good

[7]The indirect utility function gives the optimal utility level obtainable given the index price p and income Y.

[8]As a public good, E's level is considered exogenous to the individual (Horowitz et al. 2013).

is an inferior good.

Thus, the income elasticity of WTP depends on substitutability between income and environmental quality. The consequences of such a dependence are analyzed in section 4.4 within our theoretical framework.

4.2.3 Substitutability and discounting

Consider an individual's intertemporal welfare W which is defined as the sum over time of utilities at each instant.

$$W(C(\cdot),E(\cdot)) = \int_0^{+\infty} U(C(t),E(t))e^{-\delta t}dt \tag{4.2.6}$$

where δ is the rate of pure preference for the present.[9]

Along any trajectory, we can derive the discount rates relative to the economy and the environment.[10] The economic (environmental) discount rate represents the willingness to trade off present for future consumption (environmental quality). By definition,[11] the economic discount rate, r^C is the rate at which the value of a small increment of consumption changes as time changes.[12]. From this definition and using the elasticity $\eta_{C,E}$ defined in Eq. (4.2.1), we obtain the economic discount rate:[13]

$$r^C = \delta + g_C\eta_{C,C} + g_E\eta_{C,E} \ , \tag{4.2.7}$$

where $g_C = \frac{\dot{C}}{C}$ and $g_E = \frac{\dot{E}}{E}$ are the growth rates of consumption and environmental quality.

Such a discount rate can also be defined for environmental quality, using the elasticity $\eta_{E,C}$, providing the environmental discount rate:[14]

$$r^E = \delta + g_E\eta_{E,E} + g_C\eta_{E,C} \tag{4.2.8}$$

Both discount rates are the sum of three terms. The first term is the rate of pure preference for the present. The second term corresponds to the so-called *growth effect*. It depends on the

[9]Also called the utility discount rate, this is the rate at which the weight of the two-argument utility declines over time.

[10]Usually, the expression of the discount rate is derived from the Keynes-Ramsey rule, along an optimal path. Following Traeger (2011b), the derivation we use in Appendix B is valid along any given trajectory. We thus do not reduce our analysis to optimal trajectories.

[11]See Heal (1998, p.77).

[12]We can also say that r^C is the rate of change of marginal utility for consumption as time changes. $r^C = \frac{\dot{U}_C^\delta}{U_C^\delta}$ ($r^E = \frac{\dot{U}_E^\delta}{U_E^\delta}$) where U^δ is the discounted instantaneous utility.

[13]See Appendix B.

[14]The expression ((4.2.8)) for r^E was first derived by Weikard and Zhu (2005).

elasticity of marginal utility for consumption $\eta_{C,C}$ for the economic discount rate r^C, and on that for environmental quality $\eta_{E,E}$, for the environmental discount rate r^E.

The third term is the so-called *substitution effect*. It depends on the cross elasticities of marginal utility which indicate whether goods are substitutable or complementary. Thus the two discount rates depend on the substitutability between the two goods through $\eta_{C,E}$ for r^C and $\eta_{E,C}$ for r^E.

4.2.4 Substitutability and preference representation

Classical models

The two previous subsections exhibited that both the WTP for the environment and the (economic and environmental) discount rates depend on substitutability between income and the environment. In the literature, the most common function employed is the CES function. Its form is the following:

$$U^{CES}(C,E) = \left(a\, C^{1-\frac{1}{\sigma}} + b\, E^{1-\frac{1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}} \tag{4.2.9}$$

where a is the weight given to consumption, b (generally equal to $1-a$) is the weight given to environmental quality and σ is the elasticity of substitution.

Income elasticity of WTP: As subsection 4.2.2 specifies, substitutability affects the way WTP changes with income. When evaluating an environmental project, one needs to estimate willingness to pay for improving environmental quality either by implementing a method such as contingent valuation or choice experiment or by transferring existing values of WTP to a new study site. The latter especially requires adjustments of income levels since the context is different from one site to another. Recommendations for benefit transfer rely on a constant income elasticity of WTP but may lead to skewed estimations of WTP as pointed out by Barbier et al. (2016). The latter paper shows that the income elasticity of WTP is not constant. However, by defining pollution as a linear function of income, they avoid the dependance of the income effect upon substitutability. This restrains the values of the income elasticity of WTP to be positive,[15] which imposes that the environmental good is a normal good. Making an exogenous assumption on the kind of interaction between economic and environmental goods constrains the range of values that the income elasticity of WTP can take. The Edgeworth-Pareto definition of substitutability may particularly be interesting in studying the sign of the income elasticity of WTP since the cross-derivative of the indirect utility is directly involved in the formal definition of this elasticity (see subsection 4.2.2). In section 4.4, we examine the situations in which negative values of this elasticity are possible.

[15] See Equation (7) in Barbier et al. (2016).

Discounting: In dual discounting models,[16] two levels of substitutability are generally considered: (Hicks) between-goods substitutability (σ within the CES function) and intertemporal substitutability (μ within an isoelastic function), which gives the following utility function.

$$\mathscr{U} = \frac{1}{1-\frac{1}{\mu}}\left(U^{CES}\right)^{1-\frac{1}{\mu}} \tag{4.2.10}$$

Traeger (2011a) finds that depending on whether $\sigma \lesseqgtr \mu$, both the consumption and environmental discount rates decrease/are constant/increase over time. The cross derivative of this function or equivalently the E-P substitutability is as follows.

$$\mathscr{U}_{xy} = \frac{abC^{\frac{1}{\sigma}}E^{\frac{1}{\sigma}}\left(\left(aC^{1-\frac{1}{\sigma}}+bE^{1-\frac{1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}\right)^{1-\frac{1}{\mu}}(\mu-\sigma)}{\left(aCE^{\frac{1}{\sigma}}+bC^{\frac{1}{\sigma}}E\right)^{2}\sigma\mu} \tag{4.2.11}$$

This cross derivative is positive if $\mu > \sigma$ and negative if $\mu < \sigma$. Therefore, substitutability between consumption and environmental quality depends only on the sign of the difference between σ and μ, two exogenous parameters characterizing the utility function. In particular, the kind of relationship between the two goods does not depend on their quantities, thus neither on the context (*i.e.* income and environmental quality). And when it comes to discount rates estimation, this assumption constrains the evolution (and the values) of the discount rates.

Other models

An extension of the CES utility function with a subsistence requirement (as described by Heal (2009)) has been studied by Baumgärtner et al. (2015b) and is as follows.

$$U(C,E) = \begin{cases} U_l(E) & \text{for } E \leq \bar{E} \\ U_h(C,E) & \text{else} \end{cases}$$

where $\bar{E}$ is the subsistence level under which preferences are lexicographic and

$$U_h(C,E) = \left(a\,C^{1-\frac{1}{\sigma}} + b\,(E-\bar{E})^{1-\frac{1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}} \tag{4.2.12}$$

They show that the elasticity of substitution (in the sense of Hicks) between consumption and ecosystem services is not constant but depends on the levels of consumption and environmental goods as well as the subsistence requirement. Then in a market setting, which means that the environmental good becomes a market good, they show that the elasticity of substitution monotonically increases with income and decreases with the subsistence level. In the Edgeworth-Pareto sense however, this extended CES function (as well as the classical CES utility function)

[16] As in Guesnerie (2004), Hoel and Sterner (2007), Gollier (2010), Kögel (2009).

only allows for complementarity between goods (see the cross derivative below) since $E > \bar{E}$.

$$U_{h_{CE}}(C,E) = \frac{a\, b(E-\bar{E})^{\frac{1}{\sigma}} C^{\frac{1}{\sigma}} \left(b(E-\bar{E})^{1-\frac{1}{\sigma}} + aC^{1-\frac{1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}}{\sigma \left(a(E-\bar{E})^{\frac{1}{\sigma}} C + b(E-\bar{E}) C^{\frac{1}{\sigma}}\right)^{2}} \tag{4.2.13}$$

One may argue that an individual may judge two goods as substitutes in a context and complements in another (depending on her current context). Referring again to Lancaster's concept of consumer preferences, marginal utility is derived from changes in the characteristics of the bundle of "consumed" goods. The two goods may be complements for some characteristics and substitutes for others. In two different contexts (*e.g.*, if endowments are different), the characteristics of the two goods may be valued differently, or, more precisely, the individual may attribute value to different characteristics. For example, someone rich (high-income) may judge that environmental quality and private income are complements in increasing utility, as the characteristic of interest for her may be related to expensive recreational activities requiring both high income and high environmental quality. On the contrary, someone poor (low-income) may judge private consumption and environmental quality as substitutes because the two goods contribute redundantly to a same characteristic, such as housing or heating, related to the satisfaction of basic needs. Faced with a set of similar choices, these two individuals may exhibit different stated preferences, reflecting complementarity for one and substitutability for the other.

By relying on an absolute characterization of substitutability between goods, the standard representation of preferences does not allow for such cases. Our view is that such a difference in stated preferences should not be supported by fundamentally different preferences but by the same preferences resulting in different statements depending on the context. Roughly speaking, the two individuals should have the same preferences, allowing the goods to be judged as complements in some contexts and as substitutes in others. As a consequence, in our preference setting, substitutability is not an assumption anymore but depends on the context. This has important consequences on the way the willingness-to-pay for the environment evolves as income grows, and on the way the environment may be discounted in different contexts, for example by countries with different levels of development.

4.3 Theoretical model

In this section, we develop a model which allows either for substitutability or complementarity between goods. Hence, we avoid to impose a single nature of interaction between goods, *i.e.* the two interaction natures (substitutability or complementarity) are possible. We also provide an example of utility function which satisfies the assumptions of our general model in order to illustrate our point.

4.3.1 General framework

Consider a utility function U which satisfies Assumption 2 *i.e.* utility U is strictly increasing and concave in both consumption and environmental quality.

Assumption 3 *There exists a surjective function φ which takes a bundle $(C,E) \in R_{+}^{*2}$ as argument and which is positive if $U_{CE} > 0$, negative if $U_{CE} < 0$ and null if $U_{CE} = 0$.*

Function φ represents a two-dimension quantity *i.e.* an aggregation of economic and environmental "quantities".

In "equal-preference" models, individuals usually differ only according to their income. In this model, individuals have the same preferences but can differ according to their bidimensional context defined as follows.

Definition 6 (Context) *The context is defined as the endowment of the consumer in terms of both income and environmental quality, i.e., $(Y,E) \in \mathbb{R}_{+}^{*2}$.*

Consider that the consumer is endowed with income Y. The composite consumption good has a price index denoted by p. Following Ebert (2003), environmental quality is characterized as a public good *i.e.* the environmental quality E neither can be chosen nor influenced by the consumer, it is exogenously provided and rationed. The objective of the consumer is to maximize her budget-constrained utility as follows.

$$\underset{C}{\text{Max}} \ U(C,E) \ s.t. \ Y = pC \text{ and } E \text{ fixed} \tag{4.3.1}$$

The solution yields the *conditional* (to the fixed level of environmental quality) Marshallian demand function $C^{*}(Y,E,p) \equiv \frac{Y}{p}$.[17] Note that this definition of $C^{*}(Y,E,p)$ comes from the equivalence between solving eq. (4.3.1) and solving the following maximization problem (Ebert, 2003).

$$\underset{C,E}{\text{Max}} \ U(C,E) \ s.t. \ \hat{Y} = Y + wE \tag{4.3.2}$$

where $\hat{Y}$ is the virtual income and w (see eq. (4.2.3)) is the virtual price (Lindahl price) which would lead individuals to consume the exogenous level E as if it were voluntarily chosen. Put differently, this is the environmental price which, on the one hand, yields the (fixed) environmental quality level E as the *unconditional* Marshallian demand in this pseudo choice problem and, on the other hand, conserves the validity of $\frac{Y}{p}$ as the correct specification for C^{*} (Ebert, 2003; Baumgartner et al., 2016). It results that $C^{*}(Y,E,p) = C^{*}(\hat{Y},w,p)$. Hence, the indirect utility function associated to problem (4.3.1) is denoted by V such that

[17] Note that C is a composite of n market goods C_i with $i = 1,...,n$ with their own demands C_i^{*} which are aggregated in C^{*}. For example, C can be a CES good. However, the expression of the demands specific to each market good is not of interest for our point which is about the substitutability between market and non-market goods.

$V(Y,E,p) = U(C^*(Y,E,p),E)$.

We aim to relate between-goods substitutability in the good space and between-goods substitutability in the endowment space or equivalently the context.[18] According to the Edgeworth-Pareto criterion, the cross derivative in indirect utility, henceforth *contextual substitutability*, indicates substitutability between income and environmental quality within utility.

To get the contextual substitutability, we evaluate the cross derivative of the (direct) utility function at the optimum (see Appendix A).

$$V_{YE} = C^*_{YE} U_C + C^*_Y \left[C^*_E U_{CC} + U_{CE} \right] \tag{4.3.3}$$

Proposition 5 (Contextual substitutability and between-goods substitutability) *Income and environmental quality are complementary (substitutable) if and only if consumption and environmental quality are sufficiently complementary (substitutable). This depends on the demand-related cross elasticities and the elasticity of marginal utility for consumption.*

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

with $\epsilon_{C,E} = \frac{\frac{\partial C^*}{C^*}}{\frac{\partial E}{E}}$ *and* $\epsilon_{Y,E} = \frac{\frac{\partial C^*_Y}{C^*_Y}}{\frac{\partial E}{E}}$.

The proof of Proposition 5 is in Appendix A. $\epsilon_{C,E}$ stands for the elasticity of demand with respect to environmental quality. This is the variation of the demand for the private good after a 1% change in environmental quality. $\epsilon_{Y,E}$ is the cross-elasticity of the marginal demand of income with respect to environmental quality. It measures the change in marginal demand of income after a 1% variation of the environmental quality.

As Proposition 5 states, contextual substitutability does not always imply a substitutability between goods (evaluated by the sign of $\eta_{C,E}$). It depends on the demand-related cross elasticities and the elasticty of marginal utility.

4.3.2 An example

To illustrate our theoretical framework, we use an example of utility function with the following putative form. For any $(C,E) \in \mathbb{R}^{*2}_+$,

$$U(C,E) \equiv C^\gamma E^\omega - \frac{\theta}{C^\alpha E^\beta} \tag{4.3.4}$$

[18] In the sense that between-goods substitutability evaluated at the optimum (*i.e.* substituting C by the conditional demand C^*) gives between-goods substitutability in the endowment space. In other words, U_{CE} evaluated in C^* gives V_{YE}.

where $\theta > 0$ is a given parameter and $0 < \gamma, \alpha, \omega, \beta < 1$. This function satisfies the conditions of Assumptions 2 and 3.[19] For simplicity, we call it the *context-dependent substitutability (CDS) function*.[20] Figure 4.1 shows the indifference curves associated to the CDS function.

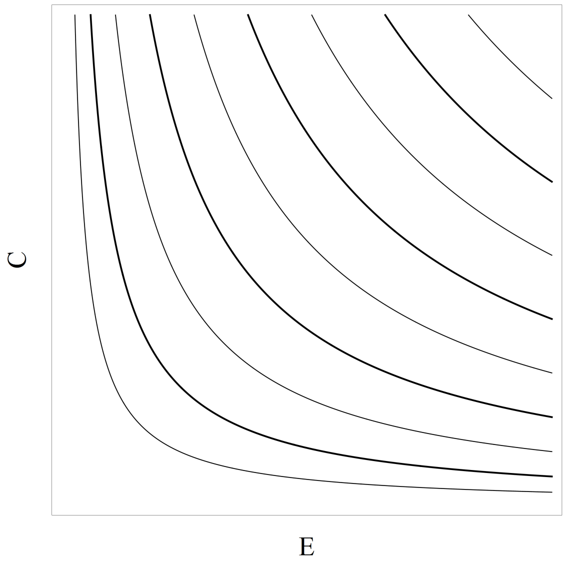


Figure 4.1: Indifference curves of the CDS utility function ($\alpha = \beta = \gamma = \omega = 0.5$ and $\theta = 100$)

The CDS utility function (eq. 4.3.4) is the sum of two terms. The first term is positive and increasing with C and E, and the second term is negative and also increasing in C and E. The higher C and E, the more negligible the second term. To ease the interpretations, we shall refer to this second term as the "needs" part of the utility. In the limiting case where $\theta = 0$, this “needs” term vanishes and the function reduces to the classic Cobb-Douglas utility function case (namely the ”classic” term of the utility function). On the contrary, when C and E are low, the second term of the sum is not negligible and reduces utility.

The cross derivative of the CDS utility function is the following.

$$U_{CE} = U_{EC} = \gamma\omega C^{\gamma-1}E^{\omega-1} - \theta\alpha\beta C^{-\alpha-1}E^{-\beta-1} \tag{4.3.5}$$

Its sign depends on the combination of the quantities of each good as follows:

$$\forall\, C,E > 0 \begin{cases} U_{CE} > 0 \;\Leftrightarrow\; C^{\gamma+\alpha}E^{\omega+\beta} > \theta\frac{\alpha}{\gamma}\frac{\beta}{\omega} \\ U_{CE} < 0 \;\Leftrightarrow\; C^{\gamma+\alpha}E^{\omega+\beta} < \theta\frac{\alpha}{\gamma}\frac{\beta}{\omega} \\ U_{CE} = 0 \;\Leftrightarrow\; C^{\gamma+\alpha}E^{\omega+\beta} = \theta\frac{\alpha}{\gamma}\frac{\beta}{\omega} \end{cases}$$

where $\varphi(C,E) = C^{\gamma+\alpha}E^{\omega+\beta} - \theta\frac{\alpha}{\gamma}\frac{\beta}{\omega}$ is the CDS-specific bidimensional quantity (whose dimensions are economic and environmental) as defined in Assumption 3. This is illustrated in

[19]Two other possible functions are $U(C,E) \equiv C^{\gamma}E^{\omega} + \theta\ln(C^{\alpha} + E^{\beta})$ and $U(C,E) \equiv CE - e^{\theta - C - E}$.

[20]The preferences represented by U are not homothetic. The properties of function U are consistent with preferences satisfying completeness, continuity, transitivity, non-satiation.

Figure 4.2. Note that all the graphs in the paper display the red color for positive values and the blue color for negative values.[21]

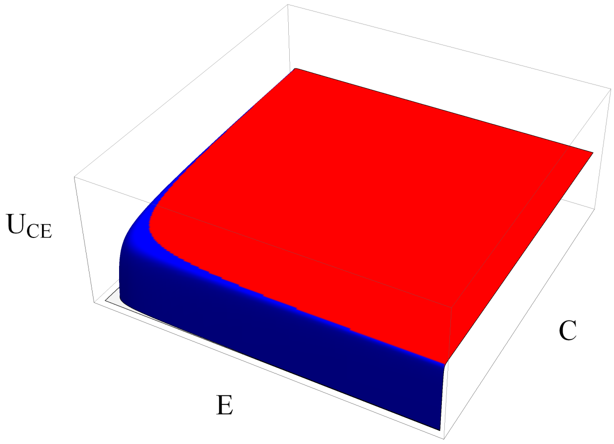


Figure 4.2: Between-goods substitutability within the CDS (direct) utility function ($\alpha = \beta = \gamma = \omega = 0.5$, $\theta = 100$ and $Y^{\max} = E^{\max} = 100$)

The frontier between the substitutability domain (in blue) and the complementarity domain (in red) is where $\varphi(C,E)$ equates zero. The higher this bidimensional quantity (represented by φ), the more complementary consumption and environmental quality become in providing utility. Our framework can be interpreted in terms of characteristics of goods. For example, a forest has different characteristics. While it provides individuals with food and fuel wood which are related to basic needs, it also has recreational properties (*e.g.* hiking, animals observation and preservation, tree-trekking) which are associated with higher income levels. Fuel wood has substitutes in the market like fuel oil but recreational activities require both income and a good environmental quality (complementary).

As described in the previous subsection, we follow Ebert (2003, p.439) in considering the income-equivalent WTP for environmental quality at level E as the product of the marginal willingness to pay w and the number of units E.[22]

Therefore, this allows us to derive the context-dependent substitutability as follows.

$$\text{For } \; C = C^*(Y,E,p) \begin{cases} V_{YE} > 0 \;\Leftrightarrow\; Y^{\gamma+\alpha}E^{\omega+\beta} > \theta \frac{\alpha}{\gamma}\frac{\beta}{\omega} p^{\alpha+\gamma} \\ V_{YE} < 0 \;\Leftrightarrow\; Y^{\gamma+\alpha}E^{\omega+\beta} < \theta \frac{\alpha}{\gamma}\frac{\beta}{\omega} p^{\alpha+\gamma} \\ V_{YE} = 0 \;\Leftrightarrow\; Y^{\gamma+\alpha}E^{\omega+\beta} = \theta \frac{\alpha}{\gamma}\frac{\beta}{\omega} p^{\alpha+\gamma} \end{cases}$$

[21] This is the case for all the objects of study in the paper *e.g.* cross derivatives, elasticities, etc.

[22] For the CDS function, from eq. (4.2.3) in section 4.2, $w = \frac{Y\left(\beta\theta + \omega E^{\omega+\beta}\left(\frac{Y}{p}\right)^{\gamma+\alpha}\right)}{E\left(\alpha\theta + \gamma E^{\omega+\beta}\left(\frac{Y}{p}\right)^{\gamma+\alpha}\right)}$.

The context-dependent substitutability is illustrated in Figure 4.3. The function $\Phi(Y,E) = Y^{\gamma+\alpha}E^{\omega+\beta} - \theta\frac{\alpha}{\gamma}\frac{\beta}{\omega}p^{\alpha+\gamma}$ can be viewed as the CDS economic-ecological wealth function. As this bidimensional wealth grows, income and environmental quality become more complementary within utility. This is supported by the environmental Kuznets curve. For relatively low levels of income, a substitution of environmental quality (*e.g.* using environmental resources without regulation) for consumption occurs. From a certain level of income, a greater value is assigned to environmental quality and thus, there is more preservation of the environment. Consider for example an individual whose income is relatively low and environmental surroundings relatively good (*e.g.* a forest which allows for collecting wood fuel). Then, wood fuel from the forest substitutes for oil fuel bought at the supermarket in the sense that they are redundant in utility. Wood fuel here provides the individual with (virtually) higher income which allows her to reach a (non-virtually) higher level of utility.

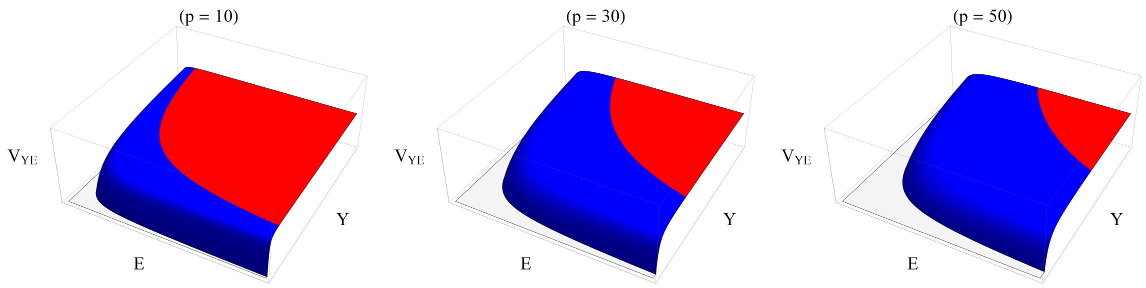


Figure 4.3: Contextual substitutability within the CDS (indirect) utility function ($\alpha = \beta = \gamma = \omega = 0.5$, $\theta = 100$ and $Y^{\max} = E^{\max} = 100$)

In Figure 4.3, the frontier between the substitutability domain (in blue) and the complementarity domain (in red) depends on the price of the private good p. As p increases (*i.e.* purchasing power[23] decreases), the substitutability domain increases. This means that the individual tends to consume less private goods and compensates with environmental substitutes. For the sake of comparison, we provide in Appendix C the same graphs for the CES utility function.

4.4 Contextual substitutability and income elasticity of WTP

This section derives the impacts of the theoretical model developed in section 4.3 on the income elasticity of willingness to pay.

[23]Note that real income concerns would only rely on dividing Y by p if the share of the total virtual income (see $\hat{Y}$ in eq. (4.3.2)) allocated to the consumption of environmental goods were zero.

4.4.1 General results

As eq. (4.2.4) puts forward, the sign of the income elasticity of WTP depends on the sign of the cross derivative of the indirect utility denoted by V_{YE}.

