Essays on public good provision: experimental and empirical evidence

University of Hamburg

Faculty of Business, Economics and Social Sciences

Cumulative dissertation

to obtain a doctorate in

business, economics, and the social sciences

„Dr. rer. pol.“

(Pursuant to the doctoral degree regulations of 18 January 2017)

submitted by

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Hamburg, 16.12.2024

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Datum der Disputation: 10.04.2025

Acknowledgments

"By seeking and blundering we learn."
Johann Wolfgang von Goethe, 1825

My work during the last years would not have been possible without the help of many dear friends and colleagues. Although each chapter includes an exhaustive list of everyone that contributed to getting those projects to fruition, there are some people that have a special place in my heart for their help, guidance, and support throughout these four and a half years.

I am most grateful to my supervisors Andreas Lange and Moritz Drupp. I could not have done it without their support, guidance and helpful comments. I am especially indebted to Andreas for his relentless support for pursuing my own research ideas, his backing to explore new fields and interests, and the financial support for working on them. I am also thankful to Moritz for always being available and his guidance when looking for a place to do my research stay.

During my work, I have met great researchers with whom I have worked, and who have become dear friends. My gratitude goes to Sofia Badini and Juliane Koch, it has been a pleasure to work with them as co-authors and learned together. My work has benefited from comments and feedback from many colleagues, especially Pier Basaglia and Sebastian Renner. I would like to thank my colleagues Claudia, Enrico, Finn and Yannick for their friendship and support during these years.

I am grateful to my colleagues at the Department of Geography and Environment for their comments and ideas. I learned a lot from them during my research visit, especially from my supervisor there, Eugenie Dugoua. Special thanks to the WiSo Graduate School and my chair for the financial support for this research visit. I am also grateful to Prof. Dr. Torben Klarl for his invitation to do a research visit at the Faculty of Business Studies and Economics of the University of Bremen. I appreciate all the comments that I got from them and their help in accessing data necessary for this work.

During part of my research, I was generously supported by the Free and Hanseatic City of Hamburg as part of their funding framework 'Science for Society'. I am also grateful to the WiSo Research Laboratory and the Vienna Center for Experimental Economics for their technical assistance with the experiments that I conducted. I am specially grateful to Angelika Wilke for her help and guidance through all the administrative procedures in the university.

Lastly, I would like to thank my family and friends who supported me through this time. Especially to my parents and sister, that have always supported me and encouraged me in all my endeavours. I would not be here without them. Thanks to Kristina, my better half, for her relentless support, her love and understanding.

I could not have made it without all of you.

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Chapter 1

Introduction

The first fundamental theorem of welfare economics states that in the absence of market failures, a market equilibrium is Pareto efficient. This theorem is a fundamental cornerstone of modern economic thought, but it depends on a number of assumptions that do not always hold true. For example, market failures do happen in markets where firms have monopolistic power, in cases when agents have imperfect information, or when the provision or consumption of a good produces an externality. When the provision of a given good produces a positive externality that the provider cannot capture, we talk about public goods. As the private benefit that the provider gets from providing them is smaller than the social benefits stemming from their provision, these goods tend to be under-provided – the private provision of public goods is smaller than the welfare-maximising level. Similarly, a so-called public bad is a good that is over-provided, as the provider does not face the negative externalities of its provision.

The problematic provision of public goods and bads has been a topic of study for decades (Olson Jr, 1971; Samuelson, 1954), as their nature means that their private provision is never done at the socially optimum level. In this dissertation, I study the difficulty of providing these public goods. In particular I study the case of two types of public goods: innovation (Chapter 2) and local public goods (Chapter 3 and 4). By using a quasi-experimental approach (Chapter 2) and laboratory experiments (Chapters 3 and 4), I study how individuals and firms make decisions regarding public good provision. Chapter 2 studies the effects of the introduction of a carbon tax on firms' green innovation outcomes. Chapter 3 analyses how individuals make public good provision decisions when facing a weakest link public good such as illness eradication. Lastly, Chapter 4 studies how individuals provide a local public good in a network where their spatial location matters for their benefits from the provision.

Chapter 2 studies the effects on green innovation of the the Ecotax reform, a tax raised on electricity and fuel consumption introduced in Germany in 1999. Innovation is a classic example of a public good suffering from under-provision, as firms investing in R&D projects cannot perfectly capture the positive knowledge externalities that their advances generate (Stiglitz and Rosengard, 2015). This problem is especially salient in green technologies, as they also suffer from environmental externalities that hinder investments in clean technologies (Veugelers, 2012). Previous studies have found that carbon price mechanisms can incentivise companies to innovate in climate change mitigation technologies (aus dem Moore et al., 2022; Calel, 2020; Calel and Dechezleprêtre, 2016). Some studies find that this positive effect is not equally distributed across firms, as they differ in the financial and human capital resources that they can access to pursue this product innovations (Costa-Campi et al., 2015; Stucki et al., 2018; Zhang et al., 2019). This chapter aims to shed some light on how firms' innovation responses to the incentives derived from environmental regulation differ depending on their characteristics.

To analyse this heterogeneous effect, I use patent data to study the effects on green product innovation of the Ecotax. I use matching techniques to find suitable counterfactuals to the German affected firms, and use a difference-in-differences design to study their different response to otherwise similar foreign firms. This approach allows the estimation of causal effects of the regulation, strengthening the external validity of the results. I find no evidence that the Ecotax reform had an effect on green transport innovation. The baseline results show that the reform had a negative effect on the number of green energy patents filed by small firms, although this effect is not robust to different specifications. Lastly, some potential explanations for this null effect are discussed, ranging from the small price effect of the reform to exceptions included in the policy that aimed to protect larger firms' competitiveness.

This study contributes to the strand of the literature studying the induced innovation triggered by environmental regulation (Porter and van der Linde, 1995). Environmental policies such as carbon price mechanisms have been found to have a positive impact on green innovation (Popp, 2010, 2019). In particular, it sheds light on how different firms respond to these incentives depending on their characteristics such as size and sector of activity. By using patent data, an outcome of innovation activities, this study finds no robust evidence of a causal effect of the Ecotax reform on green product innovation. These results raise questions about how policies should reconcile the short-term lose of competitiveness due to higher input prices with long-run benefits from higher innovation investments.

Chapter 3 considers the problems of providing global public goods with a weakest link technology, such as disease eradication. To this date, smallpox is the only human illness that has been eradicated, thanks to an international vaccination effort undertaken during the 1960s and 1970s (Barrett, 2007). The monetary benefits of this eradication in terms of lives saved, long-term debilitating symptoms prevented and savings of vaccination and healthcare costs vastly outweigh the costs of the program (Barrett, 2013; Thompson and Tebbens, 2007). Contemporary eradication efforts against other diseases such as polio, yaws and dracunculiasis have not been successful, what raises the question of why the provision of such a cost-effective public good is not yet achieved (Barrett, 2003). Eradication of illnesses are a weakest-link public good, as the illness has to disappear from every country and region for a number of years to be considered eradicated. This is especially challenging considering the financial constraints that some countries face and how difficult it might be to access and vaccinate communities living in remote and isolated areas.

This study models this problem by using a laboratory experiment. In this experiment, six participants interact together in a circular network in a public good provision game, where the public good that each participant receives is the minimum of the provision done by her and her two direct neighbors. This setting allows for the analysis of how individuals provide a public good in a setting where they are directly affected by the provisions of their closest connections, while maintaining the importance of the lowest provision in the network. Additionally, a common intermediary account mechanism is introduced to study how funding systems might help in the provision of said public good for poor participants, taking inspiration from the system used by the World Health Organisation during the smallpox eradication campaign (Barrett, 2007).

The main findings show that the spatial distribution of participants in terms of their heterogeneous income affects the average group payoff. In particular, participants are worse off when they are clustered together based on their endowment compared to when they are alternating. Participants also tend to make large in-kind transfers to their direct connections, highlighting the importance of the neighborhood as a focal point in the provision decisions. Introducing a common intermediate account is shown to have no effect on average payoffs of participants, though it decreases inequalities across rich and poor players. Lastly, when participants face an unequal total investments inside of their neighborhood, they tend to respond by reducing investments in the highest-invested location instead of increasing them in the lowest.