Proposition 6 (Context-dependent income elasticity of WTP) *The income elasticity of WTP can only be negative if there is a contextual substitutability between income and environmental quality i.e.* $V_{YE} < 0$*.*

Proposition 6 relies on eq. (4.2.4). As $V_Y > 0$, $V_E > 0$ and $V_{YY} < 0$, the common case of positive income elasticity of WTP is possible for both contextual substitutability and contextual complementarity. Put differently, there is no condition on the nature of the interaction between income and environmental quality. However, a necessary condition for a negative income elasticity is that $V_{YE} < 0$. This case is not common in the literature, yet of interest. This means that WTP decreases as income grows, which makes environmental quality an inferior good in such a context.

Corollary 1 (Inferior good) *An environmental good can only be classified as an inferior good if there is a contextual substitutability.*

The necessary condition for environmental quality to be considered as an inferior good is that more income reduces the marginal utility of environmental quality. In other words, there is a compensation which operates between these two endowments. If V_{YE} is negative enough *i.e.* if substitutability is strong enough, the income rise leads an individual to neglect the environment for more convenient market substitutes.

According to Proposition 6 and Corollary 1, our theoretical model thus allows for a classification of environmental goods as either normal goods or inferior goods. This is not possible with classical functions such as the CES function. Indeed, as shown by Ebert (2003), the income elasticity of WTP under the CES specification is constant and equal to the inverse of the elasticity of substitution (see graphs in Appendix C). This makes negative values of this elasticity impossible.

It is as well worthwhile linking *between-goods* substitutability with the income elasticity of WTP. Since eq. (4.2.4) exclusively shows the link between contextual substitutability and the income elasticity of WTP, the relationship between contextual substitutability (in indirect utility) and between-goods substitutability (in direct utility) is helpful. Based on Propositions 6 and 5, the income elasticity of WTP can be related to between-goods substitutability as follows.

Proposition 7 (WTP and between-goods substitutability) *The income elasticity of WTP can only be negative if consumption and environmental quality are sufficiently substitutable. A sufficient condition for between-goods substitutability is that* $\eta_{C,C} < \frac{\epsilon_{Y,E}}{\epsilon_{C,E}}$*.*

The proof of Proposition 7 is straightforward. As far as $\epsilon_{Y,E} - \epsilon_{C,E}\,\eta_{C,C}$ is positive, $\eta_{C,E}$ is positive as well, which means that consumption and environmental quality are substitutable by definition. Thus, the elasticity of marginal utility for consumption $\eta_{C,C}$ needs to be sufficiently low. Recalling that $\eta_{C,C} = -C\frac{U_{CC}}{U_C}$, a low $\eta_{C,C}$ means that utility is weakly concave in C.

4.4.2 Numerical illustration with the CDS function

According to Proposition 6, we derive the conditions under which a negative income elasticity of WTP is possible with the CDS specification.

Proposition 8 *If* $\frac{\alpha\omega}{\beta\gamma} < \frac{(\gamma+\alpha-1)^2}{(\gamma+\alpha+1)^2}$, *there are contexts in which the income elasticity of WTP,* ε^Y_{WTP}, *is negative.*

The proof of Proposition 8 is in Appendix D. These conditions are satisfied for the following set of parameters (among others) of the CDS function: $\alpha = \beta = \gamma = 0.99$ and $\omega = 0.01$. Figure 4.4 illustrates this case.

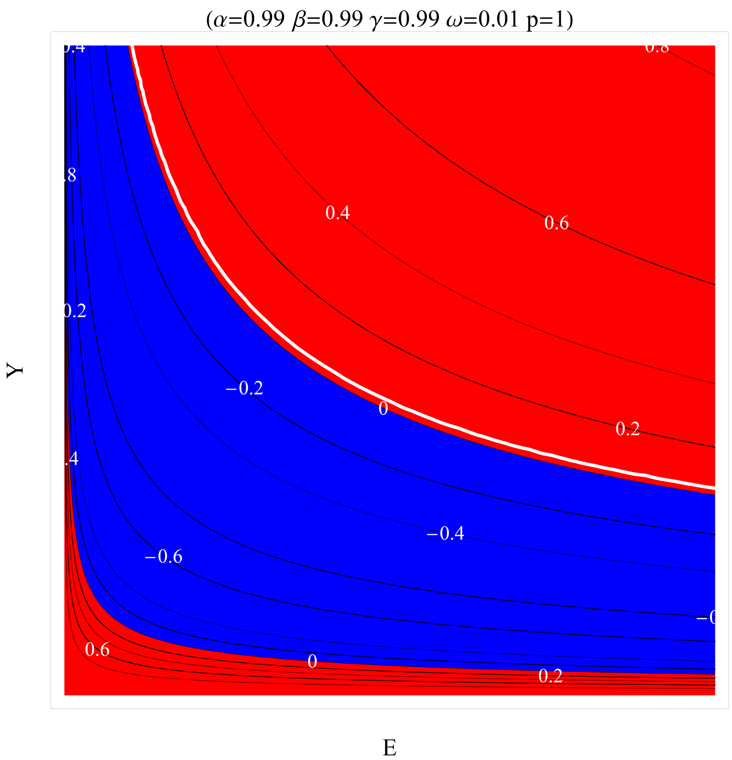


Figure 4.4: Income elasticity of WTP under the CDS utility function

The black lines in Figure 4.4 indicate the levels of the income elasticity (white values displayed on the lines). The blue area illustrates the economic-ecological wealth set under which an individual tends to give less for the environment as her income rises. The two red areas indicate that the income elasticity is positive as classically found in the literature. The white curve indicates the frontier between the substitutability (below the curve) and the complementarity (above the curve) domains. It confirms that the income elasticity of WTP can only be negative when income and environmental quality are substitutable. The CDS function thus allows for a classification of environmental goods as inferior goods.[24]

When the economic-ecological wealth is very low, an individual is willing to pay for the environment as her income increases (first red domain). This is in line with the environment being classified as a necessity (normal) good for very low levels of income. Think of a forest which is the only resource some individuals may have to survive (it provides fuel wood, food and water). If the little money they have is not enough to purchase in a supermarket substitutes of what the forest provides, then preserving the forest by, if necessary, sacrificing their little income as much as they can is probably the best way to maximize their utility. This is in line with the safety net vision of the forest (Angelsen et al., 2014). This is true till a turning point (from the first red area to the blue area) at which they get enough income to get supply (*e.g.* meat, fuel oil) from a supermarket for example. This is more convenient than hunting or collecting wood in the forest. Thus the forest becomes an inferior good (blue area) *i.e.* a substitution of the forest for more convenient private goods operates. Finally, at higher economic-ecological wealth levels (from the frontier between the blue area and the second red area), the forest can be classified as a normal good again and mostly corresponds to a complementarity between income and environmental quality. This can be interpreted as follows. Better-off individuals have more income to enjoy the forest *e.g.* paying for an access to natural areas, recreation activities such as tree-trekking, renting a boat to spend time on a wild island, etc. Thus, their utility depends in a complementary manner on both types of goods (private and environmental) because they can afford these activities which highly depend on environmental quality.

4.5 Contextual substitutability and discounting

In this section, we derive the implications of our general framework on discounting. We then give some insight on income shocks through the case of the CDS function.

4.5.1 General results

The general theoretical framework proposed in Section 4.3 leads to distinct signs of the substitution effect whether consumption and environmental quality are substitutable or complementary,[25] given growth prospects for consumption and environmental quality. Those are summarized in Table 4.1.

Proposition 9 *Context-dependent substitutability allows the substitution effect to impact differently the economic and environmental discount rates.*

[24]This is not the case for a CES function for example. The income elasticity of WTP is plotted for different values of the CES in Appendix C.

[25]When they are independent, there is no substitution effect, only the growth effect influences the discount rates.

Table 4.1: Sign of the substitution effect

	Substitution Effect			
	r^C		r^E	
	$g_E > 0$	$g_E < 0$	$g_C > 0$	$g_C < 0$
Substitutability	+	-	+	-
Complementarity	-	+	-	+

Whether consumption and environmental quality are complements ($\eta_{C,E} < 0$ and $\eta_{E,C} < 0$) or substitutes ($\eta_{C,E} > 0$ and $\eta_{E,C} > 0$), which is directly linked to the context, impacts the value of the discount rate.

Our results are more general than the results obtained in the case of an isoelastic CES utility function as commonly used in the literature on discounting.

For example, Traeger (2011a) shows that the substitution effect always increases the economic discount rate and always reduces the ecological discount rate. This is due to the assumption made on the kind of relationship between goods. Fixing the kind of relationship between the two goods determines exogenously the sign of the substitution effect,[26] hence the time evolution of the discount rates, for a given growth prospect. As a consequence, only one row of Table 4.1 is obtained in the CES case whereas our model accounts for the two rows within the same framework (no change of utility parameters).

Within our framework, consider an economic growth ($g_C > 0$) and a depreciation of environmental quality ($g_E < 0$). In the domain of complementarity, the substitution effect is positive on the economic discount rate r^C (see Table 4.1). Thus, the individual is more concerned about present than future consumption flows. This result comes from the distaste effect (Michel and Rotillon, 1995): as environmental quality will be lower in the future, and as environmental quality and consumption are complements, future utility will be reduced by environmental degradation. There is thus no reason to be very sensitive to future consumption changes and one is more prone to consume in the present when environmental quality is better. By contrast, the environmental substitution effect is negative and thus decreases the environmental discount rate r^E. This way, the individual gives a high weight to future environmental quality because consumption is increasing and would result in a higher future utility if the environment quality is good, in conjunction to high consumption.

In the domain of substitutability however, the substitution effect has opposite effects: r^C decreases and r^E increases. The individual prefers to consume produced goods in the future than in the present because *(i)* environmental quality is diminishing and *(ii)* consumption will be the substitute for the loss of environmental quality. However, she discounts more environmental quality because consumption increases so there is no need in conserving environmental quality which can be substituted for by the increasing consumption.

[26] Kögel (2009) gives details on this specification.

4.5.2 Some suggestions for income shocks testing with the CDS function

We still consider the example of a growing economy ($g_C > 0$) and a decreasing environmental quality ($g_E < 0$).

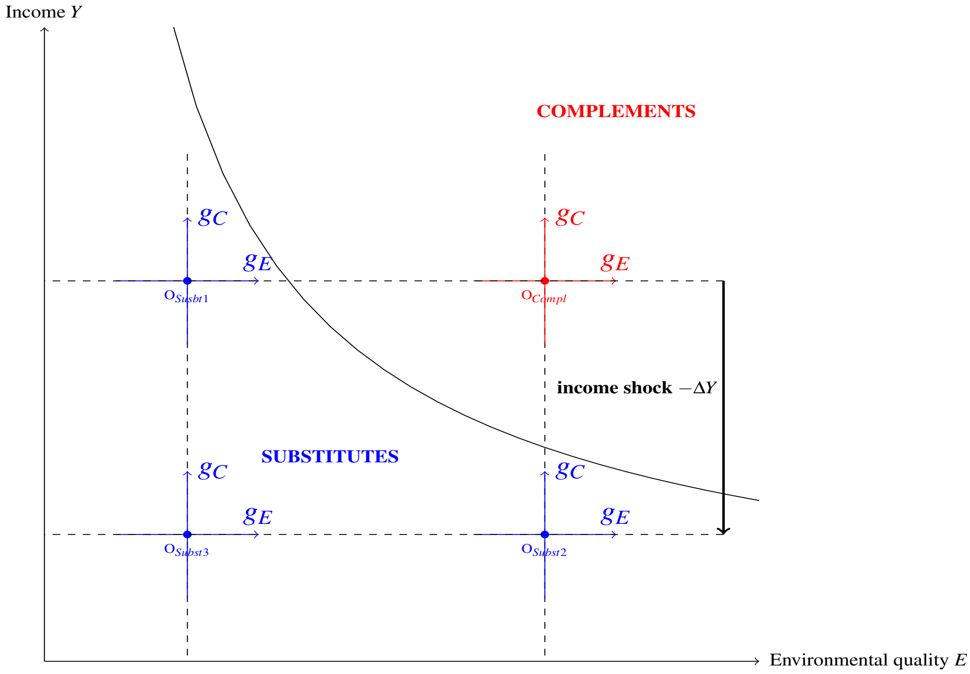


Figure 4.5: An illustration of income shock with the CDS utility function

Figure 4.5 illustrates potential income[27] shocks which may make an individual switch from a complementary context to a substitutability context. The black curve is only the frontier between the two natures of interaction. Note that all the insights hereafter are only related to the substitution effect, not the growth effect on the discount rate.[28]

Imagine an income shock occurs in the substitutability domain *i.e.* from O_{Subst1} to O_{Subst3} in Figure 4.5. The substitution effect should not change on the discount rate. However, since income and environmental quality are substitutable, the income shock can be compensated by an increase of environmental quality to provide utility. Indeed, a decrease in income increases the marginal utility for environmental quality, which makes the individual rely more on environmental goods than private goods. Angelsen et al. (2014) empirically support this view. They find that income shocks have a significant and positive impact on environmental income, which indicates that forests have the role of a "shock-absorber".

[27]For the sake of simplicity, as we are not considering a dynamic setting, we consider that the intertemporal welfare function is the sum of the instantaneous maximized utility levels. It follows that the good space (consumption and environmental quality) turns into the endowment space (income and environmental quality) by evaluating the former at (intratemporal) C^*.

[28]For a given growth prospect, the growth effect has the same effect (sign) on the discount rate before and after any income shock. Its magnitude however changes due to the elasticity of marginal utility ($\eta_{C,C}$ for r^C and η_{EE} for r^E).

Now if this income shock occurs from O_{Compl} (initial context of complementarity) to O_{Subst2} (final context of substitutability). Then, the sign of the substitution effect on the discount rate changes. If environmental quality is decreasing (*i.e.* $g_E < 0$ whatever the context), then before the shock, the substitution effect increases the discount rate for consumption (see Table 4.1). After the shock, the individual is in a context of substitutability which makes her discount future consumption less than before the shock. Indeed, the income shock makes the individual compensate the shock with environmental goods while waiting for income to grow again and compensate for the decreasing environmental quality in the future.

The benefits of a context-dependent substitutability may be particularly well-illustrated in such a context where shocks can occur in that it is possible to change the interaction of goods in providing utility to the individual. Thus, this would be interesting to study the CDS function within an intertemporal framework in the same lines as Traeger (2011a) with the additional introduction of shocks either on income or even environmental quality.

4.6 Conclusions

In this paper, we argue that heterogeneity among individuals is not relative to preferences but to the context. For this purpose, we developed a theoretical model in which all individuals have the same preferences, but their choice is dependent on the context. The novelty of our work is that it allows for different kinds of interactions between private (market) and environmental (nonmarket) goods depending on the context, that is, how income and environmental quality combine in providing utility. Contextual substitutability is crucial since it influences income effects on WTP, and discounting values which are key elements in the evaluation of public projects.

We find that the income elasticity of WTP can be negative only in a context of substitutability between income and environmental quality, whereas a positive elasticity is not associated to any particular kind of interaction. In this way, our framework contrasts with other models because the environmental good can turn into an inferior good in rather poor economic-ecological contexts (especially when income is low). While the literature focuses on utility functions which only allow for positive income elasticities, we argue that for relatively low economic-ecological wealth, WTP may decrease with income. This is suggested by the environmental Kuznets curve and mostly in line with the large empirical study of Angelsen et al. (2014) regarding rural livelihoods.

We also put forward that the way the consumption and environmental growth rates affect the economic and environmental discount rates depends on substitutability assumptions. As a consequence, in our framework, we show that the discount rates vary with the kind of relationship between consumption and environmental quality, thus according to the context. Indeed, while the growth effect on the discount rate always influences the discount rate in the same way for a given growth prospect, the substitution effect either reduces or increases the discount rate depending on contextual substitutability.

An avenue for research would be to analyze the impacts of our model on both WTP and discounting in a dynamic setting. Indeed, Horowitz (2002) derives the growth rate of WTP as follows: $\frac{\dot{WTP}}{WTP} = \varepsilon^{Y}_{WTP}\frac{\dot{Y}}{Y} + \varepsilon^{E}_{WTP}\frac{\dot{E}}{E}$. This way we could determine optimal growth rates and study the evolution of discount rates over time (with and without shocks).

A Proof of Proposition 5

In a general framework, the indirect utility is the maximum obtainable utility.

$$V(p,Y,E) = U(C^*(Y,E,p),E) \tag{A.1}$$

The first derivative of V with respect to Y is:

$$V_Y = C^*_Y(Y,E,p)U_C(C^*(Y,E,p),E) \tag{A.2}$$

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

$$V_{YE} = C^*_{YE}(Y,E)U_C(C^*(Y,E),E) + C^*_Y(Y,E)\left[C^*_E(Y,E)U_{CC}(C^*(Y,E),E) + U_{CE}(C^*(Y,E),E)\right] \tag{A.3}$$

Simplifying notations, we get:

$$V_{YE} = C^*_{YE}U_C + C^*_Y\left[C^*_E U_{CC} + U_{CE}\right] \tag{A.4}$$

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

$$V_{YE} > 0 \Leftrightarrow C^*_{YE}U_C + C^*_Y\left[C^*_E U_{CC} + U_{CE}\right] > 0 \tag{A.5}$$

$$\Leftrightarrow C^*_{YE}U_C > -C^*_Y\left[C^*_E U_{CC} + U_{CE}\right] \tag{A.6}$$

$$\Leftrightarrow \frac{C^*_{YE}}{C^*_Y} > -C^*_E\frac{U_{CC}}{U_C} - \frac{U_{CE}}{U_C} \tag{A.7}$$

$$\Leftrightarrow C^*E\frac{C^*_{YE}}{C^*_Y} > -C^*EC^*_E\frac{U_{CC}}{U_C} - C^*E\frac{U_{CE}}{U_C} \tag{A.8}$$

$$\Leftrightarrow C^*\left(E\frac{C^*_{YE}}{C^*_Y}\right) > EC^*_E\left(-C^*\frac{U_{CC}}{U_C}\right) + C^*\left(-E\frac{U_{CE}}{U_C}\right) \tag{A.9}$$

$$\Leftrightarrow \left(E\frac{C^*_{YE}}{C^*_Y}\right) > E\frac{C^*_E}{C^*}\left(-C^*\frac{U_{CC}}{U_C}\right) + \left(-E\frac{U_{CE}}{U_C}\right) \tag{A.10}$$

$$V_{YE} > 0 \Leftrightarrow \epsilon_{Y,E} > \epsilon_{C,E}\ \eta_{C,C} + \eta_{C,E} \tag{A.11}$$

We multiplied Eq.(A.7) by $C^{*}E$ to get Eq.(A.8). Similarly, we get:

$$V_{YE} < 0 \Leftrightarrow \epsilon_{Y,E} < \epsilon_{C,E}\ \eta_{C,C} + \eta_{C,E} \tag{A.12}$$

$$V_{YE} = 0 \Leftrightarrow \epsilon_{Y,E} = \epsilon_{C,E}\ \eta_{C,C} + \eta_{C,E} \tag{A.13}$$

B Discount rates' expressions

Let the present value of indirect utility at time t be denoted by $U^{\delta}(C(t),E(t),t) = U(C(t),E(t))e^{-\delta t}$. The marginal utility derived from an increment of income C at time t is

$$U_C(C(t),E(t),t) = U_C(C(t),E(t))e^{-\delta t}\ , \tag{B.1}$$

By definition, the economic discount rate, r^C is the rate of change of marginal utility for income[29] as time changes:

$$r^C \equiv -\frac{\dot{U}_C(C(t),E(t),t)}{U_C(C(t),E(t),t)} = -\frac{1}{U_C(C(t),E(t))e^{-\delta t}}\frac{d[U_C(C(t),E(t))e^{-\delta t}]}{dt} \tag{B.2}$$

As

$$\dot{U}_C(C(t),E(t),t) = \frac{d[U_C(C(t),E(t))e^{-\delta t}]}{dt} = \left(\dot{C}U_{CC} + \dot{E}U_{CE}\right)e^{-\delta t} - U_C\delta e^{-\delta t}\ , \tag{B.3}$$

we get

$$r^C = -\frac{[\dot{C}U_{CC} + \dot{E}U_{CE}] - U_C\delta}{U_C} = \delta - \frac{\dot{C}}{C}\left(C\frac{U_{CC}}{U_C}\right) - \frac{\dot{E}}{E}\left(E\frac{U_{CE}}{U_C}\right) \tag{B.4}$$

Let $\eta_{C,C} = -C\frac{U_{CC}}{U_C}$ be the elasticity of marginal utility of income with respect to income and $\eta_{C,E} = -Y\frac{U_{CE}}{U_C}$ be the elasticity of marginal utility of income with respect to environmental quality, then:

$$r^C = \delta + \frac{\dot{C}}{C}\eta_{C,C} + \frac{\dot{E}}{E}\eta_{C,E} \tag{B.5}$$

Now the same can be done for an increment of environmental quality Y. The environmental or ecological discount rate, r^Y is the rate of change of marginal utility for environmental quality as time changes

$$r^E \equiv -\frac{\dot{U}_E(C(t),E(t),t)}{U_E(C(t),E(t),t)} = -\frac{1}{U_E(C(t),E(t))e^{-\delta t}}\frac{d[U_E(C(t),E(t))e^{-\delta t}]}{dt} \tag{B.6}$$

[29]The negative sign is attributed to the fact that the discount rate is conventionally positive whereas the discount factor growth rate is negative (negative slope).

As

$$\dot{U}_E(C(t),E(t),t) = \frac{d[U_E(C(t),E(t))e^{-\delta t}]}{dt} = \left(\dot{Y}U_{EE} + \dot{C}U_{EC}\right)e^{-\delta t} - U_E\delta e^{-\delta t}\ , \qquad \text{(B.7)}$$

we get

$$r^E = -\frac{[\dot{E}U_{EE} + \dot{C}U_{EC}] - U_E\delta}{U_E} = \delta - \frac{\dot{E}}{E}\left(E\frac{U_{EE}}{U_E}\right) - \frac{\dot{C}}{C}\left(C\frac{U_{EC}}{U_E}\right) \qquad \text{(B.8)}$$

Let $\eta_{E,E} = -E\frac{U_{EE}}{U_E}$ be the elasticity of marginal utility of environmental quality with respect to environmental quality and $\eta_{E,C} = -C\frac{U_{EC}}{U_E}$ the elasticity of marginal utility of environmental quality with respect to income, then:

$$r^E = \delta + \frac{\dot{E}}{E}\eta_{E,E} + \frac{\dot{C}}{C}\eta_{E,C} \qquad \text{(B.9)}$$

C An comparative analysis of the CES and the CDS functions

Recalling that the CES function is as follows.

$$U(C,E) = \left(a\,C^{1-\frac{1}{\sigma}} + b\,E^{1-\frac{1}{\sigma}}\right)^{\frac{\sigma}{1-\sigma}} \qquad \text{(C.1)}$$

where a is the weight given to consumption, b is the weight given to environmental quality and σ is the elasticity of substitution. In this section, $a = b = 0.5$. In Figures 4.7, 4.9 and 4.10, $\sigma = 0.5$.

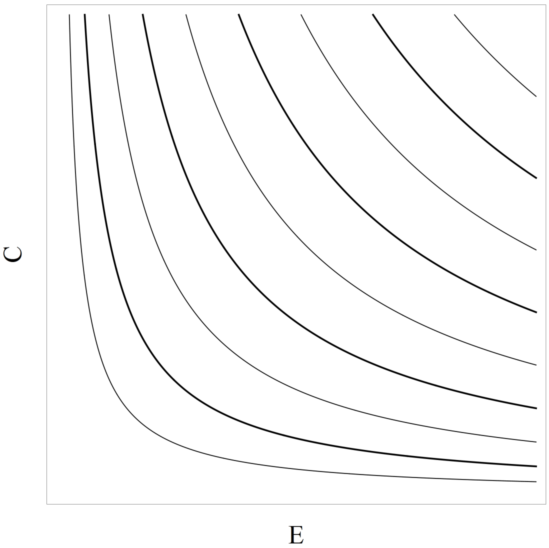


Figure 4.6: Indifference curves of the CDS function

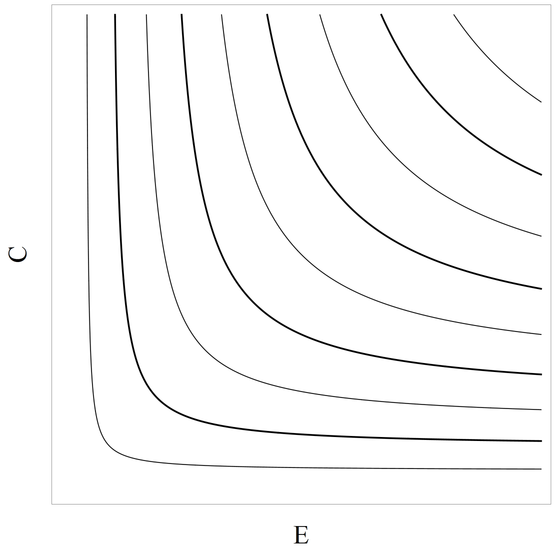
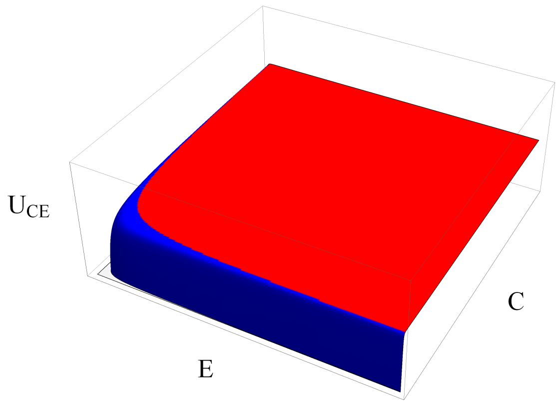


Figure 4.7: Indifference curves of the CES function

The following figure shows the CES function's income elasticity of WTP for three different



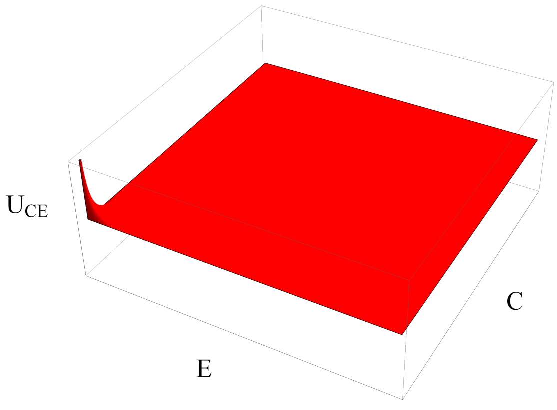


Figure 4.8: Between-goods substitutability within the CDS function

Figure 4.9: Between-goods substitutability within the CES function

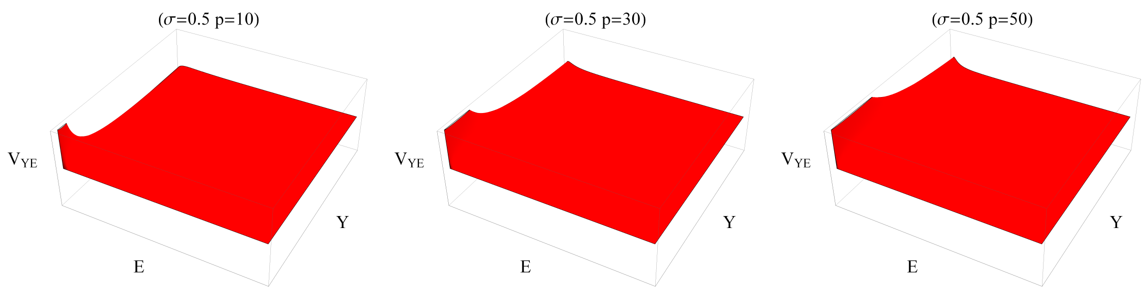


Figure 4.10: Contextual substitutability within the CES function

values of the elasticity of substitution (0.5 (Hicks complementarity), 1.01 (Cobb-Douglas) and 2 (Hicks substitutability).

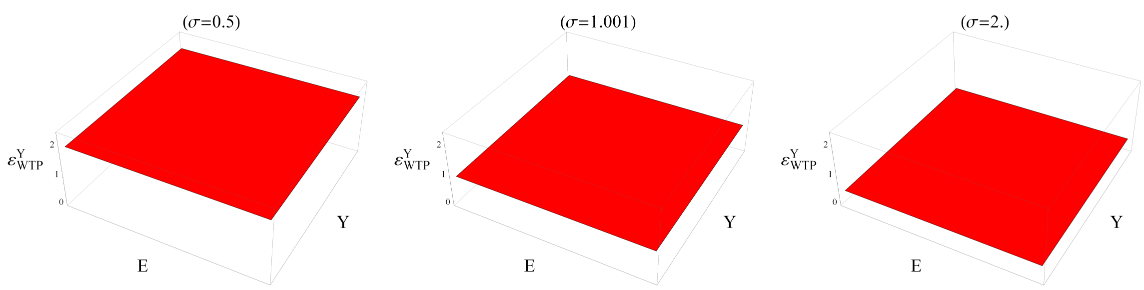


Figure 4.11: Income elasticity of WTP for the CES function

As shown by Baumgärtner et al. (2015b), the income elasticity of WTP is equal to the reverse of the elasticity of substitution, hence the constancy.

In summary, only E-P complementarity between consumption (as well as income) and environmental quality is possible with the CES function.

D Proof of Proposition 8

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

$$\begin{aligned}
\varepsilon^Y_{WTP} > 0 &\Leftrightarrow \frac{\partial WTP}{\partial Y} > 0 && \text{(D.1)}\\
&\Leftrightarrow V_{YE}V_Y - V_{YY}V_E > 0 && \text{(D.2)}\\
&\Leftrightarrow \frac{V_{YE}}{V_E} > \frac{V_{YY}}{V_Y} && \text{(D.3)}\\
&\Leftrightarrow -Y\frac{V_{YE}}{V_E} < -Y\frac{V_{YY}}{V_Y} && \text{(D.4)}\\
&\Leftrightarrow \eta_{E,Y} < \eta_{Y,Y} && \text{(D.5)}
\end{aligned}$$

$$\varepsilon^Y_{WTP} < 0 \Leftrightarrow \eta_{E,Y} > \eta_{Y,Y} \tag{D.6}$$

The sign of the income elasticity of WTP is opposite to the sign of the difference between $\eta_{E,Y}$ and $\eta_{Y,Y}$.

$$\eta_{E,Y} - \eta_{Y,Y} > 0 \Leftrightarrow \frac{\theta\alpha\beta - \gamma\omega\left(\frac{Y}{p}\right)^{\gamma+\alpha} E^{\omega+\beta}}{\omega\left(\frac{Y}{p}\right)^{\gamma+\alpha} E^{\omega+\beta} + \theta\beta} - \frac{\gamma(1-\gamma)\left(\frac{Y}{p}\right)^{\gamma+\alpha} E^{\omega+\beta} + \theta\alpha(\alpha+1)}{\gamma\left(\frac{Y}{p}\right)^{\gamma+\alpha} E^{\omega+\beta} + \theta\alpha} > 0 \tag{D.7}$$

$$\Leftrightarrow Z^2(-\gamma\omega) + Z(\theta\alpha\beta\gamma - \theta\gamma\omega\alpha - \theta\gamma(1-\gamma)\beta - \theta\alpha\omega(\alpha+1)) - \theta^2\alpha\beta > 0 \tag{D.8}$$

$$\Leftrightarrow AZ^2 + BZ + C > 0 \tag{D.9}$$

with

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

The discriminant of the polynomial $P(Z) = AZ^2 + BZ + C$ is :

$$\Delta = \theta^2(\beta\gamma - \alpha\omega)[\beta\gamma(\gamma+\alpha-1)^2 - \alpha\omega(\gamma+\alpha+1)^2)] \tag{D.10}$$

Δ is positive if and only if

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

or

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

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

$$Z_1 = \frac{4\theta\beta\gamma\alpha\omega}{\gamma\omega[\beta\gamma(\gamma+\alpha-1) - \alpha\omega(\gamma+\alpha+1) + \sqrt{(\beta\gamma-\alpha\omega)(\beta\gamma(\gamma+\alpha-1)^2 - \alpha\omega(\gamma+\alpha+1)^2)}]} \tag{D.11}$$

$$Z_2 = \frac{-4\theta\beta\gamma\alpha\omega}{\gamma\omega[\alpha\omega(\gamma+\alpha+1) - \beta\gamma(\gamma+\alpha-1) + \sqrt{(\beta\gamma-\alpha\omega)(\beta\gamma(\gamma+\alpha-1)^2 - \alpha\omega(\gamma+\alpha+1)^2)}]} \tag{D.12}$$

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

- if condition (1) holds, as $\frac{\alpha\omega}{\beta\gamma} < \frac{(\gamma+\alpha-1)^2}{(\gamma+\alpha+1)^2} \Leftrightarrow \frac{\alpha\omega}{\beta\gamma} < \frac{\gamma+\alpha-1}{\gamma+\alpha+1}$ because $\frac{\gamma+\alpha-1}{\gamma+\alpha+1} < 1$, then $B > 0$ 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 $B < 0$:

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

Only condition (1) is interesting for us to get a negative income elasticity. Then this income elasticity is negative between the curves of equation $Z = Z1$ and $Z = Z2$. Everywhere else, the income elasticity of WTP is positive.

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Chapter 5

Beyond perfect substitutability in public good games: heterogenous structures of preferences

This chapter is a first-draft working paper. The results are based on a pilot experiment. The experimental design may be subject to improvements.

Abstract

The literature on public good games is very focused on the additive separability of the values of the private and the public goods. Yet, the additive structure underlies a perfect substitutability relationship between the private and public goods, which is a strong assumption. This paper studies the effect of preference structures (substitutability *vs.* complementarity) on overcontributions within a voluntary contributions experiment in both homogenous and heterogenous groups. Within the structure of substitutability, subjects free-ride more often when they interact with subjects of the other type (complementarity) for whom it is optimal to contribute. Introducing such a heterogeneity may provide a method for the identification of free-riders. Nonetheless, an advantageous inequality aversion emerges as well. This means that under perfect substitutability, subjects tend to dislike earning too much compared to their group member whose preferences underlie complementarity, a more constraining structure.

Keywords: structure of preferences, public good game, substitutability, complementarity, heterogeneity, free-riding, inequality

JEL Classification: C71, C90, C92, D70, H41

5.1 Introduction

Public good games are mostly linear in the literature, which means that both private and public goods generate constant returns. Linear games are characterized by boundary Nash equilibrium and social optimum. This is at odds with the observation of positive contributions in the lab (Vesterlund, 2016) and considered as not realistic (Cason and Gangadharan, 2015). It partly explains the switch from linear to nonlinear games, the latter inducing interior Nash equilibrium. In the literature, the main forms of nonlinearities are the piecewise linear form (*e.g.* Bracha et al. (2011), Cason and Gangadharan (2015)), quadratic returns to the private and/or the public good (*e.g.* Sefton and Steinberg (1996)) and Cobb-Douglas payoff functions (*e.g.* Andreoni (1993) and Cason et al. (2002)).

Beyond the linear structure of public good games, all linear and most nonlinear games[1] involve an additivity of the private and the public goods returns. This additivity underlies a perfect substitutability[2] between private and public goods, which constitutes a strong assumption. Yet, the literature on public economics gives importance to the relationship between private and public goods *e.g.* Karras (1996) and Fiorito and Kollintzas (2004) regarding general private and public consumptions, Neumayer (1999), Gerlagh and Zwaan (2002) and Traeger (2011a) regarding private consumption and environmental quality. In particular, most negotiations are characterized by an interaction between agents who have different *structures of preferences*. In the context of climate change prevention for example, impacts are heterogenous across countries (Burke et al., 2015; Sterner, 2015), which leads to different (political) preferences. On the one hand, some countries may find advantageous to prevent climate change because it may enhance their economic aims, *i.e.* preventing climate change and improving GDP are rather *complementary*. This is mostly the case of vulnerable countries like those settled on islands. On the other hand, some countries have less interest in preventing climate change, especially those which are at high latitudes. Russia could for example save energy consumption and exploit more lands if the planet warms up, hence the *substitutability*. Therefore it is fundamental to account for the way private and public goods combine to provide utility.

In this paper, I investigate the effect of the structure of preferences in both homogenous and heterogenous groups, on the rate of overcontribution[3] compared to the Nash and on cooperation. I analyze behavioral determinants in the two following treatments: whether agents interact with the same or a different type of agent in terms of their preference structure.

Two structures of preference are considered: perfect substitutability and complementarity. The two structures are generated from a constant elasticity of substitution (CES) utility function but differ according to the value of the elasticity of substitution. The two structures are first evaluated separately in a between-subject homogenous treatment. Then, the two structures

[1] Including piecewise functions and quadratic returns.

[2] In the sense of Hicks. The additivity reflects independence in the Edgeworth-Pareto sense.

[3] Contributions cannot be compared directly since the Nash equilibrium across treatments changes. This will be explained in Section 5.3

are crossed in a within-subject treatment. Put differently, subjects are attributed a structure of preferences (*i.e.* a type) for the whole experiment and meet in one stage subjects with the same preference structure, and in another stage subjects with a different preference structure.

The structure of preferences is inherently linked to the strength of the social dilemma[4] as defined by Willinger and Ziegelmeyer (2001). Perfect substitutability which is underlied by a linear public good game involves the strongest social dilemma since individual and collective interests are at opposite boundaries. The more the structure is moved away from perfect substitutability (or equivalently additivity) the weaker the social dilemma, because both the Nash and social strategies move to the interior of the choice space. As in Willinger and Ziegelmeyer (2001), it is then possible in my experiment to analyze whether overcontributions persist *(i)* in a non-additive design and *(ii)* when heterogeneity of preference structures is introduced.

This is the first paper which introduces heterogenous structures of preferences within a public good game in the form of voluntary contributions. There are a few non-additive structures in the literature but either it involves homogenous groups of subjects (Andreoni, 1993; Cason et al., 2002) or a heterogeneity in terms of endowments or returns to the public good (Chan et al., 1999). Also, this paper is the first to link contributions to the public good and the substitutability between private and public good. This puts forward the inherent, yet overlooked, assumption on substitutability *vs.* complementarity between private and public goods involved in the choice of the functional form of the game.

A pilot experiment run in the University of Gothenburg mid-October 2016 allows me to provide a first insight into the effect of the structure of preferences on behavior. I find that the structure of preferences affects the rate of overcontribution. Perfect substitutability is associated with a higher rate of overcontribution and a higher proportion of zero contributions than complementarity.

Within subject's type (substitutability or complementarity), the following result stands out. Under perfect substitutability, free-riding increases in heterogenous groups compared with homogenous groups. Indeed, subjects have a higher incentive to free-ride when it is optimal for their group member (players with a complementarity structure) to contribute. This suggests that introducing heterogeneity in the preference structure provides a method to identify free-riders.

Finally, an advantageous inequality aversion emerges from subjects whose preferences underlie perfect substitutability when they interact with subjects whose preferences underpin complementarity. The formers experience aversion to earning too much compared with their group member.

The remainder of the paper is organized as follows: Section 5.2 explains why substitutability is an important concern and how it is linked to public good games. Section 5.3 describes the experimental theory and design of the experiment. Section 5.4 presents preliminary results from the pilot experiment. Section 5.5 offers preliminary conclusions and perspectives.

[4]This is the relative difference between the Nash equilibrium and the social optimum.

5.2 Background

5.2.1 Why substitutability is an important concern in public economics

A large body of empirical literature investigates the relationship between private and public consumptions or investments. It generally differs across countries. Karras (1996) and Fiorito and Kollintzas (2004) find that in the aggregate, private and public consumptions are rather complements than substitutes. On the contrary, Aschauer (1985) and Ahmed (1986) find evidence of substitutability for the respective cases of the United States and the United Kingdom. This relationship is fundamental in that it can affect international negotiations *i.e.* whether to invest or not in a common good.

It is particularly relevant to the climate change issue. Climate change impacts are heterogenous across countries (Burke et al., 2015; Sterner, 2015), even if in the aggregate, damages are negative. Giraudet and Guivarch (2016) provide a review on this aspect and show that global warming rather is an asymmetric public bad than a uniform one as commonly considered in modelling. The latitude is one central aspect of this heterogeneity: cold regions such as Russia and Canada may benefit from climate change through *e.g.* the development of new agricultural lands, better agricultural yields or lower heating expenditures, while warm regions like most African countries may suffer from more severe droughts and higher expenditures in air conditioning. Indeed, agriculture and energy use stand out as the most non-uniform GHG-related impacts on the economy (Arent et al., 2014).[5] This directly affects the structure of preferences *i.e.* whether investing in climate change prevention complements or substitutes for country economic aims.

Additionally, theoretical works show the impact of the substitutability assumption on discounting (Traeger, 2011a), which is a key aspect of decision-making be it national or international.

5.2.2 Substitutability and public good games

The perfect substitutability assumption is widespread in public good games, particularly those in the form of voluntary contributions. Linear and nonlinear games are reviewed in the following subsections, and classified as additive and non-additive games.

5.2.2.1 *Linear public good games*

The standard public good game involves linear payoffs *i.e.* where the returns from the private and the public good are constant and add up. Consider an individual i who contributes y_i to the public good out of an endowment of w_i units, thereby consumes $x_i = w_i - y_i$ units of the private

[5]For example, Costinot et al. (2016, p.207) plot the impact of climate change on the predicted relative change in productivity of two crucial crops for food production, namely wheat and rice, to particularly show the heterogeneity both between and within countries.

good. The individual's marginal value from the private good is a constant α, and the one from the public good is another constant β. Then individual i's payoff is given by the following payoff function:

$$\pi_i = \alpha(w_i - y_i) + \beta y \tag{5.2.1}$$

where $y = \sum_{j=1}^{N} y_j$ is the sum of all subjects' contributions to the public good. N is the number of subjects. The choice variable is y_i, which represents the amount subject i allocates to the public good. Then βy is the value of the public good and $x_i = w_i - y_i$ is the consumption of the private good. Notice that $\beta < \alpha < N\beta$ is a necessary condition to characterize a social dilemma. Indeed, $\beta < \alpha$ states that private returns are higher than public returns, which makes a zero contribution ($y_i = 0$) to the public good the (dominant strategy) Nash equilibrium. $\alpha < N\beta$ characterizes the social optimum ($y_i = w_i$) which is at the opposite boundary where the overall returns from the public good outweigh the private returns.

Linear structures in voluntary contributions mechanisms (VCM) have the advantage of displaying payoffs in a very simple manner to the experimental subjects. The latters are given the information of how much they earn from the private and the public goods separately since it is basically added-up. As well, free-riders are easy to identify because the Nash equilibrium and the social optimum are at opposite boundaries of the choice space. This structure is attractive by its simplicity but may not be realistic when it comes to real problems.

In the lab, the observation of contributions between 40% and 60% of subjects' endowment (Ostrom, 2000) questions the linear property of public good games, hence the search for more compatible designs with the observed pattern of contributions (Vesterlund, 2016). Therefore, it is worthwhile considering other settings where Nash and social outcomes are not at opposite boundaries *i.e.* non-linear settings.

5.2.2.2 *Nonlinear (non-additive) public good games*

Nonlinearities have been implemented in various ways in the literature. One simple way is to induce diminishing marginal returns of the private and/or the public goods. Formally, it means that α and β decrease instead of remaining constant as in the linear setting (see Eq. (5.2.1)). These nonlinearities are mostly implemented separately (Laury and Holt, 2008). If only α decreases (*i.e.* diminishing marginal value of the private good), the Nash equilibrium remains a unique dominant strategy as primarily studied by Isaac (1991) followed by *e.g.* Keser (1996) and Van Dijk et al. (2002). Quadratic returns are often employed as described below:

$$\pi_i = \alpha_1(w_i - y_i) - \alpha_2(w_i - y_i)^2 + \beta y \tag{5.2.2}$$

with α_1 and α_2 two constants and $\beta < \alpha_1$.

If only β decreases (*i.e.* diminishing marginal value of the public good), this turns the Nash equilibrium into a non-dominant strategy.[6]

$$\pi_i = \alpha(w_i - y_i) + \beta_1 y - \beta_2 y^2 \tag{5.2.3}$$

with β_1 and β_2 two constants and $\alpha < \beta_1$. Sefton and Steinberg (1996) compare the first type of nonlinearity (dominant Nash strategy) with the second type (non-dominant Nash strategy). They find that the variance of contributions regarding the non-dominant strategy is higher since it is less clear to determine how cooperation can be achieved in such a framework. Globally, there is still an observation of more contributions than the Nash equilibrium predicts (Laury and Holt, 2008), even when the location of the interior Nash equilibrium is moved within the choice space (see Isaac and Walker (1998)[7] and Willinger and Ziegelmeyer (2001)).

Another simple way of introducing nonlinearities is the piecewise linear form of public returns as Bracha et al. (2011) and Cason and Gangadharan (2015) use in their respective experiments. The cost of contributing is increasing in a discrete manner as contributions increase. It induces both an interior social optimum and a dominant-strategy unique Nash equilibrium.

$$\pi_i = w_i - cost(y_i) + return(y) \tag{5.2.4}$$

with

$$cost(y_i) \begin{cases} \delta_1 y_i & \text{if } y_i \in [0, NE] \\ \delta_1\, NE + \delta_2\, y_i & \text{if } y_i \in [NE, SO] \\ \delta_1\, NE + \delta_2\, SO + \delta_3\, y_i & \text{if } y_i \in [SO, w_i] \end{cases}$$

and

$$return(y) \begin{cases} 0 & \text{if } y < FC \\ \beta y & \text{if } y \geq FC \end{cases}$$

where $0 < \delta_1 < \beta < \delta_2 < 2\beta < \delta_3$ (increasing cost of contributing), NE and SO are the Nash and social contributions, and FC is a fixed cost which conditions the provision of the public good.

The common pool resource allocation literature focused on nonlinearities as well (Ostrom et al., 1992). But the additivity is a rule which also applies to most of this type of games.

All these types of nonlinear designs are very focused on the interior Nash equilibrium, which is an important concern regarding the observation of overcontributions in the lab for example. Nonlinear games allow for interior Nash equilibrium. However, as linear games, most of them are additive *i.e.* private and public returns are additively separable, which is a strong assumption. This raises the question of the relationship between private and public goods which is at the core of the literature in public economics (*e.g.* environment, health, investment). Closer to functions employed in theoretical works, Andreoni (1993) uses a Cobb-

[6] In other words, the strategy depends on the others' contribution.

[7] Except for very high positions of the Nash equilibrium. Still undercontributions for the high treatment were smaller than overcontributions in the other lower treatments, which indicates a propensity to cooperation.

Douglas function to assess crowding out. He imposes a minimum required contribution (like a tax) for each individual in order to move the boundary toward the Nash equilibrium and finds that the contributions increase but by less than the amount of the tax, hence the partial crowding out effect. Cason et al. (2002) also use a Cobb-Douglas function to study spitefulness across Japanese and American subjects. They find that American subjects are very close to the Nash predictions. Chan et al. (1999) use a linear function to which they add a Cobb-Douglas component to study the effect of heterogenous[8] agents on aggregate contributions. As highlighted in subsection 5.2.1, many situations involve the interaction of individuals with different preferences, not only regarding their endowment or the return they get from investing in a public project, but in the structure of their preferences. This structure inherently makes the magnitude[9] of the social dilemma vary. When one shifts away from additive separability of the private and the public values, both the Nash equilibrium and the social optimum move away from the extremes ends of the choice space.

5.3 Experimental environment

5.3.1 Theory

Two subjects 1 and 2 decide how much to contribute to a public good.[10] They are initially endowed with w_i where $i = 1,2$ that they have to allocate either to the public good y or to their own consumption of the private good $x_i = w_i - y_i$. The total provision of the public good hence results in $y = y_1 + y_2 + q$ where q is an initial exogenous quantity[11] of the public good and where y_1 and y_2 are the respective subjects' contributions. A utility-maximizer in this framework has the following decision problem:

$$\max\ u_i(x_i, y) \text{ s.t. } x_i + y_i = w_i \tag{5.3.1}$$

with u_i subject's i utility function. Subjects are distinguished according to their (supposed or attributed) preference structure (either substitutability or complementarity between the private and the public goods). To achieve this, I use an integer-approximation of a CES payoff function to convert contributions to the two different goods into each participant's payoffs:

$$u_i(x_i, y) = (\alpha\, x_i^{1-\frac{1}{\varepsilon_i}} + (1-\alpha)\, y^{1-\frac{1}{\varepsilon_i}})^{\frac{\varepsilon_i}{\varepsilon_i - 1}} \tag{5.3.2}$$

[8] In terms of endowment and returns to the public good.