This study contributes to three strands of the literature. First, it contributes to the studies analysing the provision of weakest-link public goods (Hirshleifer, 1983; Vicary and Sandler, 2002; Caparrós and Finus, 2020a,b), in particular related to illness eradication (Barrett, 2016). Secondly, it contributes to the field of voluntary contributions to public goods in networks (Boosey, 2017; Gallo and Yan, 2023; Rosenkranz and Weitzel, 2012; Zhang and He, 2021). Lastly, this is one of the first empirical studies analysing the role of endowment heterogeneity in public good provision within spatial contexts.

Chapter 4 studies how the local nature of some public goods affects the provision decisions of individuals. The benefit stemming from the provision of many public goods (as well as the harm from public bads) is usually concentrated in the vicinity of the provision –

e.g. quality of schools, green spots, or air and water pollution. Simultaneously, individuals might differ in their capacity of providing the public good, for example, when they have different income or wealth levels. This raises questions about distributional concerns that have received increased attention in public debates and academic circles (Avery and Pathak, 2021; Banzhaf et al., 2019; Epple and Romano, 1998). In this chapter, the interaction between the locality of the benefits from public goods and spatial heterogeneity of individuals is studied. This analysis takes inspiration from current discussions of the benefits of having mixed vs. segregated neighborhoods in terms of income of the individuals (e.g. Thurber et al., 2018).

This study uses an experimental setting similar to the one used in Chapter 3, where a group of six participants interact together in a public good provision game in a circular network. In this experiment, the public good has a summation technology, so participants benefit directly from all the provisions made in the locations closest to themselves in the network. This setting allows to differentiation of prosocial and distributional concerns from participants, as well as reciprocal preferences, as participants cannot only choose *how much* to contribute but also *where* to contribute, and therefore *who* benefits from their contribution.

The main findings of this study are the following. First, participants tend to transfer a large portion of their investments to their direct neighbors. Second, the spatial location of participants matter in their investment decisions. There is redistribution from rich to poor participants, but when participants are clustered together by their endowment, this redistribution is exclusively triggered by the rich participants at the border of their cluster. Lastly, participants reciprocate the investment decisions of their neighbors – they increase their investments benefiting prosocial neighbors, while decreasing them for the non-cooperative ones.

This study contributes to recent studies on voluntary provision of public goods in networks (Boosey, 2017; Cassar, 2007; Gallo and Yan, 2023; Kirchkamp and Nagel, 2007; Rosenkranz and Weitzel, 2012; Zhang and He, 2021), adding the relatively unexplored role of endowment heterogeneity and how it is affected by spatial aspects. In particular, this is one of the first studies to explore the role of endowment heterogeneity in said networks. It also extends the type of reward/punishment decisions that participants have access to compared to other options previously explored in the literature (Kingsley, 2016).

Overall, the following three chapters aim to answer different questions related to public good provision. For this, different methodologies were chosen that best fit to the research question at hand. In Chapter 2, quasi-experimental approaches (matching and difference-in-differences) are used to analyse the effect of a particular implementation of carbon price mechanisms on green innovation. This approach allows the study of the causal effect of environmental regulation on green innovation. Chapter 3 and Chapter 4 use laboratory experiments to study how individuals make decisions regarding public good provision when their spatial allocation matters in terms of how they benefit from the public good provided. This permits me to study the behavior of individuals in a simplified model of real-world scenarios, what simplifies the interpretation of their behavior at the expense of having a lower external validity.

References

aus dem Moore, N., Brehm, J., and Gruhl, H. (2022). Driving innovation? Carbon tax effects in the Swedish transport sector. *Working Paper*.

Avery, C. and Pathak, P. A. (2021). The distributional consequences of public school choice. *The American Economic Review*, 111(1):129–152.

Banzhaf, S., Ma, L., and Timmins, C. (2019). Environmental justice: The economics of race, place, and pollution. *Journal of Economic Perspectives*, 33(1):185–208.

Barrett, S. (2003). Global disease eradication. *Journal of the European Economic Association*, 1(2-3):591–600.

Barrett, S. (2007). The smallpox eradication game. *Public Choice*, 130(1):179–207.

Barrett, S. (2013). Economic considerations for the eradication endgame. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 368(1623):20120149.

Barrett, S. (2016). Coordination vs. voluntarism and enforcement in sustaining international environmental cooperation. *Proceedings of the National Academy of Sciences*, 113(51):14515–14522.

Boosey, L. A. (2017). Conditional cooperation in network public goods experiments. *Journal of behavioral and experimental economics*, 69:108–116.

Calel, R. (2020). Adopt or innovate: Understanding technological responses to cap-and-trade. *American Economic Journal: Economic Policy*, 12(3):170–201.

Calel, R. and Dechezleprêtre, A. (2016). Environmental policy and directed technological change: evidence from the European carbon market. *Review of Economics and Statistics*, 98(1):173–191.

Caparrós, A. and Finus, M. (2020a). The corona-pandemic: a game-theoretic perspective on regional and global governance. *Environmental and Resource Economics*, 76(4):913–927.

Caparrós, A. and Finus, M. (2020b). Public good agreements under the weakest-link technology. *Journal of Public Economic Theory*, 22(3):555–582.

Cassar, A. (2007). Coordination and cooperation in local, random and small world networks: Experimental evidence. *Games and Economic Behavior*, 58(2):209–230.

Costa-Campi, M. T., García-Quevedo, J., and Segarra, A. (2015). Energy efficiency determinants: An empirical analysis of Spanish innovative firms. *Energy Policy*, 83:229–239.

Epple, D. and Romano, R. E. (1998). Competition between private and public schools, vouchers, and peer-group effects. *The American Economic Review*, 88(1):33–62.

Gallo, E. and Yan, C. (2023). Efficiency and equilibrium in network games: An experiment. *Review of Economics and Statistics*, 105(6):1515–1529.

Hirshleifer, J. (1983). From weakest-link to best-shot: The voluntary provision of public goods. *Public Choice*, 41(3):371–386.

Kingsley, D. C. (2016). Endowment heterogeneity and peer punishment in a public good experiment: cooperation and normative conflict. *Journal of Behavioral and Experimental Economics*, 60:49–61.

Kirchkamp, O. and Nagel, R. (2007). Naive learning and cooperation in network experiments. *Games and Economic Behavior*, 58(2):269–292.

Olson Jr, M. (1971). *The Logic of Collective Action: Public Goods and the Theory of Groups, with a new preface and appendix*, volume 124. Harvard University Press.

Popp, D. (2010). Innovation and climate policy. *Annual Review Resource Economics*, 2(1):275–298.

Popp, D. (2019). Environmental policy and innovation: a decade of research. *NBER Working Paper*.

Porter, M. E. and van der Linde, C. (1995). Toward a new conception of the environment-competitiveness relationship. *Journal of economic perspectives*, 9(4):97–118.

Rosenkranz, S. and Weitzel, U. (2012). Network structure and strategic investments: An experimental analysis. *Games and Economic Behavior*, 75(2):898–920.

Samuelson, P. A. (1954). The pure theory of public expenditure. *The review of economics and statistics*, pages 387–389.

Stiglitz, J. E. and Rosengard, J. K. (2015). *Economics of the public sector: Fourth international student edition*. WW Norton & Company.

Stucki, T., Woerter, M., Arvanitis, S., Peneder, M., and Rammer, C. (2018). How different policy instruments affect green product innovation: A differentiated perspective. *Energy Policy*, 114:245–261.

Thompson, K. M. and Tebbens, R. J. D. (2007). Eradication versus control for poliomyelitis: an economic analysis. *The Lancet*, 369(9570):1363–1371.

Thurber, A., Bohmann, C. R., and Heflinger, C. A. (2018). Spatially integrated and socially segregated: The effects of mixed-income neighbourhoods on social well-being. *Urban Studies*, 55(9):1859–1874.