[9] Or strength, as put forward by Willinger and Ziegelmeyer (2001).

[10] I chose to run a two-subject experiment as in Cason et al. (2002) or Van Dijk et al. (2002) who also use payoff tables. The use of payoff tables involves that the size of the table increases in the number of players, which would make the payoff table more complicated to read.

[11] q only allows me to ensure that there is a unique Nash equilibrium in the payoff table.

where ε_i is the constant elasticity of substitution between x_i and y for subject i, α is the return from private consumption. ε_i is varied across a 2×2 treatments design as shown in Table 5.1.

Table 5.1: Treatments according to the preference structure

Preference structure	ε value	S	C	$S \times C$	$C \times S$
Substitutability	$\varepsilon_i > 1$	×		×	×
Complementarity	$\varepsilon_i < 1$		×	×	×

[a] S and C are between-subject treatments. Subjects are attributed a type (either S or C) during the whole experiment.
[b] S / $S \times C$ and C / $C \times S$ are within-subject treatments. Subjects both experience a treatment in homogenous groups (S, C) and heterogenous groups $S \times C$ and $C \times S$.

When ε_i tends to infinity, the CES payoff function reduces to a linear public good game as presented in subsection 5.2.2.1, which underlies perfect substitutability between the private and the public goods. When $\varepsilon_i = 0$, the CES function reduces to the Leontieff function. This boundary case is not considered in the analysis because it does not generate any social dilemma (*i.e.* the Nash equilibrium is socially-efficient). However when ε_i is less than 1, a large degree of complementarity between goods is generated. Note that a Cobb-Douglas function relies on $\varepsilon_i = 1$,[12] which is an intermediate case between perfect substitutability and perfect complementarity.

To simplify notations, I denote by $\gamma_i = 1 - \frac{1}{\varepsilon_i}$ such that the CES utility function can be rewritten as:

$$u_i(x_i, y) = (\alpha\, x_i^{\gamma_i} + (1-\alpha) y^{\gamma_i})^{\frac{1}{\gamma_i}} \tag{5.3.3}$$

Using a monotonic transformation for the experiment, the payoff function results in:

$$\pi_i(x_i, y) = C + \left((\alpha\, (w_i - y_i)^{\gamma_i} + (1-\alpha)(y_i + y_{-i})^{\gamma_i})^{\frac{1}{\gamma_i}}\right)^{\eta} \tag{5.3.4}$$

where C and η are positive constants.

Despite the large body of literature on public good games which reports overcontributions compared to the Nash equilibrium, the traditional theory of pure self-interested individuals is retained as a benchmark in this experiment. As shown in Appendix A, the Nash equilibrium results in the following contributions:

$$\forall\, i\; y_i^* = \frac{1}{1 + \mu_i + \mu_{-i}} ((1 - \mu_i + \mu_{-i}) w - \mu_i\, q) \tag{5.3.5}$$

with $\mu_i = \left(\frac{1-\alpha}{\alpha}\right)^{\frac{1}{\gamma_i - 1}}$ and $w = w_i = w_{-i}$ by assumption. $-i$ denotes the individual in the

[12] *E.g.* Andreoni (1993) and Cason et al. (2002) use Cobb-Douglas payoff functions.

same group as subject i.

In the homogenous case (treatments S or C), $\gamma = \gamma_i = \gamma_{-i}$ (hence $\mu = \mu_i = \mu_{-i}$), resulting in:

$$y_1^* = y_2^* = \frac{1}{1+2\mu}(w - \mu\, q) \tag{5.3.6}$$

Regarding the Pareto efficient outcome,[13] let θ be the share of subject i's contribution. The general case in which participants are heterogenous in terms of their preference structures ($S \times C$ and $C \times S$ treatments)) is determined by the pair (θ, y) which satisfies the following equation and is represented in Figure 5.7 in Appendix B for the parameters values of the experiment reported in Table 5.2.

$$y^{\gamma_1 - 1}\left(w\theta(y-q)\right)^{1-\gamma_1} + y^{\gamma_2 - 1}\left(w - (1-\theta)(y-q)\right)^{1-\gamma_2} = \frac{\alpha}{1-\alpha} \tag{5.3.7}$$

Table 5.2: Utility Function Parameters Value Common to all Treatments

Parameter	Value
w	12
α	0.595
q	0.1426

In the homogenous case, θ is considered equal across the two participants pertaining to the same group, which leads to the following social optimum:

$$y_1^{s.o.} = y_2^{s.o.} = \frac{1}{2}(y^{s.o} - q) \tag{5.3.8}$$

where $y^{s.o} = \frac{(\theta\ q+w)(2(1-\alpha))^{\frac{1}{1-\gamma}}}{\alpha^{\frac{1}{1-\gamma}} + \frac{1}{2}(2(1-\alpha))^{\frac{1}{1-\gamma}}}$ (see Appendix B).

Though, in practice in the literature on public good games, the social optimum is determined by the maximum of the sum of individuals' payoffs. In the heterogenous case, the social optimum corresponds to the highest Pareto efficient optimum.

5.3.2 Experimental treatments

The experiment includes a 2×2 design. For each type of subject (S or C), the homogenous treatment implies that a group is composed of two subjects with identical payoff functions (same type). In Treatment S (for substitutability), both subjects have linear payoffs. Treatment

[13] This is determined by the Samuelson condition and the feasibility condition as detailed in Appendix B.

C is characterized by complementarity between the public and private goods. The preference structure (hence payoffs structure) is the same for both subjects as well.

Conversely, the two other treatments, namely $S \times C$ and $C \times S$, are characterized by groups of two subjects with different preference structures (different types). One subject decides how much to contribute to the public good upon linear payoffs (type S) while the other one has payoffs characterized by complementarity (type C).

Treatment S reduces to a standard homogenous linear public good game. It is the baseline treatment of the experiment with $\varepsilon_1 = \varepsilon_2 = 1000$.[14] The Nash equilibrium and the social optimum are at opposite boundaries: free-riding (*i.e.* contributing zero to the public good) is the best self-interested strategy whereas contributing everything is socially optimal. The Nash equilibrium is a dominant strategy in this treatment. Since returns from the private and the public goods are additive, they are usually displayed separately in the literature *i.e.* gains from the private good and gains from the public good. In my experiment though, for the sake of homogeneity across treatments, subjects S are provided with payoff tables as illustrated in Figure 5.1.

YOUR CONTRIBUTION

THE OTHER GROUP MEMBER'S CONTRIBUTION

Perso →		12	11	10	9	8	7	6	5	4	3	2	1	0
↓	Group → ↓	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
12	0	264 264	259 277	253 291	248 305	243 321	238 337	233 355	229 373	225 392	221 413	217 434	213 457	209 480
11	1	277 259	271 271	265 284	259 298	254 313	249 329	244 346	239 364	234 383	230 403	225 424	221 446	217 469
10	2	291 253	284 265	278 278	272 292	266 306	260 322	255 338	249 356	244 374	239 394	235 414	230 435	226 458
9	3	305 248	298 259	292 272	285 285	279 299	273 314	267 330	261 347	255 365	250 384	245 404	240 425	235 447
8	4	321 243	313 254	306 266	299 279	292 292	286 307	280 323	273 339	267 357	262 375	256 395	251 415	245 437
7	5	337 238	329 249	322 260	314 273	307 286	300 300	293 315	287 331	280 348	274 366	268 385	262 405	257 427
6	6	355 233	346 244	338 255	330 267	323 280	315 293	308 308	301 324	294 340	288 358	281 376	275 396	269 417
5	7	373 229	364 239	356 249	347 261	339 273	331 287	324 301	316 316	309 332	302 349	295 368	288 387	282 407
4	8	392 225	383 234	374 244	365 255	357 267	348 280	340 294	332 309	325 325	317 341	310 359	303 378	296 397
3	9	413 221	403 230	394 239	384 250	375 262	366 274	358 288	349 302	341 317	333 333	326 350	318 369	311 388
2	10	434 217	424 225	414 235	404 245	395 256	385 268	376 281	368 295	359 310	350 326	342 342	334 360	326 379
1	11	457 213	446 221	435 230	425 240	415 251	405 262	396 275	387 288	378 303	369 318	360 334	351 351	343 370
0	12	480 209	469 217	458 226	447 235	437 245	427 257	417 269	407 282	397 296	388 311	379 326	370 343	361 361

Figure 5.1: Detailed payoff table provided to participants in Treatment S

In all treatments, payoff tables are read as follows: the columns are for the subject's own

[14] It can be checked that a CES function with such parameters and a linear function with the same parameters are equivalent in terms of payoffs.

contribution numbers (filled in dark red) and the rows are for the co-player's contribution numbers (filled in dark blue). Red payoffs are the subject's payoffs and blue payoffs are the other group member's payoffs. Personal contributions are also displayed above the contributions possibilities in order to help subjects understand that their choice of contributions to the public good determines directly how many tokens they assign to their personal or private activity.

Treatment C underlies complementarity with $\varepsilon_1 = \varepsilon_2 = 0.7$. This treatment is homogenous, with a non-additive functional form implying interior Nash equilibrium and social optimum. It is optimal for both subjects to contribute 3 which is a non-dominant strategy[15] in this treatment. Non-dominant strategies generally induce more variance of contributions (Sefton and Steinberg, 1996). Though, in this experiment, it is easy to find what is the dominant strategy by interval of the other's contributions. So, depending on their belief and gain of experience along the game, subjects can find an "interval-based" dominant strategy. [16]

YOUR CONTRIBUTION

THE OTHER GROUP MEMBER'S CONTRIBUTION

Perso →		12	11	10	9	8	7	6	5	4	3	2	1	0
↓	Group → ↓	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
12	**0**	170 / 170	186 / 187	206 / 213	222 / 241	232 / 269	236 / 297	233 / 325	226 / 353	215 / 380	201 / 406	187 / 431	175 / 456	170 / 480
11	**1**	187 / 186	209 / 209	228 / 234	241 / 260	248 / 285	248 / 310	243 / 334	233 / 357	219 / 380	203 / 402	188 / 424	175 / 445	170 / 465
10	**2**	213 / 206	234 / 228	251 / 251	260 / 273	263 / 294	260 / 315	252 / 335	239 / 355	223 / 374	205 / 393	189 / 410	175 / 428	170 / 444
9	**3**	241 / 222	260 / 241	273 / 260	279 / 279	278 / 297	272 / 314	260 / 330	244 / 346	226 / 362	207 / 377	189 / 391	176 / 405	170 / 419
8	**4**	269 / 232	285 / 248	294 / 263	297 / 278	292 / 292	283 / 306	268 / 319	250 / 332	230 / 344	209 / 356	190 / 367	176 / 378	170 / 389
7	**5**	297 / 236	310 / 248	315 / 260	314 / 272	306 / 283	293 / 293	276 / 303	255 / 313	233 / 322	211 / 331	191 / 340	176 / 348	170 / 356
6	**6**	325 / 233	334 / 243	335 / 252	330 / 260	319 / 268	303 / 276	283 / 283	260 / 290	236 / 297	212 / 303	192 / 310	176 / 316	170 / 322
5	**7**	353 / 226	357 / 233	355 / 239	346 / 244	332 / 250	313 / 255	290 / 260	265 / 265	239 / 270	214 / 274	192 / 278	176 / 282	170 / 286
4	**8**	380 / 215	380 / 219	374 / 223	362 / 226	344 / 230	322 / 233	297 / 236	270 / 239	242 / 242	216 / 245	193 / 247	176 / 250	170 / 252
3	**9**	406 / 201	402 / 203	393 / 205	377 / 207	356 / 209	331 / 211	303 / 212	274 / 214	245 / 216	217 / 217	193 / 218	176 / 220	170 / 221
2	**10**	431 / 187	424 / 188	410 / 189	391 / 189	367 / 190	340 / 191	310 / 192	278 / 192	247 / 193	218 / 193	194 / 194	177 / 194	170 / 195
1	**11**	456 / 175	445 / 175	428 / 175	405 / 176	378 / 176	348 / 176	316 / 176	282 / 176	250 / 176	220 / 176	194 / 177	177 / 177	170 / 177
0	**12**	480 / 170	465 / 170	444 / 170	419 / 170	389 / 170	356 / 170	322 / 170	286 / 170	252 / 170	221 / 170	195 / 170	177 / 170	170 / 170

Figure 5.2: Detailed payoff table provided to participants in Treatment C

The complementarity structure is easy to identify. Considering that the other group member contributes zero, subject C gets the lowest payoff (170) at the extreme ends of the table *i.e.* when she contributes zero and when she contributes everything. Indeed, subjects C are better off when they both enjoy the private good and the public good. If subject C contributes all her

[15] The best response depends on the contribution of the other individual in the same group.

[16] *E.g.* in Figure 5.2, when the other's contribution is between 3 and 4, it is better to contribute 3. When between 1 and 2, it is better to contribute 4.

endowment, then the private component of her utility is zero, which keeps her from enjoying the public good for any contribution of the other subject. Conversely, if she contributes nothing to the public good and the other member also contributes zero, she gets the lowest payoff as private benefits cannot be enjoyed without public benefits. Typically, subjects of type C are more constrained by the structure of their preference than subjects S because they need both increases of the public good and the private good benefits to increase their payoff.

Treatment $S \times C$ and $C \times S$ depart from the two other treatments in that it is payoff-asymmetric. Subject S chooses how much to contribute according to a payoff table which reflects sub-

YOUR CONTRIBUTION

THE OTHER GROUP MEMBER'S CONTRIBUTION

Perso →		12	11	10	9	8	7	6	5	4	3	2	1	0
↓	Group → ↓	0	1	2	3	4	5	6	7	8	9	10	11	12
12	0	264 170	259 187	253 213	248 241	243 269	238 297	233 325	229 353	225 380	221 406	217 431	213 456	209 480
11	1	277 186	271 209	265 234	259 260	254 285	249 310	244 334	239 357	234 380	230 402	225 424	221 445	217 465
10	2	291 206	284 228	278 251	272 273	266 294	260 315	255 335	249 355	244 374	239 393	235 410	230 428	226 444
9	3	305 222	298 241	292 260	285 279	279 297	273 314	267 330	261 346	255 362	250 377	245 391	240 405	235 419
8	4	321 232	313 248	306 263	299 278	292 292	286 306	280 319	273 332	267 344	262 356	256 367	251 378	245 389
7	5	337 236	329 248	322 260	314 272	307 283	300 293	293 303	287 313	280 322	274 331	268 340	262 348	257 356
6	6	355 233	346 243	338 252	330 260	323 268	315 276	308 283	301 290	294 297	288 303	281 310	275 316	269 322
5	7	373 226	364 233	356 239	347 244	339 250	331 255	324 260	316 265	309 270	302 274	295 278	288 282	282 286
4	8	392 215	383 219	374 223	365 226	357 230	348 233	340 236	332 239	325 242	317 245	310 247	303 250	296 252
3	9	413 201	403 203	394 205	384 207	375 209	366 211	358 212	349 214	341 216	333 217	326 218	318 220	311 221
2	10	434 187	424 188	414 189	404 189	395 190	385 191	376 192	368 192	359 193	350 193	342 194	334 194	326 195
1	11	457 175	446 175	435 175	425 176	415 176	405 176	396 176	387 176	378 176	369 176	360 177	351 177	343 177
0	12	480 170	469 170	458 170	447 170	437 170	427 170	417 170	407 170	397 170	388 170	379 170	370 170	361 170

Figure 5.3: Detailed payoff table provided to subjects S in Treatment $S \times C$

stitutability between the private and public goods while Subject C decides according to a complementarity-payoff table. The Nash equilibrium is for subject S to contribute nothing and for subject C to supply 5. Notice that the Nash equilibrium does not change for subjects S from the homogenous to the heterogenous treatment because it is a dominant strategy. Though, since subjects C have a non-dominant Nash strategy, their optimal contribution from Treatment C to Treatment $S \times C$ changes.

A summary of the key experimental characteristics in each treatment is provided in Table 5.3.[17] The constants C and η of the payoff function (see eq. (5.3.4)) are respectively set to 170

[17]Contributions and payoffs displayed here are rounded.

and 2.304.

Table 5.3: Specifications of the experimental treatments

		Treatment S	**Treatment** C	**Treatment** $S \times C$	
		Both Subjects	*Both Subjects*	*Subject S*	*Subject C*
ε	Value	1000	0.7	1000	0.7
Nash choice	Contribution	0	3	0	5
	Payoff	264	279	337	236
Social choice	Contribution	12	5	12	0
	Payoff	361	293	209	480
Gain to cooperation	%	36.7	5.0	-38	103.4

Notice that the gain to cooperation[18] is greater in Treatment S than in Treatment C. This is intrinsic to the complementarity preference structure. In Treatment C, since the Nash and social outcomes are interior to the choice space, the gain to cooperation (or equivalently the strength of the social dilemma) is smaller than in Treatment S where these outcomes are at opposite boundaries. Note that the gain to cooperation turns negative for subjects S in the heterogenous treatment $S \times C$. This is because they now play with subjects for whom contributing is optimal. On the contrary, the gain to cooperation of C is very high because they now play with subjects for whom contributing nothing is optimal, which incentivizes C subject to contribute more in order to get their maximum payoff.

Thanks to the use of detailed payoff tables all along the experiment, the degree of transparency across treatments is held constant. This format of payoffs presentation is necessary in that the payoff structure is not separable. Andreoni (1993) and Cason et al. (2002) also use this format. Even in separable designs like in Bracha et al. (2011) and Yamakawa et al. (2016), payoff tables are employed for the sake of clarity and comprehensiveness. For a review on the use of payoff tables in public good games, see Saijo (2008).

5.3.3 Experimental design and procedures

The experiment was computerized using the software z-Tree (Fischbacher, 2007). A pilot experiment was run in the University of Gothenburg with 48 students.[19] Subjects were recruited through the ORSEE procedure (Greiner, 2004).

Instructions were read aloud and the reading of the payoff table was explained on a short slide show.[20] Instructions are provided in Appendix D. Then, they followed instructions on the

[18]It is the relative difference between the Nash and the social outcomes.
[19]4 sessions with 12 subjects each.
[20]They had 5 more minutes to review the instructions after I read it.

computer. A preliminary incentivized question to elicit attitude towards risk was first asked to subjects. I used the simple single-shot method of Gneezy and Potters (1997)[21] to achieve this. The attitude towards risk may explain the choice of individuals especially subjects C whose Nash strategy is non-dominant.[22]

During one session, half of subjects were randomly attributed a type, either type S or type C, and the other half, the remaining type. During 10 periods (first part), subjects were randomly paired with each other subject of the same type one at a time[23]. This means they were scattered in homogenous groups. Therefore, the first part consisted at the same time of Treatment S and Treatment C (between-subject design). For another 10 periods (second part), the strangers matching design still applied but each group was composed of one subject with type S and one subject with type C, which resulted in heterogenous groups. This constituted the $S \times C$ and $C \times S$ treatments. From the first to the second part, for every subject, only the payoffs of the other group member changed *i.e.* the red payoffs in the tables remained the same.
To control for order effects (homogenous-heterogenous treatments), the counterbalanced order was also run in different sessions.[24]

Thus the experiment encompassed two features: a between-subject design in the sense that subjects were attributed a type for the entire session but a within-subject design in the sense that all subjects experienced both a homogenous treatment (either S or C depending on their type) and a heterogenous treatment ($S \times C$ or $C \times S$ depending on their type). A global within-design is implemented because I investigate whether interacting with somebody who has different preferences changes one's behavior. It allows for an analysis of type-specific reactions to heterogeneity in preference structures.

Subjects were provided with two payoff tables (one compressed and one detailed[25]) labelled according to the part they were going through. Appendix C provides the compressed payoff tables. To improve clarity, their payoff was colored in red and written in bold in the tables while their co-player's payoff was in blue and not bold.[26] At each period, they had to decide how much they contribute to the group account. They were told that the tokens not contributed were automatically assigned to their personal account which only benefits them, not the other player. Also, they were asked to guess the contribution of the other group member. On the one hand, it gave insight of how to understand the table *i.e.* fixing your belief facilitates the choice

[21] Reviewed in Charness et al. (2013).

[22] Subjects C may hesitate between two strategies around the Nash strategy and choose a lower contribution if they are risk averse for example.

[23] I chose a strangers matching design following Andreoni and Croson (2008)'s recommendations: "if a prediction is based on a single-shot equilibrium, then a strangers condition will be most appropriate".

[24] Two sessions of 12 subjects each were run under the *regular* treatment described here, and another two sessions were run under the *counterbalanced* treatment.

[25] They were told that the compressed table was a reduced form of the detailed one which allowed them to get acquainted with the reading of the payoff table. 56.25% of the subjects found it useful or very useful. 27.08% found it was not useful at alland 16.67% were undecided.

[26] This is similar to Bracha et al. (2011)'s design.

of your contribution. On the other hand, subjects were encouraged[27] to pay attention to the other's contribution and/or payoff.

Before entering the paying periods, subjects answered 10 control questions to make sure they understood the task.[28] They also went through 2 practice periods to get acquainted with the presentation of payoffs.

The payoff function and tables used in the practice periods were different from the paying periods to educate them on how the table works. Five minutes were given to subjects for the reading of both their first and second parts payoff tables.

At the end of the session, two numbers were randomly drawn so as to determine subjects' real earnings: one period from part 1 and one period from part 2. The earnings from the experiment were the average payoff from these two periods.[29] The average payoff was 210 SEK.

5.3.4 Predictions

Standard predictions are based on theoretical ground. Behavioral conjectures go beyond the theoretical predictions to identify behavior motives in each treatment.

5.3.4.1 *Standard predictions*

Since the Nash strategy changes from one treatment to the other, I cannot compare directly the levels of contributions. As a variable of comparison, I use the difference between the Nash equilibrium and experimental observations relatively to the distance between the maximum possible contribution (endowment w) and the Nash contribution. In other words, the deviation to the Nash is normalized by the decision space over Nash,[30] so that overcontributions relative to the Nash are compared across treatments. The rate of overcontribution is defined as in Willinger and Ziegelmeyer (2001):

$$d^* = \frac{y_i - y_i^*}{w - y_i^*} \tag{5.3.9}$$

In addition to being able to compare all treatments, it allows me to determine whether the overcontribution pattern observed in the linear public good game (S) extends to Treatment C, which is the first research question. Put differently, do subjects tend to overcontribute whatever the structure of their payoffs?

[27]They earned an additional amount (20 EMUs, see Instructions in Appendix D) if they guess exactly. This is a small amount because I do not want them to focus too much on this task compared to the contribution task. For a comprehensive review on belief elicitation, see Schotter and Trevino (2014).

[28]These questions allowed me to evaluate their understanding of the task.

[29]I chose to pick two random numbers instead of usually one to avoid large differences between subjects C's payoffs and subjects S's payoffs. Indeed, subjects S are more likely to earn less in the homogenous treatment than the heterogenous relatively to subjects C. Conversely subjects C earn relatively less than subjects S in the heterogenous treatment.

[30]Over (and not under) Nash because the Nash strategy of subjects S is zero so they can only overcontribute.

A strict application of the theory to every treatment leads to Hypothesis 1.

Hypothesis 1 (Pure self-interest) *The rate of overcontribution is zero for all treatments.*

In other words, subjects play the Nash strategy in all treatments. However, strictly positive overcontributions are often noticed in linear experiments like Treatment *S* (Ostrom, 2000) and persist in nonlinear experiments. In the latters, overcontributions are found smaller as the Nash equilibrium increases (Willinger and Ziegelmeyer, 2001) and even turn negative when the level is high (Isaac and Walker, 1998). Overcontributions are generally interpreted as a natural tendency to cooperation.

Hypothesis 2 (Invariant rate of overcontribution) *For subjects S, the rate of overcontribution remains the same in homogenous and heterogenous groups.*

Since subjects *S*'s Nash strategy is the same across the homogenous and heterogenous treatments, there is no theoretical reason for a change of their rate of overcontribution.

5.3.4.2 *Behavioral conjectures*

I expect less overcontributions in Treatment *C* because the Nash equilibrium is interior. This is a classical prediction when studying nonlinear games.

Conjecture 1 (Overcontribution differences) *Subjects C overcontribute less than subjects S in homogenous groups.*

As Vesterlund (2016) put forward, one reason for the introduction of interior Nash equilibrium (thus nonlinear games) in the literature was to check whether it corresponded more to the observed pattern in linear public good games (non-zero contributions). For example, with a Nash contribution of 8 (out of 24), Cason et al. (2002) find no significant differences between observed contributions and the Nash contribution, for American subjects. They used a highly nonlinear (Cobb-Douglas) function.

The rest of this subsection relies on the second research question of the paper namely, whether interacting with a different type of individual changes one's behavior motives. Indeed, while the previous subsection is based upon theory, it is worthwhile raising other concerns which may motivate subjects' decisions. Subjects come to the lab with their own preferences which may affect their behavior.

Conjecture 2 (Free-riding) *Subjects S contribute zero more often in the heterogenous treatment than in the homogenous treatment.*

For subjects S, playing with subjects C whose optimal decision is to contribute 5 strengthens their incentive to free ride compared with playing with their peers. This outcome is likely to arise during the last periods of the heterogenous treatment since subjects may need to learn the other group member's strategy.[31]

Conjecture 3 (Social optimum) *Contributions of subjects C reflect the social optimum in the homogenous treatment.*

It is easy to identify the social optimal outcome in Treatment C because it is close to the Nash.[32] Thus, I expect subjects C to contribute the social optimal amount of tokens rather than the Nash amount. Due to learning effects, this might be observed only for the last periods of the homogenous treatment.

When comparing S's payoffs with C's payoffs (see Figure 5.3 for such a comparison), it can be noticed that subjects C basically earn less than subjects S.[33] This may lead to inequality aversion for both subjects. It is then worthwhile studying how much subjects S dislike being in the head of subjects C and conversely, how much subjects C suffer from being behind subjects S. For this purpose and based on Fehr and Schmidt (1999), I define respectively the advantageous and the disadvantageous inequalities as follows:

$$\varphi^{+} = \max(0, \pi_{\mathrm{i}} - \pi_{-\mathrm{i}}) \tag{5.3.10}$$

$$\varphi^{-} = \max(0, \pi_{-\mathrm{i}} - \pi_{\mathrm{i}}) \tag{5.3.11}$$

with π_i the subject's profit and π_{-i} her group member's profit.

Conjecture 4 (Advantageous inequality) *Advantageous inequality increases the rate of overcontribution of subjects S in heterogenous groups.*

In the case of inequality aversion, S can reduce the gap between her payoff and C's payoff by contributing more for a given strategy of C (refer to Figure 5.3).

Conjecture 5 (Disadvantageous inequality) *Disadvantageous inequality decreases the rate of overcontribution of subjects C in heterogenous groups.*

If subjects C are inequality averse, their only strategy to protest against inequality is to reduce their contribution in order to reduce subjects S's payoff. Therefore, they may contribute less

[31] Note that Conjecture 2 can either be tested with the contribution variable or the overcontribution variable since contributing zero is optimal for subjects S across both the homogenous and the heterogenous treatments.

[32] This is the maximum payoff on the diagonal of the table, see Figure 5.2.

[33] This is only due to the substitutability versus complementarity structure of the payoff since the monotonic transformation of the CES utility function into the payoff function is the same for both types. Indeed, the complementarity structure constrains subjects C more than subjects S are constrained by their linear structure which reflects a perfect substitutability between the personal and group benefits.

than the Nash strategy. However, this implies that they would be willing to sacrifice their profit as well. This type of inequality effect may be regarded as spitefulness in the case of subjects C.

I expect these conjectures to be sensitive to order effects. Whether subjects start with the homogenous or heterogenous treatment may lead to different behavior. Indeed, dealing in the first part with an asymmetric payoff table is harder than with a symmetric payoff table.

Finally, since beliefs are elicited and incentivized, it is worthwhile studying the stability of beliefs: since the strategy is nondominant in Treatment C, are beliefs more stable in Treatment S where the Nash equilibrium is identifiable? Then, do beliefs become more stable when subjects C enter Treatment $C \times S$ where it is easier to determine the (dominant) strategy of subject S? Do we observe the reverse for subjects S who may be confused when evaluating the payoffs of their group member of type C (because of the nondominant strategy)? Beliefs are a good indicator for the understanding and learning of subjects, thus can inform whether a conjecture is robust or not.

5.4 Preliminary results

My experiment is designed to examine *(i)* whether overcontributions persist under a structure of preferences which reflects complementarity between private and public goods, which is more in line with empirical evidence, and *(ii)* how the introduction of the heterogeneity of preference structures within groups changes behavior. In this section, I first analyze the effect of treatments on overcontributions. Then, I explore potential determinants of behavior under each type of preference structure in both homogenous and heterogenous groups with the help of panel-data econometric methods.

5.4.1 Visual inspection

Table 5.4 displays the average contributions of both types for both treatments (homogenous or heterogenous) and for the regular vs. the counterbalanced order. In the regular order, subjects first played in homogenous groups, then in heterogenous groups. In the counterbalanced order, subjects first played in heterogenous groups then in homogenous groups.

Regarding the regular order, Subjects S tend to contribute less when they play with a different type of subject (2.20) than when they play with their peers (4.42). On the contrary, subjects C tend to contribute more when they play with subjects S (3.87) than when they play with their peers (3.66). The standard deviation is lower for subjects C than subjects S. This may be due to the greater social dilemma underlied in the perfect substitutability structure. Some subjects may be more cooperative than others. By contrast, there is less social dilemma in the complementarity structure as put forward in Table 5.3.

Regarding the counterbalanced order, the same is noticed even though more slighly.

Table 5.4: Average contributions by type and treatment

	Average contributions					
	All treatments		***Regular order***		***Counterbalanced order***	
	Homog	Heterog	Homog (1)	Heterog (2)	Homog (2)	Heterog (1)
Type *S*	3.62 (0.26)	2.38 (0.20)	4.42 (0.38)	2.20 (0.32)	2.82 (0.34)	2.57 (0.24)
Type *C*	3.33 (0.11)	3.58 (0.14)	3.66 (0.17)	3.87 (0.17)	2.99 (0.15)	3.29 (0.23)

* The numbers in parenthesis next to "Homogenous" or "Heterogenous" indicate the part in which the treatment was run. For example, Homogenous (2) means that subjects played in homogenous groups during the second part of the session.

* The numbers in parenthesis inside the table are the standard errors.

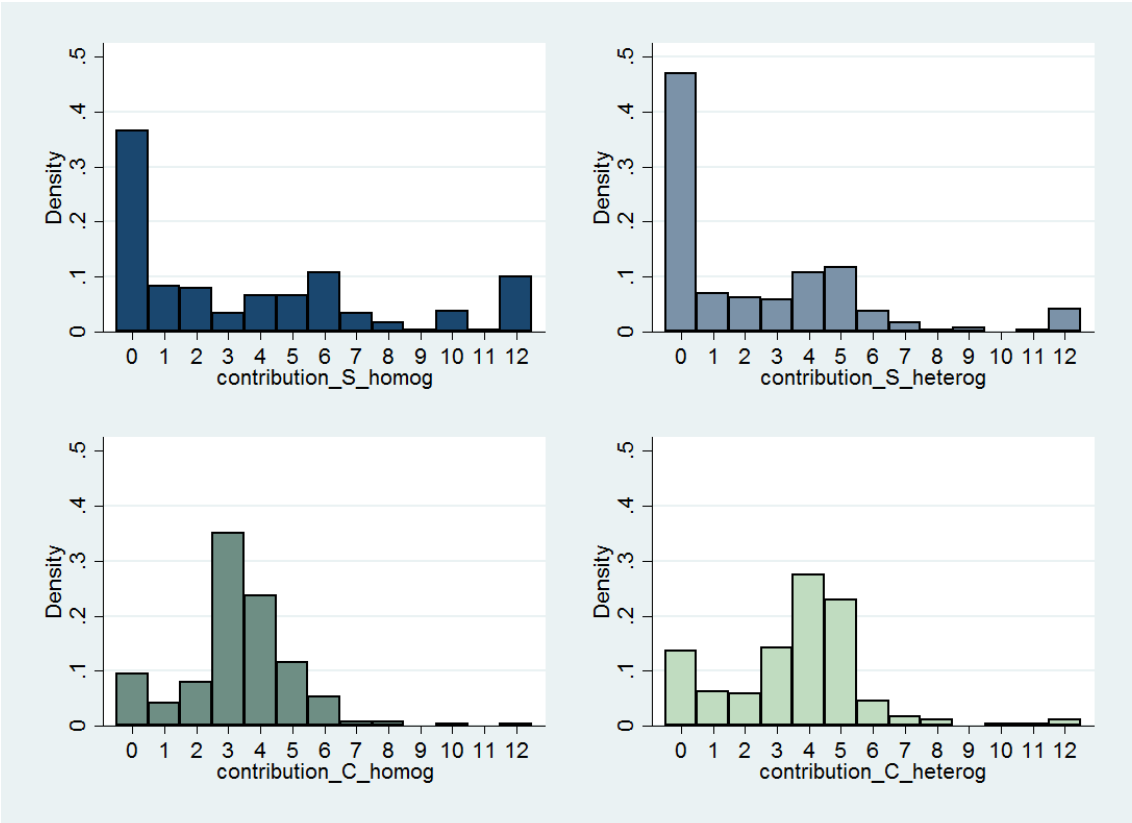


Figure 5.4: Fraction of subjects for each contribution by treatment

Figure 5.4 displays the fraction of each contribution in the different treatments. The two blue charts (at the top) represent subjects *S* densities of contributions and the two green charts (at the bottom) represent subjects *C* densities of contributions. The distributions of contributions are clearly different between the two types of subjects. Particularly, the complementarity pattern is well-illustrated by the major number of contributions inside the choice space. The perfect substitutability pattern specific to the linear (additive) game stands out as well through the large number of zero contributions.

In homogenous groups, 36.67% of subjects *S* contributed zero which is the Nash strategy.

Still, many subjects tended to cooperate. On average subjects *S* contributed 29% of their endowment, which is a bit lower than what is found in the literature on linear public good games (between 40 and 60%). This may be due to the payoff table format which is easier to understand than the sole usually given payoff function. Zero contributions increase from the homogenous (36.67%) to the heterogenous treatment (47.08%). This goes along the lines of Conjecture 2.

Subjects *C* mostly contributed 3 (35.00%) or 4 (23.75%) in the homogenous treatment and 4 (27.50%) or 5 (22.92%) in the heterogenous treatment. Note that a contribution of 4 from both players is as well associated with an egalitarian outcome in every treatment. Subjects both receive 292 (see Figures 5.1, 5.2 and 5.3), which may be a motive for egalitarian subjects.

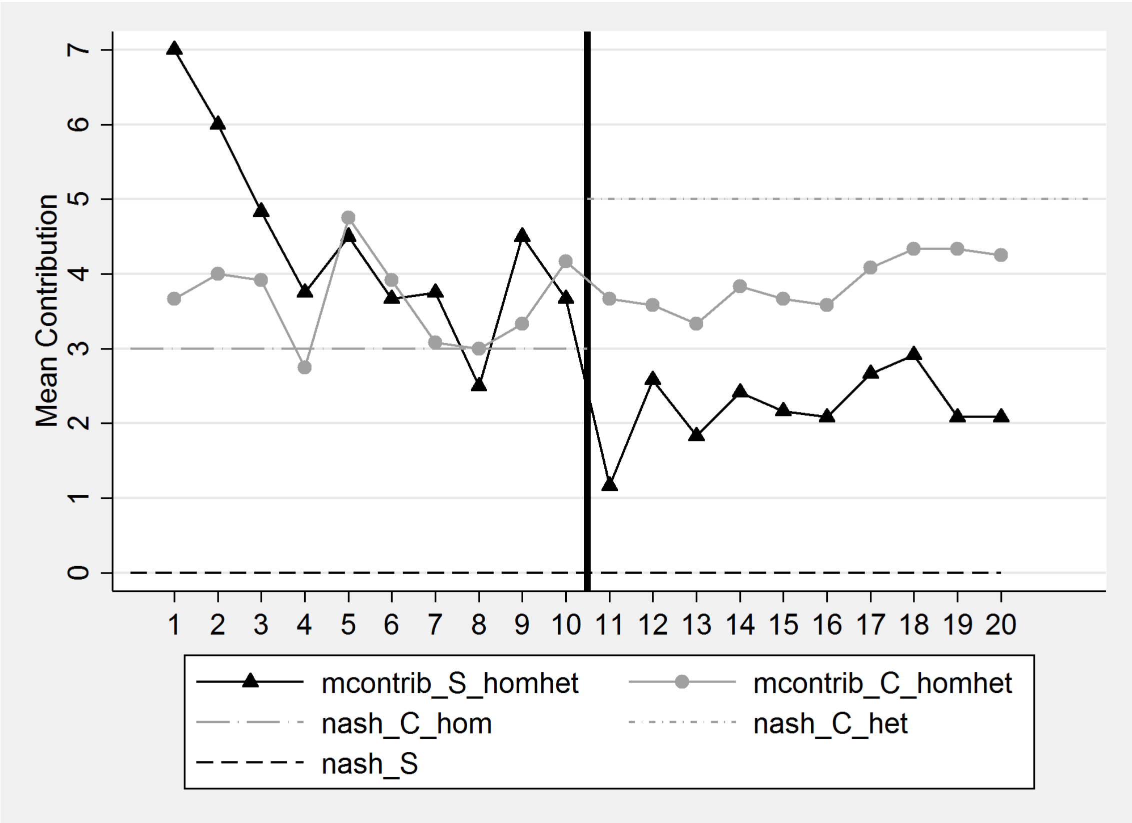


Figure 5.5: Mean contributions over periods

Figure 5.5 shows mean contributions over time for the regular order in which subjects first interacted in homogenous groups then in heterogenous groups.[34] While this is difficult to disentangle subjects *S* and *C* in Part 1 where they play with their peers, there is a clear distinction in the heterogenous treatment. In the homogenous part (from period 1 to period 10), subjects *C* contribute positive amounts of tokens which is contrary to their self-interested contribution of zero. Thus they tend to cooperate. As in the literature, there is a globally decreasing amount of contributions over periods mainly due to a learning effect. When entering the heterogenous treatment, contributions of subjects *S* drastically fall compared with those of subjects *C*. This

[34]The counterbalanced order results are in Appendix F and discussed in subsection 5.4.2.3 which deals with order effects. In summary, due to a design problem, the graph of mean contributions for the counterbalanced order (Figure 5.12) is not suitable for interpretation.

is due to the fact that subjects S now play with subjects C for whom it is optimal to contribute. It looks like free-riding strongly operates in the heterogenous part as Conjecture 2 predicts.

For subjects C, there seems to be a few differences in contributions between the homogenous and the heterogenous treatments. The contributions look more stable than subjects S's contributions. This can be explained by the weaker social dilemma they experience compared with subjects S. Contributions seem less variable in the heterogenous treatment. This could be due to the learning effect. Another potential reason would be that it is easier to identify subjects S's strategy since it is dominant compared to subjects C. This leads subjects C to keep contributing rather high amounts of tokens in the heterogenous treatment as the other player (subject S) contributes globally less than them.

5.4.2 Structure of preferences and treatment effects

To be able to compare treatments, the variable of interest is the rate of overcontribution compared to the Nash rather than the contribution, as explained in subsection5.3.4. The first subsection analyzes the effect of the type of preference structure (either perfect substitutability or complementarity) on overcontributions, so this is a between-subject analysis. The second subsection examines the effect of the treatment (homogenous versus heterogenous groups) on overcontributions within types. The third subsection offers a preliminary analysis of order effects, *i.e.* whether first playing in homogenous then in heterogenous groups or the reverse affects the results.

5.4.2.1 *Structure of preferences and type*

The first research question deals with whether complementarity between private and public goods reduces the rate of overcontribution compared with perfect substitutability.

Table 5.5 displays the mean overcontribution of subjects S and subjects C in each of the treatments, homogenous and heterogenous. Hypothesis 1 (whether the overcontribution rate is zero) is first tested for each treatment and each subject type. Since non-parametric tests are not fitted to test such a hypothesis, a bootstrap is first operated in order to ensure the normal distribution of overcontributions so as to perform a (parametric) t test.

Result 1 *Subjects in general are not purely self-interested individuals whether they interact with the same or a different type of subject.*

As displayed in Table 5.5, the null hypothesis is rejected at the 1% level for each treatment and each subject type.

Then, a (non-parametric) Mann Whitney test is run in order to test for the equality of mean overcontributions across subject types. Does the structure of preferences affect the rate of overcontribution? Do overcontributions persist under the complementarity structure? The Mann

Table 5.5: Average overcontributions by type and treatment

		Homogenous	Heterogenous
S	Overcontribution (std. err.)	30% (0.02)	20% (0.02)
	Bootstrap t test	**16.85**	**16.12**
	***p*-value**	***0.0000***	***0.0000***
C	Overcontribution (std. err.)	4% (0.01)	−20% (0.02)
	Bootstrap t test	**2.89**	**-7.55**
	***p*-value**	***0.004***	***0.0000***
	Mann Whitney test	**8.353**	**14.712**
	***p*-value**	***0.0000***	***0.0000***

[a] The null hypothesis of the bootstrap t test is that overcontributions are equal to zero (refer to Hypothesis 1).
[b] The null hypothesis of the Mann Whitney test is that overcontributions for subjects *S* and subjects *C* are equal (refer to Conjecture 1).

Whitney test rejects the null hypothesis of equal means at the 1% level, resulting in a lower level of overcontributions for subjects *C* than subjects *S*, as expected in Conjecture 1.

Result 2 *The structure of preferences affects the rate of overcontribution.*

Result 3 *In homogenous groups, subjects overcontribute less under a structure of complementarity than under a structure of perfect substitutability.*

Result 3 is in line with the literature on interior Nash equilibrium. The higher the Nash equilibrium, the lower the rate of overcontribution, except for very high levels of the equilibrium (Willinger and Ziegelmeyer, 2001).

In the heterogenous treatment, the rate of overcontribution of subjects *C* turns negative, which means that they undercontribute. This may be explained by an aversion to inequality. Subjects *C* should theoretically contribute more (5) in the heterogenous treatment than in the homogenous treatment (3) while subjects *S* should contribute zero. Given the higher Nash outcome of subjects *S* (337) than subjects *C* (236), subjects *C* may want to penalize subjects *S*. The inequality aversion conjecture will be tested in subsection 5.4.2.2. Another potential explanation is that subjects *C* expect a positive contribution from subjects *S*. Since subjects *C*'s strategy is non-dominant, the more subjects *S* contribute, the less subjects *C* should contribute if they want to maximize their outcome. In this respect, it is interesting to test whether overcontributions of subjects *C* increase across periods in the heterogenous treatment, as they learn across periods the strategy of their co-player. For the latter potential explanation, a (non-parametric) paired-sample sign test is run to examine whether the overcontributions in the first five periods of the heterogenous treatment are equal to the overcontributions in the five last periods. There is however no significant difference between the first and last five periods (two-sided *p*-value =

0.9170).

Finally, Conjecture 3 is rejected by a bootstrapped t test ($z = -8.49$, p-value=0.000). This means that even though the social optimum is easily identifiable for subjects C in homogenous groups, this is not the main strategy employed.

5.4.2.2 *Structure of preferences and heterogeneity*

The second research question deals with the effect of within-groups heterogenous preference structures on the rate of overcontribution. For this purpose a paired-sample sign test[35] is performed in order to compare each type of subjects across the homogenous and the heterogenous treatments.

Table 5.6: Average overcontributions by type and treatment

		Average rates of overcontribution		
Type	Treatment	First 5 periods	Last 5 periods	All periods
S	Homogenous	36% (0.03)	24% (0.03)	30% (0.02)
	Heterogenous	20% (0.02)	19% (0.02)	20% (0.02)
	Sign test p value	**0.0015**	**0.7239**	**0.0076**
C	Homogenous	3% (0.02)	4% (0.02)	4% (0.01)
	Heterogenous	−19% (0.03)	−22% (0.03)	−20% (0.02)
	Sign test p value	**0.0000**	**0.0000**	**0.0000**

[a] Numbers in parenthesis are the standard errors of the mean of overcontributions.
[b] The null hypothesis of the sign test is that the mean of overcontribution when subjects play in homogenous groups is equal to the mean of overcontributions in heterogenous groups (refer to Conjecture 2).
[c] The sign test p-values come from the two-sided test. The one-sided p-values are exactly half of the two-sided p-values (Moffatt, 2015).

Table 5.6 shows the rate of overcontribution for the two types and the two treatments, and across all periods, the first five periods and the last five periods. Roughly, one can notice that overcontributions are reduced in the heterogenous treatment compared to the homogenous treatment for both types S and C. There is strong evidence that the rate of overcontribution is different under the heterogenous treatment for both subjects across all periods. Note however that the evidence is mixed for subjects S as regards the last five periods.[36] Subsection 5.4.2.3 explains this different result by an order effect.

Result 4 *Whether subjects interact with the same or a different type of subject affects the rate of overcontribution.*

[35] A Wilcoxon signed ranks test results in the same conclusions. However the paired-sample sign test has been preferred here because the signed ranks test is not completely distribution-free (Moffatt, 2015, p.84).

[36] The comparison of the last five periods of the homogenous and heterogenous treatments does not result in a significant difference between the two treatments for subjects S.

Another interesting information in this table is the comparison of overcontributions as periods pass. In the homogenous treatment, overcontributions seem to globally decrease across periods for subjects *S* (from 36 to 24%) whereas overcontributions very slightly increase for subjects *C* (from 3 to 4%). In the heterogenous treatment, overcontributions very slighly decrease over periods for both subjects. The only significant result is the decrease of overcontributions in the homogenous treatment for subjects *S*.[37] There are however better ways of testing whether overcontributions increase across periods than a sign test on the first half and the last half of the total periods which is a rather rough method. A dynamic panel model may be appropriate for future investigation.

5.4.2.3 *Structure of preferences and order effects*

A within-subject design may result in different conclusions whether subjects go through one treatment first or the other. This subsection investigates whether there is an order effect on the results previously drawn regarding the effect of type and the effect of the treatment (homogenous *vs.* heterogenous) on the rate of overcontribution.

Type: Tables 5.7 and 5.8 show the rate of overcontributions across type and treatment for respectively the regular and the counterbalanced orders.

Table 5.7: Average overcontributions by type and treatment in the regular order

		Homogenous	Heterogenous
S	Overcontribution (std. err.)	37% (0.03)	18% (0.02)
	Bootstrap t test	**12.00**	**10.96**
	***p*-value**	***0.0000***	***0.0000***
C	Overcontribution (std. err.)	7% (0.02)	−16% (0.02)
	Bootstrap t test	**4.12**	**-5.30**
	***p*-value**	***0.000***	***0.0000***
	Mann Whitney test	**6.337**	**10.354**
	***p*-value**	***0.0000***	***0.0000***

[a] The null hypothesis of the bootstrap t test is that overcontributions are equal to zero (refer to Hypothesis 1).

[b] The null hypothesis of the Mann Whitney test is that overcontributions for subjects *S* and subjects *C* are equal (refer to Conjecture 1).

There is no order effect on Results 2 and 3 (see Mann-Whitney tests in Tables 5.7 and 5.8), which confirms that the structure of preferences affects the rate of overcontribution, and particularly that subjects *C* overcontribute less than subjects *C* in the homogenous treatment. However, Result 1 is impacted by the order effect. In the counterbalanced order, subjects *C* contribute as the theory predicts when they interact with their peers. As the homogenous

[37] A sign test was performed and resulted in a p-value of 0.0000.

Table 5.8: Average overcontributions by type and treatment in the counterbalanced order

		Homogenous	Heterogenous
S	Overcontribution (std. err.)	23% (0.03)	21% (0.02)
	Bootstrap t test	**10.72**	**10.52**
	***p*-value**	***0.0000***	***0.0000***
C	Overcontribution (std. err.)	−0% (0.02)	−24% (0.03)
	Bootstrap t test	**-0.05**	**-5.03**
	***p*-value**	***0.957***	***0.0000***
	Mann Whitney test	**5.796**	**10.485**
	***p*-value**	***0.0000***	***0.0000***

[a] The null hypothesis of the bootstrap t test is that overcontributions are equal to zero (refer to Hypothesis 1).
[b] The null hypothesis of the Mann Whitney test is that overcontributions for subjects S and subjects C are equal (refer to Conjecture 1).

treatment is run after the heterogenous treatment, subjects had time to learn across periods, whereas in the regular order, subjects first play in homogenous groups thus gain experience on this treatment. This learning effect explains the lower overcontributions in the counterbalanced order (−0%) compared with the regular order (7%).