Veugelers, R. (2012). Which policy instruments to induce clean innovating? *Research policy*, 41(10):1770–1778.

Vicary, S. and Sandler, T. (2002). Weakest-link public goods: Giving in-kind or transferring money. *European Economic Review*, 46(8):1501–1520.

Zhang, L., Cao, C., Tang, F., He, J., and Li, D. (2019). Does Chinas emissions trading system foster corporate green innovation? Evidence from regulating listed companies. *Technology Analysis & Strategic Management*, 31(2):199–212.

Zhang, Y. and He, L. (2021). Theory and experiments on network games of public goods: inequality aversion and welfare preference. *Journal of Economic Behavior & Organization*, 190:326–347.

Chapter 2

Heterogeneous effects of carbon taxation on green innovation

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Abstract

In this study, I assess the effect that a German tax reform affecting electricity and fuel consumption had on green innovation. The empirical analysis uses data from EPO's PATSTAT database, covering patents related to green technologies from 1990 to 2009, as well as firm-level information from Bureau van Dijk's Orbis database. By using a matching difference-in-differences design, I estimate the effect of the reform on the green innovation activities of firms. The results show no evidence that the Ecotax affected the number of green energy and transport patents filed by German firms already involved in green innovation. Furthermore, no effects are found either when differentiating firms by their size or economic sector of activity. Potential explanations for this finding are discussed, raising questions on how exceptions included in carbon pricing mechanisms might nullify incentives for innovation.

JEL classification: O30, Q55, Q58
Keywords: Induced innovation, green innovation, environmental policy, carbon tax.

2.1 Introduction

In the last years, a renewed policy effort has focused on environment and climate protection, as exemplified by the Inflation Reduction Act in the US or the European Green Deal in the EU. These policies aim to solve major environmental challenges, that will require profound, systemic changes in the means of transport, energy production and manufacturing. Achieving some of the goals of said policies will require the development and deployment of technologies that are not yet available (International Energy Agency, 2021). In fact, one of the ultimate aims of many environmental policies, as it was the case with the EU Emissions Trading System (EU ETS), is that they should incentivise firms to invest in green technologies and in low-carbon R&D (European Commision, 2005, 2011). Prior research finds a positive effect of different types of environmental policies on green innovation at a country level, suggesting that, on average, firms do respond to the incentives outlined by said policies (Popp, 2019).

Yet, the green innovation effects of environmental regulation might depend on firms' characteristics (e.g. size or sector of activity). If this differential response exists, the industrial composition of a country would play a crucial role in the final aggregate effect on innovation of any piece of regulation. Previous studies show indirect evidence that not all firms give the same importance to low-carbon innovation. Costa-Campi et al. (2015) find that energy efficiency improvements are more likely to be considered important by large companies than smaller ones. Similarly, a recent survey of the European Investment Bank found that EU SMEs are less likely to invest in green technologies and products than larger firms (European Investment Bank, 2023). In terms of the sector of activity, manufacturers are more likely to develop new energy technologies for end-users compared to service firms, as they offer products that can directly incorporate said developments (Stucki et al., 2018). Although there is evidence that firms value green innovation differently depending on their characteristics such as size or productivity (DeCanio and Watkins, 1998), most of this evidence comes from survey studies, with hardly any evaluation of how this translates to innovation outcomes. This study provides causal evidence of how firms' characteristics affect their green innovation outcomes when facing environmental regulation.

To analyse whether environmental policies are more successful in inducing green innovation outcomes in some particular type of firms, I study the Ecotax reform introduced in Germany in 1999. This reform raised new taxes on electricity and fuel consumption, with rates that increased in yearly steps from 1999 to 2003. By 2003, the total increase of electricity taxes was 2.1 cents per kWh and of 15.5 cents per liter on fuel taxes (Görres, 2005). This translates to an implicit cost of carbon of €58 ($65) per ton of CO_2 for diesel and €66 ($74) for gasoline (Basaglia et al., 2023). With the exception of Basaglia et al. (2023), no other study has assessed the effect of this reform on German green innovation.

My analysis starts by estimating causal effects of the Ecotax on German firms' green patenting records, and assessing how these effects are affected by the size of the firms' technology portfolio and economic sector of activity. For this, I use a matching difference-in-differences approach to compare German firms with firms from other OECD countries that are similar in terms of their economic sector of activity, age, patent portfolio, and experience in green innovation.

I find no evidence of an effect of the Ecotax on the expected number of green energy and transport patents applied by German firms previously involved in green innovation. Furthermore, there is no evidence of an heterogeneous effect in green transport innovation depending on their size or sector of activity of the firm. Similarly, I do not find evidence of an effect of the reform on green energy patenting activity. Some potential explanations to these findings are discussed, such as the small scope of the tax introduction, exceptions to the tax included in the reform, and lack of mechanisms to index the tax rate to increases in energy and fuel prices.

This study contributes to a prolific strand of the literature studying directed technological change and induced innovation in green technologies. The idea of induced innovation can be traced back to the seminal work of Hicks (1932). Later, the Porter hypothesis reinterpreted it in the context of environmental policy, stating that regulations that raise the prices that firms face due to their emissions also incentivise them to develop and adopt new low-emission technologies (Porter and van der Linde, 1995). Numerous studies have found empirical evidence that supports this hypothesis. This positive effect is found across a variety of different environmental policies: tradable pollution permits (Popp, 2003), emissions standards (Brunnermeier and Cohen, 2003; Jaffe and Palmer, 1997; Lanjouw and Mody, 1996; Popp, 2006), buildings energy standards (Noailly, 2012), energy efficiency standards (Newell et al., 1999), international protocols (Dugoua, 2023), or feed-in-tariffs (Reichardt and Rogge, 2016). Popp (2010) and Popp (2019) offer a comprehensive summary of the empirical evidence of the induced innovation hypothesis.

Specifically, this study builds on previous works that assess the effect of market-based environmental policies on green innovation. This is particularly important as the effect of taxes on green innovation might be larger than equivalent price increase, due to the higher salience of the tax (Andersson, 2019; Sterner, 2012). A majority of studies find a positive effect of carbon prices on green innovation (e.g. aus dem Moore et al., 2022; Basaglia et al., 2023; Calel, 2020; Calel and Dechezleprêtre, 2016; Zhang et al., 2019), although some do not find a significant effect (e.g. Kim et al., 2017; Rogge et al., 2011; Schmidt et al., 2012).

Even in the face of increasingly stringent environmental policies, green R&D investments that lead to patenting are a relatively uncommon practice among firms (Calel, 2020).

Furthermore, the decision of whether to engage in green innovation at all is itself influenced by firms characteristics (DeCanio and Watkins, 1998). Company size has been found to have a positive effect on likeliness to pursue energy efficiency projects (Costa-Campi et al., 2015; De Marchi, 2012; DeCanio and Watkins, 1998; Veugelers, 2012). Productivity levels have also been linked with the probability of investing in energy efficiency (Costa-Campi et al., 2015; Rennings and Rammer, 2009). Evidence of the effect of export propensity is mixed, with Costa-Campi et al. (2015) finding a positive effect, while De Marchi (2012) does not find any significant effect.

A further challenge that firms must overcome is the high costs of said R&D efforts. Zhang et al. (2019) finds that carbon pricing schemes have a positive effect on green innovation, but this effect is smaller in sectors with high levels of competition, what suggests that said competition leaves fewer resources available to invest in R&D. Similarly, Howell (2017) finds that energy start-ups' patenting and revenue benefit from early public funding, pointing that small, high-tech firms may face financial constraints in their early stages. Using firm survey data from manufacturing companies based in Austria, Germany and Switzerland, Stucki et al. (2018) find a negative effect of carbon taxes on green product innovation, while they find a positive effect on green process innovation. The authors argue that financially-constrained firms may need to divert funds to finance projects aimed at reducing their energy use, detracting resources from (potential) product innovation projects – a constraint especially severe for SMEs. Access to other resources, such as equipment and previous innovative experience, positively affects green innovation (De Marchi, 2012), what indicates that technical know-how and having a specialised workforce are also potential constraints that firms might face.