Treatment: Tables 5.9 and 5.10 show the rate of overcontributions across type and treatment for respectively the regular and the counterbalanced orders across the first five periods, the last five periods and all periods.

Table 5.9: Average overcontributions by type and treatment in the regular order

		Average rates of overcontribution		
Type	Treatment	First 5 periods	Last 5 periods	All periods
S	Homogenous	43% (0.04)	30% (0.05)	37% (0.03)
	Heterogenous	17% (0.03)	20% (0.04)	18% (0.03)
	Sign test *p* value	**0.0000**	**0.0410**	**0.0000**
C	Homogenous	9% (0.03)	6% (0.02)	7% (0.02)
	Heterogenous	−20% (0.04)	−13% (0.03)	−16% (0.02)
	Sign test *p* value	**0.0000**	**0.0000**	**0.0000**

Contrary to the general results presented in Table 5.6, the effect of the treatment (homogenous *vs.* heterogenous) is significant for the last five periods for subjects S as well in the regular order. Playing in heterogenous groups reduces the overcontributions in every case as for the general results.

However, in the counterbalanced order, during the last five periods, subjects S overcon-

Table 5.10: Average overcontributions by type and treatment in the counterbalanced order

		Average rates of overcontribution		
Type	Treatment	First 5 periods	Last 5 periods	All periods
	Homogenous	29% (0.04)	18% (0.04)	23% (0.03)
S	Heterogenous	24% (0.03)	19% (0.03)	21% (0.02)
	Sign test p value	**0.7608**	**0.1877**	**0.2185**
	Homogenous	−2% (0.03)	2% (0.02)	0% (0.02)
C	Heterogenous	−17% (0.05)	−31% (0.04)	−24% (0.03)
	Sign test p value	**0.0000**	**0.0000**	**0.0000**

tribute slightly more in the heterogenous treatment, which is at odds with the previous conclusions. Though, this result is not significant, which explains the non-significant test result in the aggregation of the regular and the counterbalanced orders (see Table 5.6). Result 4 does not hold for subjects S.

Thus, there is clearly an order effect on the results. This is also noticed across periods in Appendix F. This seems to be attributed to confusion of subjects in the counterbalanced order. One explanation is the use of a symmetric (homogenous) payoff table for the control questions and the two practice periods in both the regular and the counterbalanced orders. This means that subjects in the counterbalanced order trained on a homogenous treatment while they started the paying periods in heterogenous groups. This may have confused them during the first periods of the game *i.e.* during the heterogenous treatment. The learning effect may have a role as well. A decrease in contributions is often observed and attributed to a learning effect in repeated public good games. Therefore, whether one starts in homogenous groups or heterogenous groups may be affected by this learning effect. For future research, confusion could be studied in order to disentangle it from any other treatment effect, order effect or learning effect.

5.4.3 An exploration of behavioral determinants

This subsection is a preliminary analysis of behavior motives. First, free-riding outcomes are studied across treatments. Second, inequality aversion is explored.

5.4.3.1 *Free-riding*

In this subsection, the number of free-riding outcomes is compared across treatments. Figure 5.6 shows the proportion of free-riding outcomes by type in both homogenous and heterogenous groups.

The first thing to note is that the proportion of free-riding outcomes is much larger among subjects S than subjects C. This is due to the two different structures of preferences, perfect

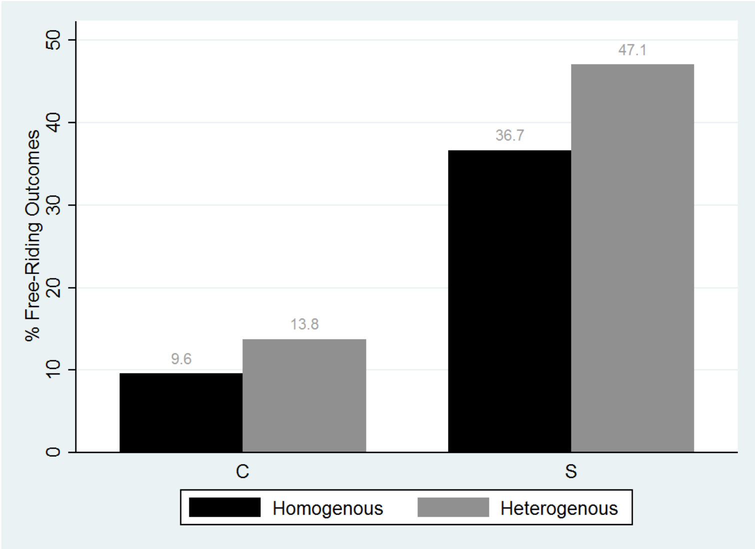


Figure 5.6: Percentage of free-riding outcomes by type

substitutability underlying an incentive to free-ride and complementarity underlying an incentive to contribute positive amounts. A Mann-Whitney test confirms this pattern ($z = 10.564$, p-value = 0.0000).[38]

Result 5 *Free-riding occurs more often under a perfect substitutability structure than under a complementarity structure of preferences.*

Regarding subjects S, free-riding is likely to occur more often in the heterogenous than the homogenous treatment as Conjecture 2 predicts. This is what the bar chart confirms: 47.1% zero contributions are reported in heterogenous groups while only 36.7% are observed in homogenous groups. The sign test provides strong evidence (two-sided p-value = 0.0066) that the percentage of free-riding outcomes is higher in the heterogenous treatment than in the homogenous treatment, which is in line with Conjecture 2.

Result 6 *Under perfect substitutability, free-riding occurs more often in heterogenous groups than in homogenous groups.*

Subjects S have a strong incentive to free-ride when they interact with subjects C for whom it is optimal to contribute positive amounts. Note that this is in line with the -38% gain to cooperation reported in Table 5.3 which reflects the absence of social dilemma for subjects S in heterogenous groups.

While subjects C have no incentive to free-ride, some of them seem to rely on a positive contribution from their group member: 9.6% in the homogenous treatment and 13.8% in the heterogenous treatment. Free-riding is thus higher in the heterogenous treatment as for subjects S, but this is not significant (two-sided sign test p-value = 0.2026).

[38]The same test has been perform separately for homogenous groups ($z = 7.029$, p-value =0.0000) and heterogenous groups ($z = 7.929$, p-value = 0.0000).

Interestingly, the heterogenous treatment may constitute an identification method of free-riders. For future research, a typology of subjects could be worthwhile to draw from the results. Indeed, if subjects S do not contribute zero in such a setting where there is no gain to cooperation, their behavior motives may rely on other-regarding preferences such as kindness, (advantageous) inequality aversion or altruism.

5.4.3.2 *Inequality aversion*

In this subsection, I use a panel data framework. One advantage is that many determinants of behavior can be investigated simultaneously. Another advantage lies in the explicit recognition that n (here 48) subjects are observed making a decision in each of the T (here 20) periods. Using panel-data modeling, I propose the following general framework to test, in particular, for the influence of advantageous and disadvantageous inequalities on the rate of overcontribution:[39]

$$overcontrib_{it} = \mathrm{x}'_{it}\beta + z'_{i,t}\alpha + \epsilon_{it}, \quad i = 1,...,48, \quad t = 1,...,20 \tag{5.4.1}$$

$overcontrib_{it}$ is the dependent variable *i.e.* the rate of overcontribution of subject i at period t with $i = 1,...,48$ and $t = 1,...,20$. The vector x'_{it} is the vector of explanatory variables as summarized in Table 5.11. ϵ_{it} is the composite error term (with an assumed mean zero and variance σ^2_ϵ).

There are K regressors in $x_{i,t}$, not including a constant term. $z'_{i,t}$ is the heterogeneity, or equivalently, the individual effect. z_i contains a constant term and a set of subject-specific variables which may be observed or unobserved, all of which are taken to be constant over periods. Eq. (5.4.1) is a classical regression model: if z_i is observed for all individuals, then the entire model can be treated as an ordinary linear model and fit by least squares. Basically, three kinds of estimators may be used to estimate eq. (5.4.1) , depending on the way the individual effect $z_{i,t}$ is specified.

If z_i is supposed to only contain a constant term, then ordinary least squares provides consistent and efficient estimates of the common α and the slope vector β. Eq. (5.4.1) then becomes:

$$overcontrib_{it} = \mathrm{x}'_{it}\beta + \alpha + \epsilon_{it} \tag{5.4.2}$$

Eq. (5.4.2) corresponds to the pooled regression model.

If z_i is unobserved, but correlated with x_{it}, then the least squares estimator of β is biased and inconsistent as a consequence of an omitted variable. In this instance, eq. (5.4.1) becomes:

$$overcontrib_{it} = \mathrm{x}'_{it}\beta + \alpha_i + \epsilon_{it} \tag{5.4.3}$$

where $\alpha_i = z'_{i,t}\alpha$ embodies all the observable effects and specifies an estimable conditional mean. Eq. (5.4.3) corresponds to the fixed effects (FE) model. This FE approach takes α_i to be

[39]Note that the following notations are independent of those in subsection 5.3.1.

a subject-specific constant term in the regression model. The term fixed is used here to indicate that the term does not vary over time. The FE estimator is essentially a linear regression which includes a set of $n-1$ dummy variables, one for each subject in the data set (one is excluded to avoid the dummy variable trap). The presence of such dummies has the consequence that the intercept is estimated separately for each subject.

Finally, the unobserved individual heterogeneity, however formulated, may be assumed to be uncorrelated with the included variables. Then eq. (5.4.1) may be formulated as follow:

$$overcontrib_{it} = \mathrm{x}'_{it}\beta \ + \ \alpha \ + u_i + \ \epsilon_{it} \tag{5.4.4}$$

Eq. (5.4.4) corresponds to the random effects (RE) model where u_i is a subject-specific random element, similar to ϵ_{it}, except that for each subject, there is but a single draw that enters the regression identically in each period. The RE model does not estimate the intercept of each subject. It merely recognizes that they are all different, and sets out to estimate only their variance σ_u^2 (Moffatt, 2015).[40]

Table 5.11: Description of explanatory variables

Variable name	Description	Mean	Std Dev	Min	Max
heterogenous	1 if heterogenous groups	0.5	0.5002	-	-
l_mbovercontrib	Past group member's overcontribution	0.0842	.3428	-.7143	1
l_profit	Past profit	237.0821	62.6720	170	480
l_freeriding	1 if past contribution = 0	.2632	0.4406	-	-
l_adv_ineq	Past advantageous inequality	17.6552	44.1131	0	309.9828
l_disadv_ineq	Past disadvantageous inequality	59.8354	68.7481	0	309.9986
expprofit	Anticipated profit	285.9425	49.8608	170	480
exp_adv_ineq	Anticipated advantageous inequality	28.6479	54.6710	0	309.9828
exp_disadv_ineq	Anticipated disadvantageous inequality	20.8991	50.9428	0	309.9828

[a] The "l_" prefix indicates a lagged variable. This type of variable allows for an analysis of subjects' gain of experience *i.e.* potential learning effects. Even though the experiment relies on a strangers matching, subjects gain knowledge on the average strategy of their group members over periods.
[b] The "exp_" prefix (like expected) indicates subjects' belief or guess of the results of a period.

A general model including all types and treatments is first analyzed. Nonetheless, based on the evidence from the non-parametric tests run in subsection 5.4.2, it is worthwhile distinguishing the four following subsamples in order to disentangle behavior motives in each group.

- subjects S in homogenous groups
- subjects S in heterogenous groups
- subjects C in homogenous groups
- subjects C in heterogenous groups

[40]For the sake of comparison between the FE and the RE models, note that in the FE model, the intercept for subject i would be $\alpha + u_i$, $i = \{1,...,n\}$ *i.e.* each subject i has its own intercept.

In this paper, the relationship between the rate of overcontribution and its main determinants, as specified in eq. (5.4.1) is estimated with a FE model for all models *i.e.* the general model on the whole sample and the models on the four subsamples. The choice of a FE model is based upon the Hausman test.[41]

Table 5.12 shows the results of the FE model for the whole sample (Model 1) and the four subsamples (Models (2) to (5)). All these models are reduced models.[42] The general results (from both the RE and the FE models) are in Appendix G.1 for the sake of robustness.

Regarding the general model (Model (1)), the within-treatment variable (*heterogenous*) *i.e.* whether subjects are interacting in homogenous or heterogenous groups, is significant at the 1% level. Whatever the type of subject, interacting in heterogenous groups reduces the rate of overcontribution compared with interacting in homogenous groups. This is in line with the results from subsection 5.4.2. The anticipated profit (*expprofit*) increases the rate of overcontribution (significant at the 1% level), which is intuitive: subjects contribute relatively to what they expect to earn. The anticipated advantageous inequality (*exp_adv_ineq*) decreases the rate of overcontribution (significant at the 1% level), which demonstrates a tendency to free-ride. Conversely, the anticipated disadvantageous inequality influences positively the rate of overcontribution (significant at the 1% level). The less subjects earn relatively to their group member, the more they contribute. This could be interpreted as a hedging effect or a tendency to cooperate depending on the type of subjects. This will be further interpreted in the between-subject analysis below. Indeed, the general model does not say much about the differences across types and treatments regarding some variables. It only provides the influence of each variable in the aggregate, hence the decomposition into subsamples. Refer to Appendix G.2 for an analysis of the effect of crossed variables (type, treatment) in the general model.

Within-subject analysis: Models (2) and (3) are compared within type *S* and Models (4) and (5) are compared within type *C*. The past other member's overcontribution (*l_mbovercontrib*) is significant at the 1% level in both Models (2) and (3). Interestingly, in homogenous groups, the past other member's overcontribution influences positively the rate of overcontribution whereas in heterogenous groups, the effect is negative. This illustrates the tendency to cooperation when subjects *S* play with their peers: if subjects tend to cooperate, this catalyzes positive contributions. However, there is no incentive to cooperate in heterogenous groups: the more subjects *C* overcontribute, the less subjects *S* have an interest in overcontributing. The past profit (*l_profit*) is significant at the 10% level in Model (2) and at the 5% level in Model (3). The effect has different signs in homogenous to heterogenous groups within subjects *S* population. This further supports the previous conclusion. In homogenous groups, the more subjects *S* earn in the past period (which is directly linked to their group member's contribution) the more

[41]This choice further justifies the subdivision of the sample into four subsamples since the between-treatment variable *i.e.* the type of subject is a time-invariant dummy variable which cannot be identified by the FE model.

[42]The variables which were not significant at the 10% level were dropped.

Table 5.12: Fixed effects model results

	General	SUBJECTS S		SUBJECTS C	
		Homogenous	Heterogenous	Homogenous	Heterogenous
	Model (**1**)	Model (**2**)	Model (**3**)	Model (**4**)	Model (**5**)
	Overcontribution	Overcontribution	Overcontribution	Overcontribution	Overcontribution
heterogenous	-0.1207***				
	(0.0232)				
l_mbovercontrib	-0.0538***	0.0244***	-0.0138***		
	(0.0169)	(0.0086)	(0.0060)		
l_profit		0.0002*	-0.0002**		
		(0.0001)	(0.0001)		
l_freeriding		0.0117*			0.1170**
		(0.0067)			(0.0506)
l_adv_ineq		-0.0002**	0.0003**		
		(0.0001)	(0.0001)		
l_disadv_ineq		0.0001***			0.0007*
		(0.0001)			(0.0004)
expprofit	0.0060***	0.0104***	0.0113***	0.0033***	0.0040***
	(0.0007)	(0.0002)	(0.0003)	(0.0011)	(0.0005)
exp_adv_ineq	-0.0057***	-0.0081***	-0.0085***	-0.0042***	-0.0044***
	(0.0005)	(0.0001)	(0.0002)	(0.0006)	(0.0010)
exp_disadv_ineq	0.0051***	0.0061***	0.0064***	0.0048***	0.0060***
	(0.0003)	(0.0001)	(0.0002)	(0.0004)	(0.0004)
constant	-1.5145***	-2.7747***	-2.9219***	-0.8672***	-1.3810***
	(0.2254)	(0.0621)	(0.0727)	(0.3091)	(0.1115)
Nb obs	912	228	228	240	228
Nb groups	48	24	24	24	24
R^2_adj	0.6900	0.9853	0.9879	0.6043	0.6557
FE cluster	*subject*	*subject*	*subject*	*subject*	*subject*
F test FE	16.29	7.84	9.88	8.75	2.25
(*p*-value)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0015)
BP LM test RE	1,189.30	56.9765	66.3799	125.6575	3.3304
(*p*-value)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.03401)
Hausman test	42.0311	52.4083	40.2340	27.4591	29.6695
(*p*-value)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0002)

[*] p-value< 0.1, ** p-value< 0.05, *** p-value< 0.01

[a] The numbers under each significant coefficient in parenthesis are the standard errors calculated on the basis of a bootstrap.

[b] *Nb obs* and *Nb groups* indicate respectively the number of observations and the corresponding cross-sectional units of the panel-data sample used to perform each regression. *F test FE* and *BP LM test RE* correspond respectively to the poolability tests of the FE model and the RE model against the pooled regression model which does not account for individual heterogeneity.

[c] The *Hausman test* tests the null hypothesis that the extra orthogonality conditions imposed by the RE estimator are valid. If the regressors are correlated with u_i, the FE estimator is consistent but the RE estimator is not consistent. If the regressors are uncorrelated with u_i, the FE estimator is still consistent, albeit inefficient, whereas the RE estimator is consistent and efficient.

they cooperate. In heterogenous groups, the more they get profit from the past period, the less they are incentivized to contribute to the group account since they would earn less.[43] The past advantageous inequality ((*l_adv_ineq*) is significant at the 5% level and influences negatively (positively) the rate of overcontribution in homogenous (heterogenous) groups. Advantageous inequality at the previous period decreases subjects *S*'s contribution, which reveals the incentive to free-ride in homogenous groups. There seems to be no aversion to inequality in this situation where the payoffs are symmetric (subjects decide upon the same payoff tables). Though, the past advantageous inequality in heterogenous groups increases the rate of overcontribution, which illustrates that even though subjects *S* tend to earn relatively more than subjects *C*, they experience a certain level of advantageous inequality aversion, in the sense that they dislike having a too much higher profit compared with their group member. Result 7 thus confirms Conjecture 4.

Result 7 *For subjects whose preferences underlie perfect substitutability, an advantageous inequality aversion emerges when they interact with subjects whose preferences underlie complementarity.*

Between-subject analysis: A past zero contribution from the subject (*l_freeriding*) influences positively the rate of overcontribution for both subjects *S* in homogenous groups (significant at the 10% level) and subjects *C* in heterogenous groups (significant at the 5% level), but for different reasons. A past zero contribution of the former increases the tendency to cooperation because subjects may observe positive contributions from some of their group members, which indicate that they could earn more. For the latter, it may be due to a learning effect *i.e.* trying to free-ride as a subject *C* is not a good strategy (reduces profit) whatever the other member contributes, except when the latter contributes more than 6 which is quite seldom (see bar charts in Figure 5.4). Past disadvantageous inequality (*l_disadv_ineq*) increases the rate of overcontribution for subjects *S* in homogenous groups (significant at the 1% level) and for subjects *C* in heterogenous groups (significant at the 10% level). This demonstrates a willingness to increase profit rather than a distaste of inequality. Subjects *C* do not sacrifice their profit by penalizing subjects *S* for earning relatively more. They rather seem to adapt to their payoff structure or hedge against low profits by contributing more even though their group member does not or does less. This contradicts Conjecture 5. This effect is less intuitive for subjects *S*. Being disadvantaged does not result in less contributions as would predict *(i)* an aversion to inequality or *(ii)* their incentive to free-ride. It cannot be interpreted as a hedging effect since the latter would be to free-ride in subjects *S* setting.

Anticipated advantageous inequality (*exp_adv_ineq*) is significant at the 1% level for all types and all treatments. It decreases the rate of overcontribution. When subjects believe that they will earn more than their group member, this decreases their contribution, suggesting

[43]This is in accordance with their negative gain to cooperation. See Table 5.3.

their willing to free-ride. However, this is twice as more important for subjects S than for subjects C,[44] which is in line with their incentives. Anticipated disadvantageous inequality is also significant at the 1% level for all types and treatments. Expecting to earn less than one's group member increases the rate of overcontribution, which could be interpreted as a hedging effect for subjects C: by contributing more, they may hedge against the uncertain contribution of their group member. As for the past disadvantaged inequality, it is less intuitive for subjects S. Further analysis is necessary to conclude on the effects of both the past and anticipated disadvantageous inequality for subjects S.

5.5 Conclusions, limits and perspectives

This paper investigates *(i)* whether the structure of preferences affects behavior in a voluntary contributions experiment, and *(ii)* whether the interaction of subjects with different structures of preferences changes behavior compared with a situation in which subjects interact with their peers. Put differently, I examine whether there is a link between the CES specification (elasticity of substitution) and behavioral determinants. Regarding the first research question, I provide evidence that in homogenous groups *i.e.* with symmetric payoffs, the rate of overcontribution is lower under complementarity than under substitutability between the private and the public goods. Therefore, the overcontribution pattern is mitigated by the complementarity structure, which is in line with the literature on interior Nash equilibrium. Additionally, free-riding occurs more often under perfect substitutability than under the complementarity structure, which is in line with the associated incentives to free-ride. Still some subjects with a low elasticity of substitution contribute zero, which suggests that they rely on the contribution of their group member to increase the public good level while they keep a high level of private good.

Within each structure of preferences, I provide evidence for the second research question. Under perfect substitutability, subjects free-ride more often when they interact with the other type of subject (complementarity) for whom contributing positive amounts is optimal.

The free-riding results hold in both the non-parametric tests and the fixed effects model. The latter was performed to investigate the role of inequality aversion in the rate of overcontribution. It results that only subjects with a high elasticity of substitution experience aversion to advantageous inequality. In other words, advantageous inequality influences positively the rate of overcontribution. Another result is that the anticipated advantageous inequality effect on the rate of overcontribution is twice as much important under perfect substitutability as under complementarity. This is in line with the underlied constraints of the complementarity structure which requires an increase of both the private and the public goods to increase utility.

[44]The coefficients of Model (2) and Model (4) can be compared since their confidence intervals do not overlap (respectively [-0.0083162 ; -0.0077688] and [-0.0053558 ; -0.0030638]). Identically, the coefficients of Model (3) and Model (5) can be compared since the confidence intervals are [-0.0088809 ; -0.0082106] and [-0.0064517 ; -0.0023764] respectively.

The main limit of the results from this pilot experiment is the order effect. Indeed, there seem to be confusion occurring in the counterbalanced order due to the homogenous practice payoff table whereas subjects start the paying periods directly in heterogenous groups. The design will be corrected so that subjects in the counterbalanced order get a heterogenous practice payoff table whereas subjects in the regular order get a homogenous payoff table. In other words, the practice payoff table must correspond to the first part of the experiment *i.e.* whether it is run in homogenous or heterogenous groups. Still, it seems harder to understand an asymmetric payoff table, which does not ensure the absence of order effects even after this adjustment. The end questionnaire and control questions of the experiment suggest that the instructions were clear enough to understand the game. Thus, the presentation of the payoff tables and the instructions will be kept as they are for the next larger experiment.

Some variables from the end questionnaire and the elicitation of risk aversion were not used in this analysis. Especially, risk aversion may affect the rate of overcontribution. The remaining problem is that such a dummy variable (whether subjects are risk-averse or not) is time-invariant. Thus, its effect on overcontributions cannot be analyzed with a FE model as the Hausman test recommends. The search for more appropriate models is necessary for further research. Also, the stability of beliefs have not been analyzed yet. A dynamic panel model may help determine this stability as well as provide a better analysis of the break from the homogenous to the heterogenous treatment over time.

Besides, it is possible that a larger proportion of free-riders was assigned to type *C* or type *S*. To control for such a problem, a one-shot dictator game may be run before starting the game in order to spread evenly across the two types the subjects identified as free-riders.

An analysis of confusion would be interesting in this rather pioneering design. Anderson et al. (2008) provide the logit equilibrium model[45] which allows for the investigation of the error hypothesis and altruism which are questions of interest here. This model explains Nash-like behavior in some contexts and deviations from the Nash equilibrium in others. It has been used for example by Willinger and Ziegelmeyer (2001).

A similar experiment in the context of climate change may provide insight into climate change negotiations. The main difference in the results would lie in the fact that some individuals care for the environment while others do not.

Finally, for further research, this experiment could be adapted for an analysis of wealth

[45]"*This approach involves introducing random elements, interpreted as either bounded rationality or unobserved preference shocks, into an equilibrium analysis. Individuals' choices are assumed to be positively, but not perfectly, related to expected payoffs, in that decisions with higher expected payoffs are more likely to be selected. With repeated (random) matchings, the choice probabilities of one player will affect the beliefs, and hence the expected payoffs, of others. The equilibrium is a fixed point: the choice probabilities that determine expected payoffs correspond to the probabilities determined by expected payoffs via a probabilistic choice rule (Rosenthal, 1989; McKelvey and Palfrey, 1995). The degree of bounded rationality is described by an error parameter, and the equilibrium probabilities converge to a Nash equilibrium as this parameter goes to zero.*" (Anderson et al., 2008, p.550).

effects and wealth inequality effects on the contributions to the public good, as interestingly raised in Baumgartner et al. (2016).

A Solving for Nash equilibrium

Player 1 (resp. 2) is expected to maximize her own utility taking player's 2 (resp. 1) contribution as given. Therefore, we solve:

$$\max_{y_1} u_1(x_1, y) \qquad \text{s.t.} \qquad x_1 + y_1 = w_1 \tag{A.1}$$

Substituting the budget constraint and the public good provision expression $y = y_1 + y_2$ into player's utility function, we get

$$u_1(x_1, y) = u_1(w_1 - y_1, y_1 + y_2) = \Bigg(\underbrace{\alpha(w_1 - y_1)^{\gamma_1} + (1-\alpha)(y_1 + y_2)^{\gamma_1}}_{A}\Bigg)^{\frac{1}{\gamma_1}}.$$

FOC (Nash):

$$\begin{aligned}\frac{\partial u_1}{\partial y_1} &= 0\\ &= \frac{1}{\gamma_1} A^{\frac{1}{\gamma_1}-1}\left(-\alpha\gamma_1(w_1 - y_1)^{\gamma_1 - 1} + (1-\alpha)(y_1 + y_2)^{\gamma_1 - 1}\right)\end{aligned}$$

with $A^{\frac{1}{\gamma_1}-1} \neq 0$ and $\frac{1}{\gamma_1} \neq 0$.

$$\frac{\partial u_1}{\partial y_1} = 0 \tag{A.2}$$

$$\Leftrightarrow -\alpha\gamma_1(w_1 - y_1)^{\gamma_1 - 1} + (1-\alpha)(y_1 + y_2 + q)^{\gamma_1 - 1} = 0 \tag{A.3}$$

$$\Leftrightarrow \alpha\gamma_1(w_1 - y_1)^{\gamma_1 - 1} = (1-\alpha)(y_1 + y_2 + q)^{\gamma_1 - 1} \tag{A.4}$$

$$\Leftrightarrow \left(\frac{w_1 - y_1}{y_1 + y_2 + q}\right)^{\gamma_1 - 1} = \frac{1-\alpha}{\alpha} \tag{A.5}$$

$$\Leftrightarrow w_1 - y_1 = \underbrace{\left(\frac{1-\alpha}{\alpha}\right)^{\frac{1}{\gamma_1 - 1}}}_{\mu_1}(y_1 + y_2 + q) \tag{A.6}$$

$$\Leftrightarrow w_1 - \mu_1(y_2 + q) = y_1(1 + \mu_1) \tag{A.7}$$

$$\Leftrightarrow y_1^* = \frac{w_1 - \mu_1(y_2 + q)}{1 + \mu_1} \tag{A.8}$$

y_1^* is the best response function of player 1 to any strategy y_2 of player 2.

Symmetrically, $y_2^* = \frac{w_2 - \mu_2(y_1 + q)}{1 + \mu_2}$ with $\mu_2 = \left(\frac{1-\alpha}{\alpha}\right)^{\frac{1}{\gamma_2 - 1}}$.

The Nash equilibrium is the intersection between the two best response curves so that it is the solution of the following system:

$$\begin{cases} y_1^* = \frac{w_1 - \mu_1(y_2+q)}{1+\mu_1} \\ y_2^* = \frac{w_2 - \mu_2(y_1+q)}{1+\mu_2} \end{cases}$$

By substituting y_2 in y_1 and isolating y_1, we get:

$$y_1^* = \frac{1}{1+\mu_1+\mu_2}\left((1+\mu_2)w_1 - \mu_1 w_2 - \mu_1\, q\right) \tag{A.9}$$

Homogenous case: If players have the same preference structure, then $\mu_1 = \mu_2 = \mu$. Since $w_1 = w_2 = w$, the Nash equilibrium is as follows:

$$y_1^* = y_2^* = \frac{1}{1+2\mu}(w - \mu\, q) \tag{A.10}$$

Heterogenous case: Consider that player 1 has an elasticity of substitution which tends to infinity ($\varepsilon_1 \to \infty$ or $\gamma - 1 \to 1$ *i.e.* perfect substitutability case). It is equivalent to solve the Nash equilibrium by considering a linear utility function for Player 1 (*i.e.* the right extreme case of a CES function). Then Player 1 and Player 2 have the following respective preferences:

$$\begin{cases} u_1(x_1, y) = \left(\alpha x_2^{\gamma_1} + (1-\alpha)y^{\gamma_1}\right)^{\frac{1}{\gamma_1}} \\ u_2(x_2, y) = \left(\alpha x_2^{\gamma_2} + (1-\alpha)y^{\gamma_2}\right)^{\frac{1}{\gamma_2}} \end{cases}$$

Player 1's best strategy is to contribute zero to the public good (standard linear public good game Nash equilibrium) hence $y_1^* = 0$.

y_2^* (as derived in Eq. (A.8)) is the best response function of Player 2 to any strategy y_1 of Player 1 such that $y_2^* = \frac{w_2}{1+\mu_2} - \frac{\mu_2}{1+\mu_2}(y_1^* + q)$.

Thus, the Nash equilibrium is such that:

$$\begin{cases} y_1^* = 0 \\ y_2^* = \frac{w_2}{1+\mu} - \frac{\mu}{1+\mu} q \end{cases}$$

with $\mu = \left(\frac{1-\alpha}{\alpha}\right)^{\frac{1}{\gamma-1}}$.

B Solving for Pareto optima

The level of public good provision is found by using the Samuelson rule, the feasibility rule and the allocation rule.

The Samuelson rule states that the sum of the marginal rates of substitution equals the marginal rate of transformation (prices ratio).
Since

$$\forall\, i \begin{cases} \frac{\partial u_i}{\partial x_i} = \frac{K}{\gamma_i} A^{\frac{1}{\gamma_i}-1}\ \gamma_i\, \alpha\, x_i^{\gamma_i-1} \\ \frac{\partial u_i}{\partial y} = \frac{K}{\gamma_i} A^{\frac{1}{\gamma_i}-1}\ \gamma_i (1-\alpha)\, y^{\gamma_i-1} \end{cases}$$

Then $MRS^i_{y/x} = \frac{\frac{\partial u_i}{\partial y}}{\frac{\partial u_i}{\partial x_i}} = \frac{1-\alpha}{\alpha}\left(\frac{y}{x_i}\right)^{\gamma_i-1}$.

Since $p_{x_i} = p_y = 1\ \forall\ i$ in a public good experiment (because x_i and y_i are respectively considered as investments in a private good and a public good) then the Samuelson rule results in:

$$MRS^1_{y/x} + MRS^2_{y/x} = 1 \Leftrightarrow \frac{1-\alpha}{\alpha}\left(\frac{x_1}{y}\right)^{1-\gamma_1} + \frac{1-\alpha}{\alpha}\left(\frac{x_2}{y}\right)^{1-\gamma_2} = 1$$
$$\Leftrightarrow \left(\frac{x_1}{y}\right)^{1-\gamma_1} + \left(\frac{x_2}{y}\right)^{1-\gamma_2} = \frac{\alpha}{1-\alpha}$$

The feasibility rule consists in the set of budget constraints such that:

$$\begin{cases} x_1 + y_1 = w_1 \\ x_2 + y_2 = w_2 \end{cases}$$

The budget constraints can add up and give: $x_1 + x_2 = w_1 + w_2 - y_1 - y_2$.

What I call the allocation rule represents the total public good provision y derived from the two private contributions by players y_1 and y_2.

$$y = y_1 + y_2 + q \Leftrightarrow \begin{cases} y_1 = \theta(y-q) \\ y_2 = (1-\theta)(y-q) \end{cases}$$

with $\theta \in [0,1]$ the share of player's 1 contribution to the public good. A particular case is when the game is homogenous such that $\theta = \frac{1}{2}$ or equivalently $y_1 = y_2$.

Note that the following constraints always hold:

$$\begin{cases} q \geq 0 \\ w_1,\ w_2 > 0 \\ q \leq y \leq w_1 + w_2 + q \\ 0 < \alpha < 1 \\ x_1,\ x_2,\ y_1,\ y_2 \geq 0 \end{cases}$$

Combining the three rules simplifies the Samuelson rule into:

$$\left(\frac{w_1-\theta(y-q)}{y}\right)^{1-\gamma_1}+\left(\frac{w_2-(1-\theta)(y-q)}{y}\right)^{1-\gamma_2}=\frac{\alpha}{1-\alpha} \tag{B.1}$$

which can be rewritten as follows since endowments are identical:

$$y^{\gamma_1-1}\left(w_{\theta}(y-q)\right)^{1-\gamma_1}+y^{\gamma_2-1}\left(w-(1-\theta)(y-q)\right)^{1-\gamma_2}=\frac{\alpha}{1-\alpha} \tag{B.2}$$

Eq. (B.2) represents the general heterogenous contributions case (because different preference structures) which applies in Treatment $S\times C$.

Homogenous case: The particular case of symmetric contributions, such that $\theta=\frac{1}{2}$ or equivalently $y_1=y_2$, applies to Treatments S and C, and leads to the following socially optimal (abbreviated by *s.o.*) below) public good level:

$$y^{s.o}=\frac{(\theta\, q+w)\,(2(1-\alpha))^{\frac{1}{1-\gamma}}}{\alpha^{\frac{1}{1-\gamma}}+\frac{1}{2}\,(2(1-\alpha))^{\frac{1}{1-\gamma}}} \tag{B.3}$$

Then social contributions are then straightforward:

$$y_1^{s.o.}=y_2^{s.o.}=\frac{1}{2}(y^{s.o}-q) \tag{B.4}$$

It can be checked in Figure 5.7 that the Nash level of the public good is below every social level of the public good, which characterizes the social dilemma.

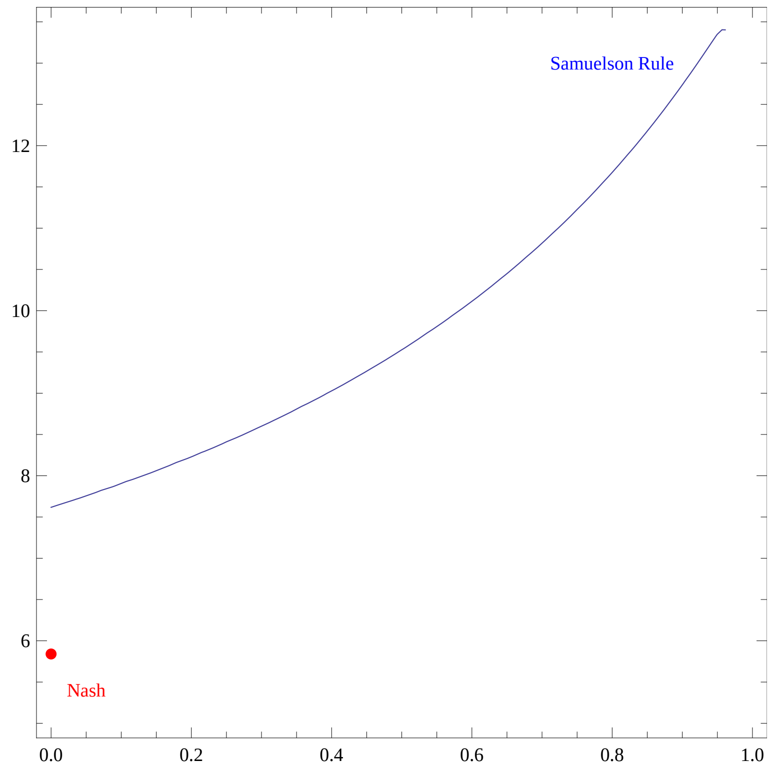


Figure 5.7: Nash equilibrium and (θ, y) combinations satisfying the Samuelson rule

C Compressed payoff table format

YOUR CONTRIBUTION

THE OTHER GROUP MEMBER'S CONTRIBUTION

Perso →		12	10	8	6	4	2	0
↓	Group → ↓	0	2	4	6	8	10	12
12	0	264 / 264	253 / 291	243 / 321	233 / 355	225 / 392	217 / 434	209 / 480
10	2	291 / 253	278 / 278	266 / 306	255 / 338	244 / 374	235 / 414	226 / 458
8	4	321 / 243	306 / 266	292 / 292	280 / 323	267 / 357	256 / 395	245 / 437
6	6	355 / 233	338 / 255	323 / 280	308 / 308	294 / 340	281 / 376	269 / 417
4	8	392 / 225	374 / 244	357 / 267	340 / 294	325 / 325	310 / 359	296 / 397
2	10	434 / 217	414 / 235	395 / 256	376 / 281	359 / 310	342 / 342	326 / 379
0	12	480 / 209	458 / 226	437 / 245	417 / 269	397 / 296	379 / 326	361 / 361

Figure 5.8: Compressed payoff table provided to participants in Treatment C

YOUR CONTRIBUTION

Perso →		12	10	8	6	4	2	0
↓	Group → ↓	0	2	4	6	8	10	12
12	0	170 / 170	206 / 213	232 / 269	233 / 325	215 / 380	187 / 431	170 / 480
10	2	213 / 206	251 / 251	263 / 294	252 / 335	223 / 374	189 / 410	170 / 444
8	4	269 / 232	294 / 263	292 / 292	268 / 319	230 / 344	190 / 367	170 / 389
6	6	325 / 233	335 / 252	319 / 268	283 / 283	236 / 297	192 / 310	170 / 322
4	8	380 / 215	374 / 223	344 / 230	297 / 236	242 / 242	193 / 247	170 / 252
2	10	431 / 187	410 / 189	367 / 190	310 / 192	247 / 193	194 / 194	170 / 195
0	12	480 / 170	444 / 170	389 / 170	322 / 170	252 / 170	195 / 170	170 / 170

THE OTHER GROUP MEMBER'S CONTRIBUTION

Figure 5.9: Compressed payoff table provided to participants in Treatment C

YOUR CONTRIBUTION

Perso →		12	10	8	6	4	2	0
↓	Group → ↓	0	2	4	6	8	10	12
12	0	264 / 170	253 / 213	243 / 269	233 / 325	225 / 380	217 / 431	209 / 480
10	2	291 / 206	278 / 251	266 / 294	255 / 335	244 / 374	235 / 410	226 / 444
8	4	321 / 232	306 / 263	292 / 292	280 / 319	267 / 344	256 / 367	245 / 389
6	6	355 / 233	338 / 252	323 / 268	308 / 283	294 / 297	281 / 310	269 / 322
4	8	392 / 215	374 / 223	357 / 230	340 / 236	325 / 242	310 / 247	296 / 252
2	10	434 / 187	414 / 189	395 / 190	376 / 192	359 / 193	342 / 194	326 / 195
0	12	480 / 170	458 / 170	437 / 170	417 / 170	397 / 170	379 / 170	361 / 170

THE OTHER GROUP MEMBER'S CONTRIBUTION

Figure 5.10: Compressed payoff table provided to participants in Treatment S in Treatment $S \times C$

D Instructions given to participants

Welcome to the lab!

You are now taking part in an experiment on decision making. Please, do not communicate with others during the experiment; we will have to stop all the experiment if one of you communicates. If you have questions, do not hesitate to ask an experimenter who will answer you in private.

OUTLINE OF THE EXPERIMENT

In this experiment, you will work in **pairs**. This means you will always be in a group of 2 persons including you. The other member of your group will be selected randomly by computer and will change at each period (22 periods in total).
You will not know who you are paired with in the room.

You will be endowed with **12 Experimental Money Units (EMUs)** for each period. Your group member also has 12 EMUs for each period. The conversion rate from EMU to SEK is the following:

1 EMU = 0.45 SEK

You have two accounts at each period. A **Personal account** which is only yours, and a **Group account** which belongs to both you and your group member.

You will have to decide how many EMUs you want to contribute (between 0 and 12) to the Group account. The EMUs you invest in the **Group account** will both benefit you and the other member of your group. The EMUs you do not contribute are automatically invested in your Personal account (so 12 - Your contribution to the Group account). The EMUs invested in your **Personal account** only benefit you, not the other group member. Therefore, your payoff in each period depends on:

1. **Your contribution to the Group account,**
2. **What you indirectly place in your Personal account** (the amount of EMUs you did not contribute to the Group account),
3. **Your group member's contribution to the Group account.**

In other words, **your payoff depends on your choice (how you allocate your EMUs between the Group and the Personal account) and your group member's choice**. In total, there will be 22 periods (2 practice periods and 20 paying periods).

Your payoff at each period is indicated in a detailed Payoff Table. Note that you received 2 Payoff Tables: a compressed Payoff Table and a detailed Payoff Table. *The compressed Table is a reduced form of the detailed Table.*

There will be **two parts** in this experiment from which you get paid. Your earnings will be calculated as follows. Two periods will be randomly selected by computer: one period from Part 1 and one period from Part 2. **Your earnings will be your average payoff from these two periods**. At the end of the experiment, your earnings will be given to you in cash in private (nobody will get to know how much you earnt).

Please check that you received the following items on your desk:

- "Instructions" (this sheet)
- Writing materials (pencil, paper)
- 2 "Practice" Payoff Tables (one compressed and one detailed)
- A "Payment Confirmation" sheet (for the end of the experiment)

DESCRIPTION OF THE EXPERIMENT

This experiment consists of the Practice Part, Part 1 and Part 2. The practice part runs for 2 periods (1 and 2) from which you do not get paid. Part 1 runs from Period 3 to Period 12 (10 periods). Part 2 runs from period 13 to period 22 (10 periods). The instructions of Part 1 and Part 2 will be given on the computer screen.

In every part of the experiment, you decide at each period how much you want to contribute to the Group account between 0 and 12 using the Payoff Tables indicated by the computer (you will use a different pair of Payoff Tables in the Practice part, Part 1 and Part 2). All participants to the experiment will decide at the same time. Therefore, you will not know how much your group member contributes before the end of each period.

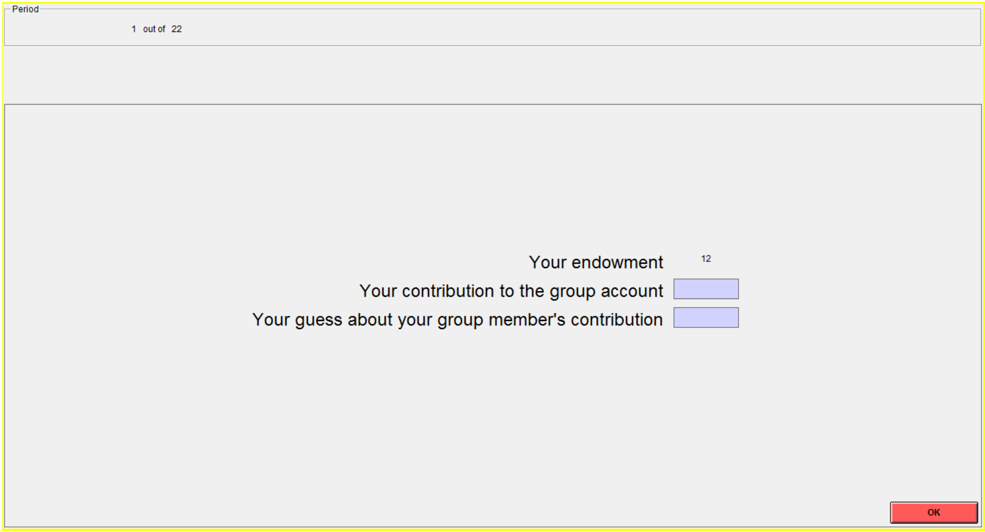
You will see the following screen at each period. Note that you have to enter the following items to validate your choice.

- Your contribution to the Group account (a number between 0 and 12)

- How much you think your group member will contribute (between 0 and 12 as well)

Once you filled these items, press the "OK" button to see your results. **Once you press the "OK" button, you cannot modify your decision anymore**.

For Part 1 and Part 2, you will have to write down your decisions and payoffs on a "Record Sheet" which will be given to you. This will allow you to keep track of your



decisions. The computer will remind it to you at each period. Note that the period number is displayed at the top left of the screen.
Once all participants have entered their decisions on the computer, the results (your payoff from this period and the contribution of your group member) will be displayed on the screen. Note that you can always check your resulting payoff in the Payoff Table.

In the next period, your group member changes randomly and you will not know who she/he is in the room.

The Payoff Tables

Please, take the "Practice" Payoff Tables. I will now explain how to read a Payoff Table.

In each part of the experiment, you have two Payoff Tables:

- The first one is a compressed Payoff Table. You can check that the contributions displayed in dark red and dark blue cells are only even numbers (0, 2, 4, 6, 8, 10 and 12).
- The second Payoff Table is the corresponding detailed Payoff Table (which displays all possible contributions from 0 to 12 and the associated payoffs).

The compressed Payoff Table (the first one) is only here if you feel uncomfortable at first sight with the detailed Payoff table (the second one). The compressed Payoff Table allows you to get used to reading a Payoff Table but is not enough to make your decision. You must **make your decision with the detailed Payoff Table** because your contribution can be any number between 0 and 12 (not only even numbers).

Like the contributions, the payoffs at each period are displayed in EMUs in the Payoff Table.

Now, look at the slideshow.

In the Payoff Table, **the row filled in dark red shows your possible contributions to the Group account** and the light red row above it shows your corresponding amount of EMUs assigned to your Personal Account (so 12 - your contribution to the Group account). Symmetrically, **the column filled in dark blue in the table shows your group member's possible contributions to the Group account**, and the column filled in light blue on the left shows his/her Personal EMUs.

The light red row and the light blue column are only here for information about what your payoff takes into account. Your choice only relies on the dark red row; the choice of your group member only relies on the dark blue column.

Inside the table, each cell displays two pieces of information to help you decide on how much you want to contribute:

1. **your potential payoffs (red numbers on the left),**
2. **the other group member's potential payoffs (blue numbers on the right).**

Your group member also has these two pieces of information. Whatever the part you go through, the blue numbers in your Payoff Table are your group member's red numbers in her/his Payoff Table, and vice-versa, whatever your group member sees as blue, you will see as red.

Now, I will go through 4 examples.

Example 1: suppose you contribute 7 and your group member contributes 8. You have to find the column corresponding to 7 and the row corresponding to 8. Your payoff and your group member's payoff will be in the cell where the two lines intersect. In this example, in red, your payoff is "134" and in blue, your group member's payoff is "126".

Example 2: suppose your group member contributes 2 and you decide to contribute 1. You have to find the row corresponding to 2 and the column corresponding to 1. This would result in your payoff being "122" (in red) and your group member's payoff being "117" (in blue).

Example 3: during the task, if you think that your group member will contribute 3, then

- by contributing 0 –> you get "127" & she/he gets "112"
- by contributing 2 –> you get "128" & she/he gets "123"
- by contributing 5 –> you get "124" & she/he gets "136"
- by contributing 9 –> you get "109" & she/he gets "151"
- by contributing 12 –> you get "74" & she/he gets "162"

Example 4: if you think that your group member will contribute 8, then

- by contributing 1 –> you get "152" & she/he gets "108"
- by contributing 6 –> you get "138" & she/he gets "123"
- by contributing 12 –> you get "82" & she/he gets "139"

Your earnings

Your earnings will depend on the two random periods, say 6 and 17 for example, selected by the computer at the end of the experiment. Your earnings are calculated as follows:

$$Earnings = Show\text{-}up\ Fee + \frac{Payoff_6 + Payoff_{17}}{2} \times 0.45 \quad \text{SEK} \tag{D.1}$$

The Show-up fee is 50 SEK. This is the same amount for all participants. You will potentially earn more in two additional tasks that will be explained on the computer screen.