This study analyses whether some specific types of firms are more responsive to the incentives established by environmental regulation in terms of their green innovation output. As pointed by Stucki et al. (2018), small firms may need to decide whether to invest their funds in decreasing their use of energy and fuel (a process innovation) vs. investing them in green R&D projects (a product innovation), what would curb their ability to develop new green technologies. Carbon pricing schemes that do not include revenue recycling mechanisms or exemptions have been found to be regressive and have a negative impact on distributional aspects (e.g. Bosquet, 2000; Conefrey et al., 2013; Oueslati et al., 2017; Peñasco et al., 2021). A similar problem arises when firms face carbon taxes without compensation mechanisms for SMEs. Policy makers should consider how these carbon pricing mechanisms may have a negative impact on SMEs, and in particular, on their ability to pursue innovative activities. Providing public R&D funding programs or grants to small firms (Criscuolo and Menon, 2015; Howell, 2017), or establishing additional subsidies for them (Andersen and Skou, 2010; Oueslati et al., 2017), may help SMEs to invest in innovation activities.

The rest of the paper is organised as follows. Section 2.2 discusses the policy landscape in Germany during the introduction of the Ecotax. Section 2.3 describes the data and Section 2.4 covers the methodology used. Section 2.5 presents the empirical results and Section 2.6 assesses the robustness of said results. Section 2.7 discusses the results and Section 2.8 concludes.

2.2 Policy background

Germany has a long history of adopting environmental policies that incentivise the development of environmentally friendly technologies, e.g. from reducing air pollution (Popp, 2006) to improving waste management (OECD, 2012). Environmental regulation in these fields fueled innovation in green technologies related to them, thanks in part to the strength and innovativeness of the German industry, what has made the country a leader on environmental innovation (Brunel, 2019; OECD, 2012).

Prior to the turn of the 20th century, most environmental policies in Germany consisted in command-and-control measures, subsidies, or voluntary agreements. Some specific taxes existed that were directly related with environmental protection, such as fuel taxes or wastewater charge. Although some developed later to cover environmental objectives, they were initially introduced without a specific environmental goal in mind (Beuermann and Santarius, 2006).

By the end of the 20th century, German policy makers proposed a more ambitious and comprehensive set of environmental policies, targeting the energy sector in particular, what would be the precursors of the *Energiewende* policy effort of the 2010s. The Renewable Energy Law of 2000 gave priority to renewable energies entering the energy pool, while political decisions such as the agreement to phase out all nuclear plants by 2022 (agreed with utility companies in 2000) shaped the future of the energy sector. Other policies, such as the liberalization of the electricity market in 1998, increased competition while also introducing uncertainty regarding electricity prices (Beuermann and Santarius, 2006).

The Ecotax reform of 1999 (*Ökologische Steuerreform*) was one of these policies. This was a new tax levied on electricity and transport fuels, that was introduced in 1999 and which rate would increase in yearly steps until 2003. The goal of the of the tax was double: reducing energy consumption, while using the raised revenues to lower workers' and employers' contributions to the pension scheme. Although the idea of an ecological tax reform was introduced in Germany in the early 1980s, the discussion only gained political momentum in the 1990s (Beuermann and Santarius, 2006). By the year 2003, the Ecotax raised 2.1 cents/kWh of electricity consumed, and 15.5 cents/liter of gasoline or diesel (Görres, 2005). After the re-election of the red-green coalition government in 2002, the government decided not to increase the rate of the tax any further after the year 2003. As the tax rate did not undergo any major adjustment after 2003, inflation and rising oil prices decreased the effective share of the tax during the following years (OECD, 2012).

The Ecotax reform included a number of exemptions. Electricity produced by renewable energies for self-consumption and electricity from renewable energy contracts, as well as biofuels, were exempted from the Ecotax (Knigge and Görlach, 2005). Manufacturing firms enjoyed a reduction of 40% of the tax rate, which benefited 120,000 companies (Umwelt Bundesamt, 2011). This reduction was higher for manufacturers with large energy consumptions, for whom the reduction of the tax rate was of 80% (Beuermann and Santarius, 2006). Around 20,000 energy-intensive manufacturing firms received a further refund of 95% of their Ecotax payments that exceeded the reductions in pension funds contributions (Umwelt Bundesamt, 2011). The reform also included a reduced 50% tax rate for electricity and fuel used by public transport, and other special exemptions applied to fuels used in energy production in cogeneration power plants (Beuermann and Santarius, 2006).

These two characteristics of the Ecotax, namely the absence of further increases in the tax rate and large number of exemptions included in the reform, make any incentives to innovate weaker. As covered in more detail in Section 2.7, the lack of an indexing mechanism would dilute the effective tax rate due to inflation and increases in fuel and electricity prices, while the exemptions shielded manufacturers with large energy bills – those that would benefit the most from energy-saving technologies – from the brunt of the tax.

2.3 Data

To measure innovation in green energy and transport technologies, I use patent data extracted form the PATSTAT database provided by the European Patent Office (EPO) (European Patent Office, 2024). In the literature on induced innovation, patent data has been used as a proxy to measure the underlying innovation activities happening at the firm level (e.g. Calel and Dechezleprêtre, 2016; Dugoua, 2023; Johnstone et al., 2010; Popp, 2003), as patents have been found to be highly correlated with technological and R&D performance at the firm and country level (de Rassenfosse and van Pottelsberghe de la Potterie, 2009; Hagedoorn and Cloodt, 2003). Patents also offer the advantage of measuring outputs of said innovation activities, compared to other potential candidates that focus on inputs (Griliches, 1998).

Advantages and shortcomings of using patent data for this purpose have been discussed in the literature and are well understood (OECD, 2009). The main benefits of patent data are that it covers long periods of time, its standards are well defined and change slowly, and that the granting procedures make patents one of the most objective measure of underlying innovative processes (Griliches, 1998). Patent documents contain a plethora of useful information for empirical studies, that allow – among other things – to pinpoint the location and date in which an invention was developed, as well as knowing which firm(s) and inventor(s) were involved in its creation. Figure 2.A.3 shows the title page of one of the extracted patent documents, as an illustrative example of the richness of information that is coded in these documents.

On the other hand, patent data presents some limitations (Griliches, 1998). Firstly, patenting is not the only way of protecting an invention, and different industries differ in their propensity to use different methods of protecting their inventions, such as keeping them as trade secrets. Secondly, patents differ in their technological and economic impact. By focusing on two sectors (namely energy and transport) and on higher-value patents (patents that were granted), some of these shortcomings can be mitigated. As an invention can be protected by more than one patent in different jurisdictions, I focus on those patents claiming priority, to prevent multiple-counting of a single technological development.

For the definition of which patents can be considered to cover green technologies, I used the Y02 CPC tag class system developed by the EPO, that identifies patents that are related to mitigation or adaptation against climate change.[1] This class system classifies each green patent into the technological field that they relate to (e.g., energy, transport, or building). For a list of the CPC codes used, see Tables 2.A.1 and 2.A.2 in Appendix 2.C. To test whether the results of the study are contingent on what technologies are considered to be green, I test the robustness of the results using an extended set of patents covering environmental technologies, which adds other IPC codes previously used in the literature.[2] The exact IPC codes of this extended definition can be found in Appendix 2.C (Tables 2.A.3 and 2.A.4).

For assigning each patent to the firm(s) that owns it, I used Orbis IP database. This database links each patent with a firm identifier (BvD ID), which allows for uniquely identifying each patent's owner(s), as well as identifying all patents hold by said firms. Furthermore, using this identifier permits linking these firms to the corporate data in-

[1] Veefkind et al. (2012) describes in detail how this tagging system was developed for the energy sector. This tagging system was eventually extended to other green technological sectors. Some of the codes included in the analysis cover technologies related to energy generation through renewable energy sources (Y02E 10) or technologies for the production of fuel of non-fossil origin (Y02E 50).

[2] In particular, they come from Johnstone et al. (2010), Dechezleprêtre et al. (2015), Aghion et al. (2016) and Popp et al. (2020).

cluded in Orbis Global database. This way, each patent application was linked to its owner(s) and their corporate information (such as year of incorporation of the firm, NACE economic sector of activity, turnover or number of employees).

The GDP data is sourced from the expenditure-side, real GDP at current purchasing power parities (in million of USD, in 2017) obtained from the Penn World Table version 10.01 (Feenstra et al., 2015), and later on transformed to GDP growth rate in percentage points. The information on public expenditure on energy and transport R&D comes from the OECD Research and Development Statistics (OECD, 2024).

The final dataset covers the yearly number of green energy and transport patents filed by German (604) and foreign (837) companies during the period 1990-2009 (after the matching described in Section 2.4). An important remark is that this dataset only covers companies that were already involved in the field of green technologies during the period of 1990-1998 – i.e. they had filed for at least one granted, green patent during this period. The reason behind this is the restriction imposed by the matching procedure discussed in Section 2.4. Table 2.1 provides descriptive statistics of the main dataset.

	Description	Unit	Mean	Std. dev.	Min	Max	Obs
$energy\_patents_{it}$	Green energy patents applied by firm i	Count	0.51	3.09	0	124	15,054
$transport\_patents_{it}$	Green transport patents applied by firm i	Count	1.20	6.05	0	167	9,647
g_gdp_{ct}	GDP growth rate of country c	%	3.18	4.51	-28.62	14.70	323
$energy\_RDD_{ct}$	Public expenditure in energy R&D, as a share of total GDP	%	2.06	1.81	0.042	8.93	257
$transport\_RDD_{ct}$	Public expenditure in transport R&D, as a share of total GDP	$*10^{-6}$	1.10	0.85	0.038	6.18	191

Table 2.1 Descriptive statistics for the 1990-2009 period. The number of observations of g_gdp_{ct} and $energy\_RDD_{ct}$ correspond to country-year combinations as they are country-level variables.

2.4 Methodology

For testing whether the introduction of the Ecotax had an effect on firms' patent activity, I use a matching difference-in-differences design. As the number of patents filed by a company in a given year is a non-negative integer, I assume that the outcome follows a Poisson distribution where the number of patents can be modeled as a function of explanatory variables:

$$E(y_{it}|x_{it}) = exp(\beta_{DiD} * D_{treated,t\geq 1999} + \beta * x_{it} + \alpha_i + \gamma_t) \tag{2.1}$$

where y_{it} are the number of green patents applied by a company i in year t, $D_{treated,t\geq 1999}$ is a dummy variable that is equal to 1 if company i is based in Germany and the year is 1999 or later, x_{it} is a vector of control variables, and α_i and γ_t are firms' and year fixed effects, respectively. Note that the effects of the right-hand side variables on the expected value of the outcome are multiplicative, not additive. A one-unit change in the magnitude of one of the explanatory variables would translate to a β*100% change in the expected number of patents observed. Most importantly for this study, the introduction of the Ecotax would have an effect of β_{DiD}*100% on the expected number of green patents filed by German firms after the year 1999.

A naive estimation of this regression presents a number of problems, the most important being that selecting counterfactuals for the affected German firms is not trivial. To tackle this challenge, I use a matching difference-in-differences design, what should reduce the bias stemming from the industrial composition of the German firms (Stuart et al., 2014). This approach matches each treated firm with a number of similar foreign companies, which allows to control for a variety of factors such as sectorial differences, input prices, and firm heterogeneity (Abadie, 2005; Heckman et al., 1998a,b; Smith and Todd, 2005). To reduce the potential differences between countries – that would not be addressed by the matching –, I create a donor pool of countries similar to Germany that did not introduce any new tax on electricity or fuel use, and that had a comparable economic development during these years.

Synthetic control methods have also been used to solve this particular challenge of not having a single credible counterfactual (Abadie and Gardeazabal, 2003; Abadie et al., 2010), but their suitability in this case is not guaranteed. First, Germany has a particularly distinct industrial and economic structure compared to other developed economies, what would make any potential counterfactual implausible. In particular, Germany has a larger export industry than other OECD countries, a higher integration in international trade, a larger share of its economy devoted to industrial activities, and it possesses a strong and versatile innovative capacity (Görres, 2005; Haščič, 2012). Second, these methods do not allow to disentangle the potential heterogeneous effect of an intervention, as they focus on outcomes aggregated at a high level.

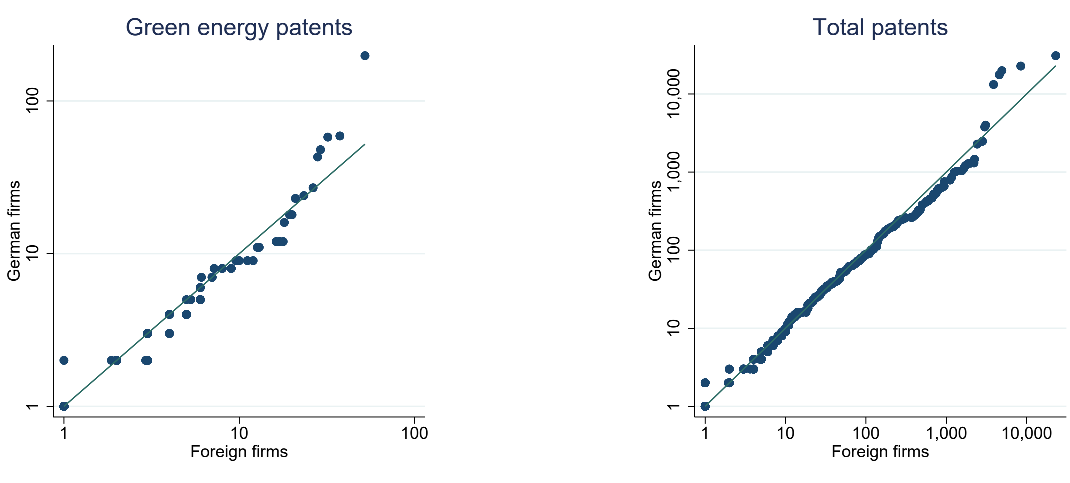
The process of finding valid counterfactuals starts by creating a donor pool of countries similar to Germany. For creating this pool, I started with all countries belonging to the OECD, as they are closest to Germany in terms of industrial and economic structure, as well as government form, what should reduce biases stemming from using foreign firms as controls (Abadie, 2021). From this list, a number of countries were eliminated. First, all countries that implemented some form of carbon tax on electricity or fuel consumption in the period between 1990 and 2009 were dropped. During the decade of 1990s, Finland, the Netherlands, Norway and Sweden introduced carbon taxes on the transport sector (Haugland, 1993; Kossoy et al., 2015). Denmark also added a carbon tax, affecting electricity use, during this decade (Haugland, 1993). Then, countries that introduced some other electricity or fuel tax or that substantially changed said taxes were dropped. This includes Belgium, that introduced a new tax raised on some energy products in 1993 (OECD, 2001); and Austria, that introduced an energy tax on gas and electricity in 1996 (OECD, 2001). Italy, the UK and Spain were also dropped as they introduced other fuel taxes not labeled as carbon taxes during the study period (Bosch, 2001; OECD, 2001). Japan was dropped due to its Top Runner program introduced in 1998, an initiative aimed at improving energy efficiency of different products, including vehicles (Osamu, 2012). Lastly, Ireland was eliminated because of its fast economic growth during the decade of the 1990s. This leaves a group of 24 potential countries from which to find matches for German firms (see list in Table 2.A.5).

As the Ecotax reform raised different tax rates to fuel and electricity consumption, as well as having different exceptions for both (see Section 2.2), the analysis of its effect is carried out separately for energy and transport green technologies. Accordingly, two different matching procedures were performed, one for firms involved in green energy innovation, and another for those involved in green transport.

Each German firm involved in green technology innovation in the 1990-1998 period was matched with up to two similar firms from the countries of the donor pool, using their propensity score as the distance metric for the matching (Dehejia and Wahba, 1999). In particular, they were matched based on their green patenting record during the 1990-1998 period, their total patent record across all technologies over that period, their year of incorporation, and their economic sector of activity (defined by the two-digit level of the NACE Rev. 2 industry classification).[3] Appendix 2.A summarises the details of the covariates used and the matching implementation. The robustness of the results in respect to the main matching specification is tested in Section 2.6.