The experiment is about to commence. Now please follow the instructions on your computer.

The following instructions were directly given on the computer screen. Note that the counterbalanced order was exactly the same as the regular order provided below except that Part 1 consisted in Part 2 and Part 2 consisted in Part 1

ONE PRELIMINARY QUESTION

Before we start the task that was explained to you, please answer the following question. Depending on your choice, you can earn an amount of money which will be added to your experimental earnings.

In this task, we give you an amount of 45 EMUs. You have to decide how much of this amount (between 0 and 45) you wish to place in the following lottery.

You have a chance of 2/3 (67%) to lose the amount you invest and a chance of 1/3 (33%) to win two and a half times the amount you invest.

The amount you do not place in the lottery (so 45 - what you invest) directly goes to your earnings. Your earnings from this task will only depend on your choice and the random number the computer selects between 0 and 100.

- If the computer picks a number between 0 and 67, you earn the amount you did not invest only,
- If the computer picks a number between 68 and 100, you earn what you did not invest plus two and a half times the amount you invested.

CONTROL QUESTIONS

Before starting the game, please answer the following questions. These questions will ensure that everyone understands the task. The correct answers will be given by the computer after you answer all questions.

This is important that you understand the game. So, raise your hand if you have any question and wait for someone to come to you.

Please use the "Practice" Payoff Table to answer the questions and follow the computer's instructions.

After you answer all questions, click "Submit" to check the correct answers. Take your time if some of your answers are wrong to understand why you made mistakes This will ensure that you understand the game.

1. Endowment
   (a) How many Experimental Money Units (EMUs) are you endowed with at each period? .....
   (b) How many EMUs does your group member have at each period? .....
2. If you decide to contribute 8 to the Group account and the other player contributes 9,
   (a) how much do you earn? .....
   (b) how much does the other player get? .....

3. If you decide to contribute 0 to the Group account and the other player contributes 4,
    (a) what are your earnings? .....
    (b) what are his/her earnings? .....
4. If you think your group member will contribute 3 and you decide to contribute 2 to the Group account,
    (a) what would be your expected earnings? .....
    (b) what would be his/her expected earnings? .....
5. If you think your group member will contribute 10 and you decide to contribute 10 tokens to the Group account,
    (a) what would be your expected earnings? .....
    (b) what would be his/her expected earnings? .....

PRACTICE

Consider the **Payoff Tables labelled "Practice"** to make your decision for the following 2 periods.
These 2 periods will not be paid, they are only for practicel. They ensure that you understand the task before the paying periods start. Follow the instructions on the computer.

THE EXPERIMENT

PART 1

Now you are entering PART 1.
Please return the "Practice" Payoff Tables (keep the "Instructions" with you). We will give you a different envelope. Open the new envelope and check that you received the following items:

- 2 Payoff Tables labelled "PART 1",
- A "Record Sheet".

Write down on your **"Record Sheet"** Subject number (which is displayed above). At each period, you have to fill out the "Record Sheet" to keep track of your decisions.
This means that the following periods affect your earnings.

In this part, for given contributions from you and your group member, you and your group member have the same payoffs.
For example, you can check in your Payoff Table that, if both of you contribute 6, you get the same payoffs. Another example: if you contribute 2 and your group member contributes 3, your payoff is the same as your group member's payoff when she/he contributes 2 and you contribute 3.
This means that you decide upon the same Payoff Tables.
Take 5 minutes to review the Payoff Tables you have just received.
Raise your hand if you have a question, an experimenter will come to you.

PART 2

Now you are entering PART 2.
Please, return the Payoff Tables labelled "PART 1". We will give you a new envelope.
Check that you received two Payoff Tables labelled "PART 2".
Your payoffs are the same compared with PART 1 (same red numbers), but your group member's payoffs are different (different blue numbers compared with PART 1)
In this part, for given contributions from you and your group member, you and your group member have different payoffs.
For example, you can check in your Payoff Table that, if both of you contribute 6, you get different payoffs whereas these payoffs were the same in PART 1. Another example: if you contribute 2 and your group member contributes 3, your payoff is different from your group member's payoff when she/he contributes 2 and you contribute 3.
Take 5 minutes to read the new Payoff Tables.

E Final questionnaire

After each session ends, subjects are asked to fill out a questionnaire.

QUESTIONS ABOUT YOU

1. How old are you?
2. Gender
3. Do you have difficulties distinguishing colors (blue from red)?
4. How much do you spend on average per month in clothes and cosmetics?
5. Are you currently working?
6. What degree are you currently studying?

7. Current study year
8. What is your Mother's highest education level ?
9. What is your Father's highest education level ?
10. What is the occupation of your Mother?
11. What is the occupation of your Father?

QUESTIONS RELATED TO THE EXPERIMENT

1. Were the instructions of the experiment clear enough?
2. How do you evaluate your understanding of the task?
3. Was the compressed table useful to understand the detailed payoff table?
4. Did you consider the other player's payoff when making your decisions?
5. Did you expect your group member to behave approximately like you in the experiment?
6. How much did the information about your group member's payoff influence your following decisions?

QUESTIONS RELATED TO YOUR PERSONALITY

1. How much do you trust strangers you meet for the first time?
2. When dealing with strangers, are you usually suspicious or wary?
3. In general, do you feel better when you earn the same amount as your group member than a different amount?
4. Explain, why you think this
5. What situation do you prefer if equal amounts are not available?

F Order effects: visual inspection

Figure 5.12 shows mean contributions over time for the counterbalanced order *i.e.* in which players were first in heterogenous then in homogenous groups. The results are less stringent in the counterbalanced order. In heterogenous groups (left part of the graoh), subjects *C* seem to globally contribute more than subjects *S* as observed previously but the difference is lower. In homogenous groups (right part of the graph), this is not clear whether subjects *S* contribute more or less than subjects *C* as observed in the regular order.

The counterbalanced order may be more confusing to subjects. This may be easier to start with the information that co-players decide upon the same payoff table as in the regular order. Another explanation can be that the practice payoff table was the same in the regular and the counterbalanced orders. This was a symmetric payoff table, which means that the practice table corresponded to the first part of the experiment in the regular order but to the second part in the counterbalanced order.

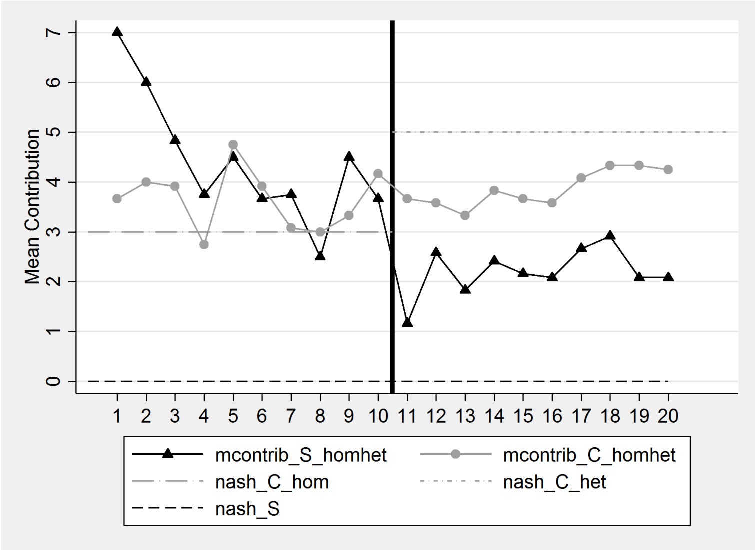


Figure 5.11: Mean contributions over periods - Homogenous -> Heterogenous[46]

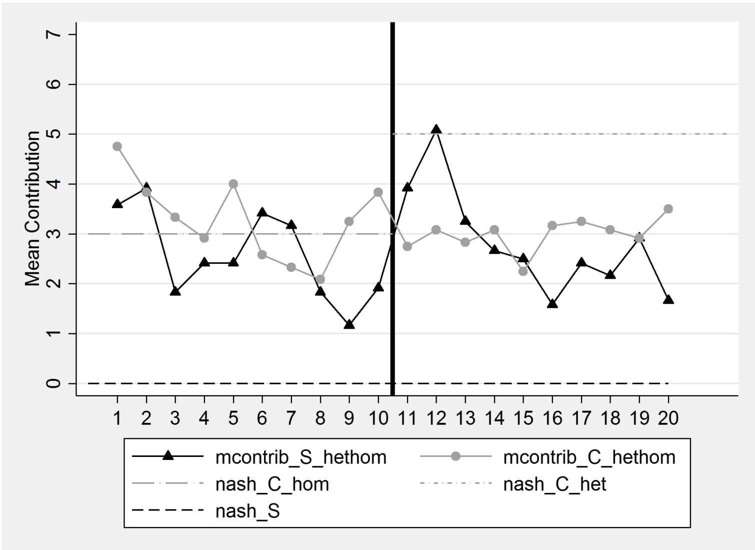


Figure 5.12: Mean contributions over periods - Heterogenous -> Homogenous

G Econometric tests

G.1 Panel Stata results: FE vs RE models

Variable	rFE_G	rRE_G	rFE_S_hom	rRE_S_hom	rFE_S_het	rRE_S_het	rFE_C_hom	rRE_C_hom	rFE_C_het	rRE_C_het
heterogenous	-0.1207***	-0.1208***								
l_memberovercontribution	-0.0538***	-0.0598***	0.0158***	0.0153***	-0.0138**	-0.0130**				
exp_disadv_ineq	0.0051***	0.0052***	0.0061***	0.0060***	0.0064***	0.0062***	0.0048***	0.0050***	0.0060***	0.0059***
exp_adv_ineq	-0.0057***	-0.0057***	-0.0080***	-0.0081***	-0.0085***	-0.0086***	-0.0042***	-0.0038***	-0.0044***	-0.0037***
expprofit	0.0060***	0.0062***	0.0104***	0.0104***	0.0113***	0.0114***	0.0033***	0.0032**	0.0040***	0.0039***
l_disadv_ineq			0.0001**	0.0001					0.0007*	0.0003
l_profit					-0.0002**	-0.0001				
l_adv_ineq					0.0003**	0.0002**				
l_freeriding									0.1170**	0.0252
Constant	-1.5145***	-1.5607***	-2.7196***	-2.7268***	-2.9219***	-2.9543***	-0.8672***	-0.8252**	-1.3810***	-1.3236***
N	912	912	228	228	228	228	240	240	228	228
sigma_u	0.1391	0.0967	0.0320	0.0224	0.0257	0.0122	0.1128	0.0652	0.0989	0.0076
sigma_e	0.1374	0.1374	0.0272	0.0272	0.0164	0.0164	0.1073	0.1073	0.1683	0.1683
rho	0.5061	0.3311	0.5806	0.4042	0.7098	0.3546	0.5248	0.2694	0.2566	0.0021
rmse	0.1374	0.1404	0.0272	0.0280	0.0164	0.0179	0.1073	0.1134	0.1683	0.1786
r2_w	0.7077	0.7071	0.9871	0.9869	0.9895	0.9890	0.6473	0.6437	0.6982	0.6832
r2_b	0.6361	0.6524	0.9849	0.9866	0.9917	0.9940	0.0697	0.0870	0.5775	0.6947
r2_o	0.6746	0.6818	0.9856	0.9866	0.9897	0.9914	0.4388	0.4557	0.6607	0.6817
r2_a	0.6900		0.9852		0.9879		0.6043		0.6557	
F_f	16.2919		9.0733		9.8789		8.7509		2.2500	
chi2	711.5874	813.0869	6.4e+03	6.1e+03	4.8e+03	5.2e+03	175.8675	229.2645	502.3517	188.7914

legend: * p<.1; ** p<.05; *** p<.01

Figure 5.13: (robust) Fixed effects and random effects models results from Stata

G.2 Panel Stata results: crossed-variables

Variable	rFE_G	rRE_G
exp_adv_ineq_C_het	-0.0045***	-0.0047***
l_profit_S_het	-0.0003***	-0.0010***
expprofit_S_hom	0.0105***	0.0060***
l_disadv_ineq_S_hom	0.0001***	0.0003*
expprofit_C_hom	0.0045***	0.0055***
exp_adv_ineq_C_hom	-0.0049***	-0.0050***
expprofit_S_het	0.0107***	0.0069***
exp_adv_ineq_S_het	-0.0082***	-0.0059***
exp_disadv_ineq_S_het	0.0062***	0.0050***
exp_disadv_ineq_S_hom	0.0061***	0.0045***
exp_disadv_ineq_C_het	0.0057***	0.0061***
exp_adv_ineq_S_hom	-0.0081***	-0.0052***
exp_disadv_ineq_C_hom	0.0053***	0.0061***
l_memberovercontrib~S_hom	0.0143**	0.0764**
expprofit_C_het	0.0035***	0.0046***
l_adv_ineq_S_het	0.0002**	0.0010***
Constant	-1.9598***	-1.4899***
N	912	912
sigma_u	0.7953	0.0275
sigma_e	0.1054	0.1054
rho	0.9827	0.0638
rmse	0.1054	0.1242
r2_w	0.8302	0.7864
r2_b	0.6843	0.9163
r2_o	0.4880	0.8429
r2_a	0.8176	
F_f	12.3324	
chi2	1.3e+04	1.5e+03

Figure 5.14: (robust) FE and RE models results from Stata for the general model with crossed-variables

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Chapter 6

General conclusion

The broad motivation behind this research was to explore the determinants of cost-benefit analysis beyond the debate on the discount rate value and environmental prices which have widely been discussed so far (see Atkinson and Mourato (2015) for an exhaustive review). Cost-benefit analysis particularly founds itself on environmental quantities and transforms it into value. Both environmental quantities accounting and the foundations of the key elements of cost-benefit analysis, namely discount rates and willingness to pay (WTP), are important to understand the heterogeneity of projects evaluations across contexts. In other words, an understanding of *(i)* quantities accounting, *(ii)* context and *(iii)* preferences (especially its structure) is required to complete a successful analysis of projects with environmental impacts.

In the following sections, I summarize the work conducted in this thesis in terms of objectives, results and contributions to the literature. Limitations of the studies are exposed as well and areas for future research are finally suggested.

6.1 Study objectives

This thesis focused on three main issues related to the evaluation of projects which entail economic (private) impacts and environmental (collective) impacts.

a. the way environmental impacts are accounted for over time;

b. the role of the structure of preferences in environmental and time preferences at the individual level;

c. the role of the structure of preferences in providing a public good, thus at the collective level.

All these aspects constitute explanations to the heterogeneity of evaluations of a single project. The first issue was examined in the context of land use change (LUC). Working on LUC is challenging and necessary because it constitutes the second largest source of greenhouse gas (GHG) emissions. The fostering of biofuel production demands an expansion of bioenergy crops, thus a switch from some land uses which store large quantities of carbon such as grasslands or forests. However, land use change is a one-shot shock (*e.g.* cutting trees) which spreads out over time in a non-uniform manner. Though, most energy policies such as the American and the European ones consider that LUC impacts spread evenly over time, which leads to a distortion of valued LUC.

The second issue aimed to overcome the exogenous assumption made on the kind of interaction between private goods and environmental goods. This is important since the results of a model strongly rely on this assumption. The substitutability assumption impacts directly the way WTP changes with income (which in turn indicates the nature of the environmental good) as well as the way an individual trades-off private and environmental goods over time.

The third issue was motivated by the fact that the widespread payoff (utility) function in public good games underlies a structure of perfect substitutability between private and public goods benefits. This is restrictive because it considers that the social dilemma is always the largest possible whereas private interests may be closer to collective ones than modeled. Additionally, the structure of preferences may differ across individuals within the same group, and this is not taken into account in the literature.

6.2 Main results

In Chapter 3, I derived the impacts of accounting LUC emissions as if they were constant over time while they are effectively not, on cost-benefit analysis outcomes. It resulted that LUC value are upward (downward) distorted when relative carbon prices grow slower than the discount rate in the case of carbon emissions (sequestrations). A slower increase of the carbon price compared to the discount rate is the most common case in the literature. While this result is theoretical, I also provide numerical evidence through the case of bioethanol production in France. For example, a 3% discount rate in combination with a 1% increase of carbon prices leads the uniform accounting of LUC sequestrations by *Miscanthus* to diminish the LUC value by 16.14% compared to what should be accounted for. Importantly, in the case of sequestrations, some projects may not be implemented when evaluated under the assumption of a uniform time distribution while they would be desirable if quantities were accounted for correctly. Conversely, in the case of emissions, some projects may be implemented under the uniform time distribution assumption while the effective time profile of emissions actually leads to non-desirable projects.

In Chapter 4, we developed a theoretical framework which allows either for substitutability or complementarity between goods depending on the context of the choice. First, this allowed us to derive the implications of such a framework on the income elasticity of WTP. It resulted that the income elasticity can be positive independently of the nature of the interaction between goods. However, a negative income elasticity can only occur in the case of substitutable private and environmental goods. The latter situation is interesting because usual models which employ a CES or Cobb-Douglas utility function only allow for positive constant income elasticities of WTP, which makes the environmental good be classified as a normal good whatever the context. In our framework, environmental quality can be an inferior good for relatively lower-income individuals. This can be interpreted as a transition towards better conditions of life in which environmental goods are substituted for more convenient private goods. Second, we showed that the consumption and environmental discount rates are also affected by the way private consumption and environmental quality interact in providing utility. The study of income shocks is relevant within our framework since an individual may experience a change in the way utility is provided (by substitutable or complementary goods), which in turn changes her behavior towards consumption and the environment. The results were illustrated by a stylized (so-called) CDS utility function.

In Chapter 5, I studied the effect of the structure of preferences (substitutability, complementarity) on overcontributions within a voluntary contributions experiment in both homogenous and heterogenous groups. It resulted that under the structure of substitutability, subjects free-ride more often when they interact with subjects of the other type (complementarity) for whom it is optimal to contribute. An interesting inequality effect emerges as well among subjects whose preferences underlie perfect substitutability. Subjects tend to dislike earning too much compared to their group member whose preferences underlie complementarity, a more constraining structure.

6.3 Main contributions

This thesis contributes to the literature on several fronts. The work presented in Chapter 3 contributes to the literature on environmental cost-benefit analysis by *(i)* raising the overlooked issue of non-uniform time distributions of GHG emissions and *(ii)* providing two simple tools to policy-makers in order to overcome distorted projects value due to this peculiar kind of time profile. While the roles of the discount rate and relative environmental prices have broadly been studied, the time distribution of environmental impacts has often been set aside. This is probably due to the way environmental impacts are assessed via the life cycle assessment method which provides time-uniform physical flows (De Gorter and Tsur, 2010). This is not an issue in the context of physical flows but becomes one when these uniform flows are incorporated in a cost-benefit analysis which treats points in time differently due to discounting and relative environmental pricing. The first tool is the so-called compensatory discount rate which allows policy-makers to have an indication of the direction of the bias of their results when they use the uniform time distribution of LUC impacts. The second tool is the carbon profitability payback period which gives information on the time at which a project starts to be environmentally profitable. By fixing a threshold payback period, policy-makers could compare project's payback periods with this threshold and base their decision of implementing the project or not according to this criterion.

The work presented in Chapter 4 departs from the literature in that it proposes a novel general framework which avoids any exogenous assumption on the relationship between goods. Substitutability and complementarity emerge from the context of the choice, not preferences. As a consequence, in our framework, environmental goods can either be classified as normal goods or inferior goods, which is a premiere to the best of my knowledge. This is supported by Tiezzi and Martini (2014, p.14) who state, "No economic theory implies that goods must be normal or inferior in all ranges of income, and cannot switch back and forth".

The work presented in Chapter 5 mainly contributes to the literature on public good games in experimental economics. This is the first study which uses a CES (utility) payoff function which allows for different structures of preferences through the value of the elasticity of substitution. This departs from the usual linear (additive) payoff function used in public good games which underlies perfect substitutability between public and private goods. Perfect substitutability is associated with the largest possible social dilemma but one may argue that social dilemmas are of different magnitudes across individuals. While some individuals may expetience an important conflict between private and collective interests, others' private interests may be more in line with social ones. This is as well the first study which introduces heterogenous structures of preferences within groups. Within-group heterogeneity has only been studied in terms of endowments and returns from the private or the public good, but not in terms of the structure of payoffs. Yet, the latter is relevant because individuals may be provided with utility differently, according to the way private and public goods benefits combine. Potentially, mixing different structures of preferences within groups may provide a way of identifying free-riders among individuals whose preferences underlie perfect substitutability. This is so because their incentive to free-ride is greater when their group member's well-being is based on complementarity between goods.

Overall, these three chapters contribute to research in decision-making regarding the environment at the individual and collective levels. While Chapter 3 directly deals with the cost-benefit analysis tool, Chapters 4 and 5 go deeper into preferences (across their structure) which underlie the evaluation of projects. The structure of preferences proved to play a consequent role in decision-making, both at the individual level and the collective level.

6.4 Limitations

Regarding Chapter 3, limits mainly regard the sequestration case. This is directly linked to the fact that there is less evidence (no clear functional form) regarding the time profile of sequestration by *Miscanthus* than in the case of emissions. Thus, the results may be improved with further empirical evidence. Another point which may be discussed is the choice of a 20 years time horizon. This is quite short compared with the period over which GHG emissions affect the atmosphere (100 years an more). Still, the greater the time horizon, the higher the bias induced by the uniform time-accounting of LUC impacts. This would then only increase the bias induced by the uniform approach.

Regarding Chapter 4, the fact that lower-income individuals are associated with substitutability between goods and higher-income individuals with complementarity can be discussed as regards the literature on resource economics. Indeed, this seems contrary to what Heal (2009) and Baumgärtner et al. (2015b) advocate *i.e.* lower-income individual well-being tends to be based on a complementarity between private goods and environmental goods. According to me, the two views are actually not at odds. This depends on the kind of constraint under which the environmental good is considered. In their framework, Heal (2009) and Baumgärtner et al. (2015b) think of environmental goods as ecosystem services which are considered in a market setting *i.e.*, individuals maximize their utility subject to an observed (one-dimension) income constraint imposed to the consumption of both the private and the environmental goods. In our framework, the environmental good is a public good which has no price, thus which is not subject to the income constraint. Individuals are endowed with a two-dimension wealth which is both economic and environmental.

Besides, the example of the CDS function is very useful in a context of public goods for which the method of Ebert (2003) can be implemented (Lindahl price). However, this function is not easily tractable in a market setting unless we impose restrictions on the parameters (exponents on the variables) of the function. This means that this function is of limited interest (under no restriction on the parameters) if one wants to analytically derive demands from two market goods.

Regarding Chapter 5, the main limit probably lies in the identification of confusion among subjects. The interpretations were given according to different possible behaviors but it is possible that confusion partially explains the results. I expect it especially concerns the counterbalanced order which is quite confusing after providing subjects with different payoff tables from what they got used to in the practice part. Finally, a better econometric analysis of the data can (and will) be led with dynamic panel modeling.

6.5 Future research

Regarding the theoretical part of this thesis, that would be interesting to develop the theoretical framework of Chapter 4. On the one hand, I mentioned in Chapter 2 the overlooked environmental effect on WTP *i.e.* how the environmental quality level influences WTP. This could be analyzed within our theoretical framework. Moreover, a further analysis of how our framework affects discount rates would allow us to derive stronger results. We particularly aim at simulating income (and environmental) shocks and observing the way discount rates and income elasticities of WTP over time are influenced under substitutability and complementarity.

Regarding the experimental part, beyond the design and econometric improvements which will be implemented, two avenues of research emerge. It would be worthwhile analyzing both wealth effects and institution effects. For wealth effects, subjects could be endowed with different amounts of tokens in order to see whether behavior changes within each structure of preferences according to the assigned endowment. For institution effects, the introduction of communication and punishment may provide a better understanding of the way the structure of preferences affects behavior in a more realistic framework.

More generally, investigating the role of the structure of preferences in decision-making seems worthwhile to me as it constitutes a source of heterogeneity across individuals and a major support for decisions towards the environment. There is a lack of empirical studies estimating the relationship between consumption and environmental quality. For example, in the discounting literature, it is not trivial estimating the cross elasticities of marginal utility whose sign are indicative of this relationship. Interesting simulations of the evolution of substitutability over time have been derived by Drupp (2016). Still, further empirical analysis is necessary to underpin theoretical works and especially to provide insights on how substitutability depends on the context and translates into behavior.

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