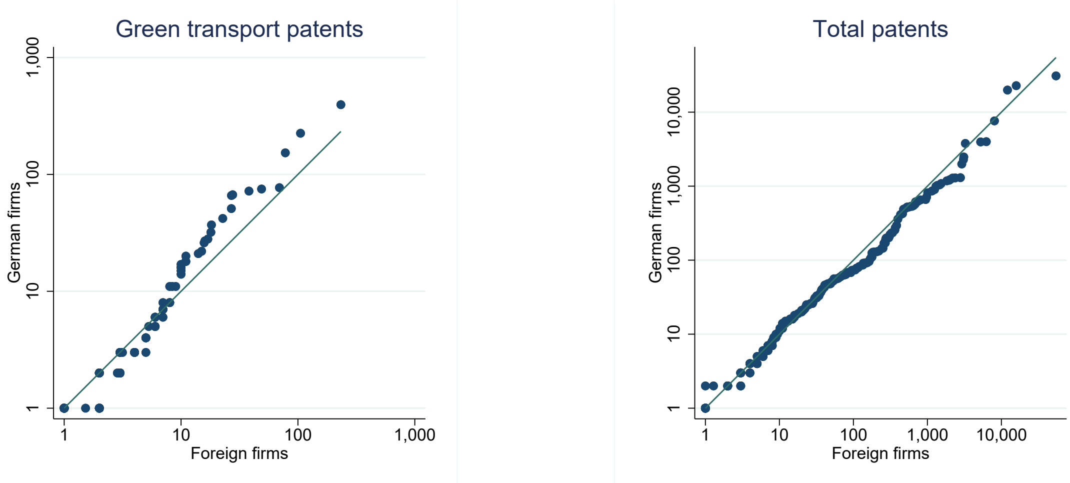
Figures 2.1 and 2.2 compare the distribution of the matched German and foreign firms in a number of key covariates used in the matching for green energy and transport firms, respectively. Looking at these figures, we can observe that the German firms and the matched foreign companies are indeed quite similar in terms of their (green) technological portfolio in the period previous to the introduction of the Ecotax. Tables 2.A.6 and 2.A.7 in the appendix show the number of matched firms that belong to different economic sectors, showcasing that a good match in terms of industrial composition is also achieved. Tables 2.A.8 and 2.A.9 show the country of origin of the matched foreign firms.

[3]Although Orbis includes data for other covariates commonly used in matching, the coverage of these variables is quite low for the study period – e.g. the data on turnover and number of employees covers only around 7% of the German firms in the sample.



(a) (b)

Figure 2.1 Comparison of matched German and foreign firms working on green energy innovation. Panel (a) shows the empirical quantile-quantile plot (e-QQ plot) for the total number of green energy patents filed during the period 1990-1998, in logarithmic scale. Each dot represents a quantile of the distribution of green patents among German firms and non-German firms. Panel (b) shows the e-QQ plot or the total number of patents filed during the period 1990-1998, in logarithmic scale.



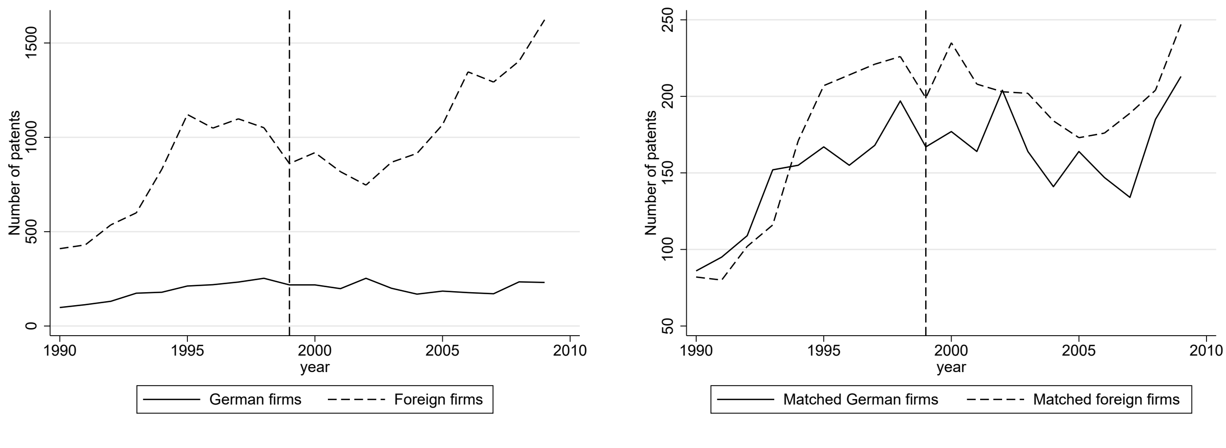
(a) (b)

Figure 2.2 Comparison of matched German and foreign firms working on green transport innovation. Panel (a) shows the empirical quantile-quantile plot (e-QQ plot) for the total number of green transport patents filed during the period 1990-1998, in logarithmic scale. Each dot represents a quantile of the distribution of green patents among German firms and non-German firms. Panel (b) shows the e-QQ plot or the total number of patents filed during the period 1990-1998, in logarithmic scale.

The main caveat of matching techniques is that they rely on the assumption that the units that are similar in some observed dimensions are also similar in the unobserved dimensions (Calel and Dechezleprêtre, 2016). A simple test to assess the quality of the matching across unobserved variables is to show whether a balance was achieved in respect to variables that were not used for the matching. Figures 2.A.1 and 2.A.2 in the appendix show the empirical distribution of two variables not used for the matching – average turnover and average number of employees in the period 1995-1998. These figures show a similar balance of these two variables between German and foreign companies, though German firms tend to have a higher turnover than the matched foreign firms.

The process of matching German firms to foreign ones is not perfect. This means that if the matching algorithm does not find a good match for a given treated unit, this firm will be dropped from the analysis. Starting from 685 German firms that applied for at least one green patent in the period between 1990 and 1998, only 604 were matched to at least one foreign company. Although this reduces the sample size, matching treated firms to fewer (but more comparable) units improves the accuracy and robustness of the estimated parameters (Dehejia and Wahba, 1999).

Figures 2.3 and 2.4 show the aggregate number of green patents filled by German vs. foreign firms over the study period. Comparing both panels of each figure, we can see that the process of matching German firms with similar, foreign firms supports the validity of the parallel trend assumption.[4] Figure 2.3b shows that the evolution of the aggregated green energy patent activity of the German firms before and after the introduction of the Ecotax follows closely the trend of the matched firms. On the other hand, Figure 2.4b also shows a similar trend between German and matched firms prior to 1999, but the number of green transport patents in Germany stagnates after the introduction of the Ecotax.

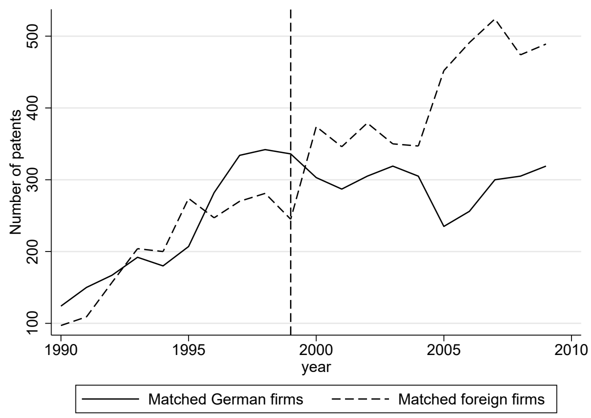


(a) (b)

Figure 2.3 Number of green energy patents applied by German and foreign firms. Panel (a) shows the aggregate number of patents filled by German and foreign firms on a given year. Panel (b) restricts the sample to only matched firms.

[4]Note that in the following analysis, the comparison is done between *firms* and not *countries*. For properly testing the parallel trend assumption, a similar graph should be created to compare each German firm with its matched, foreign counterfactual(s). Figures 2.3 and 2.4 show that this assumption holds on *aggregate* level – this should mitigate some of the concerns about the validity of the parallel trend assumption.

(a)



(b)

Figure 2.4 Number of green transport patents applied by German and foreign firms. Panel (a) shows the aggregate number of patents filled by German and foreign firms on a given year. Panel (b) restricts the sample to only matched firms.

2.5 Results

In this section, I discuss the results of the estimation of the effect of the Ecotax reform on green innovation. Recall that, due to the functional form of Equation 2.1, the coefficients estimated have a multiplicative effect on the outcome, not additive. Accordingly, a coefficient estimated to be smaller than one would mean that said variable has a negative effect on the expected outcome, while the effect would be positive if the coefficient is larger than one.

Table 2.2 presents the baseline results of the study of the effect of the Ecotax reform on green energy technologies. Columns (1) and (2) show the estimates of the average effect of the Ecotax on German firms. Column (1) estimates the model with the treatment dummy and year and firm fixed effects. Column (2) includes controls for GDP growth of the country of origin of firm i, and public expenditure in energy R&D as a percentage of the GDP. Since R&D projects require time to complete, column (2) uses a one-year lag for these two variables (Costantini et al., 2017; Noailly, 2012). Columns (1) and (2) show no evidence to support that the Ecotax had an effect on firms' green patenting on average.

As common measures of company size like turnover or number of employees are available for only a small fraction of the firms in the database, I use the total number of patents filed in the period 1990-1998 as a proxy for the firms' size. Columns (3) and (4) restrict the regression depending on the number of total patents filed by the analysed firms in the period 1990-1998. Columns (3) restricts the analysis to the smallest 90% of the firms, in

			Total patents		Sector of activity	
			Bottom 90%	Top 10%	Manufacturing	Other
	(1)	(2)	(3)	(4)	(5)	(6)
$Ecotax$	1.43	1.07	0.48**	0.99	1.07	1.09
	(0.79)	(0.15)	(-2.31)	(-0.01)	(0.09)	(0.21)
$GDPgrowth_{t-1}$		1.00	0.96	1.02	1.01	1.00
		(0.09)	(-1.18)	(0.74)	(0.15)	(-0.02)
$log(EnergyRDD)_{t-1}$		1.76	1.69*	1.85	1.54	2.03***
		(1.53)	(1.65)	(1.40)	(0.60)	(3.13)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	15,012	11,973	10,562	1,411	7,096	4,877
Firms	952	799	709	90	474	325

Robust z-statistics in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 2.2 Results for energy patents. The outcome variable is the number of green patents filled by a firm i during year t. Columns (3) through (6) restricts the sample for heterogeneous effects analysis. Columns (3) and (4) restrict it by size of patent portfolio in period 1990-1998 to the top 10% innovators (4) and the bottom 90% (3). Columns (5) and (6) restrict it by the economic sector that firm belongs to – manufacturing (5) or other (6). Regression estimated using a Poisson fixed effect model.

other words, firms with a patent portfolio smaller than the portfolio of the 90th percentile firm, while column (4) restricts it to the largest 10% of the firms. Column (3) shows that the Ecotax had a negative effect on green energy innovative activities of small firms, with a reduction of 52% (100% - 48%) of the expected number of green energy patents filed. Column (4) shows no evidence of an effect on larger companies. These results are robust to using a different threshold for the separation between small and large companies, with a decrease of the expected number of patents located between 50 and 60% (Table 2.A.10).

Lastly, to disentangle the effect of the reform on firms depending on their sector of activity, column (5) restricts the analysis to firms working on manufacturing activities, while column (6) uses firms working on other sectors. There is no evidence that the Ecotax affected the manufacturing sector differently from the rest. Interestingly, the lagged GDP growth rate does not seem to have an effect on the propensity to patent green energy technologies in any of the specifications, while public energy R&D expenditures has a positive effect on said propensity of small firms (column (4)) and non-manufacturing firms (column (6)).

Table 2.3 shows the results of the analysis for the green transport patents. Columns (1) and (2) show no evidence of an effect of the Ecotax reform on average. Columns (3) and (4) show also no evidence of a differential effect depending on firm's size, a result that is robust to different thresholds for separating firms by their size (Table 2.A.11). Finally, columns (5) and (6) also show no evidence that the reform had an effect on green transport patents filed by manufacturing firms or firms working on non-manufacturing sectors. Similarly to the case with energy patents, the lagged GDP growth rates do not seem to have an effect on green transport technologies, while public expenditure in transport R&D shows a negative effect in small and manufacturing firms. Although this latter finding might be surprising at a first glance, we should note the transport R&D data includes funding for transport systems in general (OECD, 2024), so it is not straightforward that firms will respond by favoring green transport technological developments over polluting ones.

As Section 2.6 shows, the results for green transport innovation are robust across all robustness tests, showing no evidence that the Ecotax reform had an effect on German firms already involved in green transport technologies. On the other hand, the results for green energy innovation are robust only to some of the different specifications tested, but not all. Thus, the interpretation of the results is left for Section 2.7.

			Total patents		Sector of activity	
			Bottom 90%	Top 10%	Manufacturing	Other
	(1)	(2)	(3)	(4)	(5)	(6)
$Ecotax$	0.74	0.76	0.50	0.87	0.70	1.16
	(-0.80)	(-0.62)	(-1.20)	(-0.26)	(-0.73)	(0.24)
$GDPgrowth_{t-1}$		0.96	0.95	0.97	0.98	0.93
		(-1.21)	(-0.88)	(-0.63)	(-0.70)	(-0.86)
$log(TransportRDD)_{t-1}$		0.70	0.57*	0.81	0.59**	0.85
		(-0.89)	(-1.79)	(-0.30)	(-2.05)	(-0.22)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	9,647	8,176	7,245	931	4,492	3,684
Firms	602	537	479	58	292	245

Robust z-statistics in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 2.3 Results for transport patents. The outcome variable is the number of green patents filled by a firm i during year t. Columns (3) and (4) restrict it by size of patent portfolio in period 1990-1998 to the top 10% innovators (4) and the bottom 90% (3). Columns (5) and (6) restrict it by the economic sector that firm belongs to – manufacturing (5) or other (6). Regression estimated using a Poisson fixed effect model.

2.6 Robustness checks

2.6.1 Anticipatory effects

The Ecotax reform was discussed since at least the 1980s, and gained momentum in political discussions during the federal election of 1998 (Beuermann and Santarius, 2006).

This could have let to anticipatory behavior from firms (Dekker et al., 2012), who might have increased their green innovation investments before the introduction of the tax in 1999, as found by Basaglia et al. (2023).

The red-green coalition government that introduced the Ecotax was elected in 1998. The tax reform was a prominent issue during the campaign leading up to the elections, especially for the Green Party (Beuermann and Santarius, 2006). Firms could have been aware of the implications of the following elections and adapted their innovation portfolios accordingly to focus on greener projects. Thus, I re-estimate Equation 2.1 by setting 1998 as the year of the break and re-matching the German firms that filed for at least one green patent in the period of 1990-1997 with similar foreign companies.

Tables 2.A.12 and 2.A.19 show the results of this analysis for green energy and transport patents, respectively. The results of Table 2.A.12 show no evidence of an effect of the Ecotax reform on green energy, neither on average (columns (1) and (2)) nor in the subgroups separated by size (columns (3) and (4)) or sector of activity (columns (5) and (6)). Table 2.A.19 shows a negative effect on large firms of 45%, although this effect is significant only at the 10% level (column (4)).

Following the results of Basaglia et al. (2023) that find an increase of green transport patents after the tax reform, I re-estimate the regression using 1995 as the break year, as in the year the discussions about the Ecotax started to gain traction among all parties represented in the German parliament (Beuermann and Santarius, 2006). In this case, I find no evidence of an effect of the Ecotax on green energy patents (Table 2.A.13), while it has a positive effect on green transport patents filed by non-manufacturing firms, significant at the 10% level (Table 2.A.20).

These findings indicate that the results shown in Section 2.5 are sensitive to slight variations of the timing of the introduction of the reform to which the firms could have responded.

2.6.2 Introduction of the EU-ETS

The introduction of the EU-ETS in 2005 has been found to have a positive effect on European green patenting, although the effects are relatively small – e.g., Calel and Dechezleprêtre (2016) report a 1% increase in low-carbon patenting in the European Union due to the introduction of the EU-ETS. As only a small percentage of the control firms (17% for energy and 31% for transport firms) are based in countries affected by the EU-ETS, we could expect the results presented in Section 2.5 to be positively biased, as we would be missatributing the effects of the EU-ETS on German firms as part of the Ecotax effect.

As Calel and Dechezleprêtre (2016) show, the positive effect of EU-ETS on innovation was concentrated in the firms that were directly regulated by it, so that should (partly) mitigate concerns about effect missatribution, as any potential confounding effect of the EU-ETS would be restricted to those firms.

To assess the potential confounding effect produced by the EU-ETS on the results, I re-estimate the Equation 2.1 using 2004 as the final year of the study period – meaning that the dataset used in this test contains data from 1990 to 2004. The results depicted in Table 2.A.14 show similar results to the baseline in Section 2.5, where smaller firms seem to be negatively affected by the introduction of the Ecotax reform in terms of their green energy innovation outcomes (column (5), significant at the 10 % level). The results shown in Table 2.A.21 also agree with the ones of the baseline, showing no evidence of an effect on green transport technologies.

2.6.3 Definition of green patents

Defining when a patent relates to green technologies is not trivial. Although the Y02 tag system was developed to facilitate this endeavor, some issues remain. The first one is that these tags are not given directly by patent examiners while reviewing a patent application, but are given ex-post as the results of an automatic algorithm (Veefkind et al., 2012). Although this algorithm has been developed by expert examiners of the EPO, this means that some level of uncertainty around the automatic classification cannot be avoided. A second challenge relates to the intention of the inventors while developing the invention. Unlike well-defined technology fields such as “Fertiliser” (IPC code C05) or “Musical instruments and acoustics” (IPC code G10), green technologies span multiple technological fields, all aimed at some particular environmental goal, e.g. reducing the greenhouse gas emissions related to energy production (Y02E). This means that a patent might be considered to cover green or low-carbon technologies even when the R&D efforts was not deliberately targeted to achieving an environmental goal. This may rise questions on whether firms and inventors are actively reacting to the new policy, or it is an artifact of how we define what is a green patent.

Here, I extend the definition of what is considered to be a green patent in order to assess these points (see Tables 2.A.3 and 2.A.4 for the list of the extended IPC codes). These extended list includes IPC codes described previously in the literature as being related with green technologies (Aghion et al., 2016; Dechezleprêtre et al., 2015; Johnstone et al., 2010; Popp et al., 2020). By using a list of IPC codes which are assigned during the application procedure, the shortcomings related to the algorithmic nature of the classification can be ignored. As the extended list contains IPC codes closely related to environmental protection – such as “Wind motors” (F03D) or “Fuel cells” (H01M8) –, the questions regarding the intention of the inventors can be addressed.

Tables 2.A.15 and 2.A.22 in the appendix show the results estimating Equation 2.1 with the extended list of IPC codes for green energy and green transport patents, respectively. As these tables indicate, there is no evidence of an effect of the reform on either green energy or transport innovation. The main results are then not robust to the extension of the definition of what is considered to be a green technology patent.

2.6.4 Matching specification

The analysis presented in this study relies on finding credible counterfactuals to the treated German firms. The creation of the donor pool and matching procedure described in Section 2.4 should address some of the concerns related to the validity of the found counterfactuals. However, the decision of which particular specification to use for the matching is not trivial, as different specifications might change which firms compose the final control group. To test whether the results reported in Section 2.5 are robust to different matching specifications or are an artifact of the specific implementation used, I applied the matching algorithm using different specifications. Specifically, I altered the number of neighbors selected, whether the algorithm was allowed to match multiple units to the same counterfactual, and the distance metric used for the matching.

Tables 2.A.16 and 2.A.17 show the results of the analysis when varying the matching specification, by matching each German firm involved in green energy innovation with one neighbor with replacement of the matched firms, and with one neighbor without replacement, respectively. The results depicted in Table 2.A.16 show a decrease in the likelihood of small German firms to file for green energy patents of 57%. On the other hand, Table 2.A.17 shows no evidence of this decrease. Tables 2.A.23 and 2.A.24 present the results of performing a similar matching for German firms involved in green transport innovation, matching them with one foreign firm with and without replacement (respectively). The results displayed in these tables indicate no evidence of an effect of the reform on green transport, similarly to the baseline results of Table 2.3.

In the last years, the use of propensity scores as the standard distance metric used for matching techniques has been challenged (e.g. King and Nielsen, 2019; Ripollone et al., 2018). Mahalanobis distance matching in particular has been discussed as a better matching technique, as it has been found that propensity score matching might increase imbalance across the data (King and Nielsen, 2019). Tables 2.A.18 and 2.A.25 presents the results for green energy and transport (respectively), when using another commonly used metric, the Mahalanobis distance, as the distance metric used for the matching. These tables present similar results to the baseline in Section 2.5, where the Ecotax reforms has a negative effect on the green energy innovation done by small firms, significant at the 10% (Table 2.A.18), while there is no evidence of it having an effect on green transport innovation (Table 2.A.25). These tests show that the results of green technology innovation found in Section 2.5 are robust to different matching implementations, while the results for green energy technologies are robust in two out of the three different specifications tested.

Tables 2.4 and 2.5 provide a summary of the estimates of the heterogeneous effects of the reform on green energy and transport patents, respectively, for clarity. As Table 2.4 shows, there is some suggestive evidence that small firms are negatively affected by the introduction of the reform. This effect is not robust to small variations of the timing of the reform and of the definition of what patents are considered to be related to green energy technologies. On the other hand, Table 2.5 shows no evidence of a significant effect (at the 5% level) on green transport innovation in any of the specifications. Note that none of the different matching specifications tested shows a significant positive effect of the reform on the green innovation. These results will be discussed in the next section in more detail.

		Total patents		Sector of activity	
		Bottom 90%	Top 10%	Manufacturing	Other
	(1)	(2)	(3)	(4)	(5)
Base result	1.07	0.48**	0.99	1.07	1.09
	(0.15)	(-2.31)	(-0.01)	(0.09)	(0.21)
1998-2009	0.90	0.62	0.80	1.28	0.67
	(-0.22)	(-1.42)	(-0.33)	(0.34)	(-0.66)
1995-2009	0.86	0.93	0.65	0.70	1.90
	(-0.36)	(-0.17)	(-0.77)	(-0.75)	(1.55)
EU-ETS 1999-2004	0.91	0.55*	0.73	0.79	1.22
	(-0.13)	(-1.74)	(-0.28)	(-0.23)	(0.42)
Extended IPC list	0.84	0.52	0.74	0.80	0.94
	(-0.39)	(-1.64)	(-0.47)	(-0.30)	(-0.15)
One-to-one matching,	1.18	0.43***	1.39	1.31	1.13
with replacement	(0.62)	(-3.57)	(0.73)	(0.70)	(0.36)
One-to-one matching,	0.92	0.69	0.78	0.78	1.16
without replacement	(-0.20)	(-1.24)	(-0.49)	(-0.43)	(0.40)
Mahalanobis distance	0.85	0.45*	1.00	0.93	0.79
	(-0.40)	(-1.92)	(-0.00)	(-0.09)	(-0.58)

Robust z-statistics in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 2.4 Effect of Ecotax on green energy patents. Summary of coefficient of interest estimated across base results (Section 2.5) and robustness tests (Section 2.6). All regressions include year and firm fixed effects, as well as controls for GDP growth and public R&D investments as a share of the GDP. egression estimated using a Poisson fixed effect model.

		Total patents		Sector of activity	
		Bottom 90%	Top 10%	Manufacturing	Other
	(1)	(2)	(3)	(4)	(5)
Base result	0.76	0.50	0.87	0.70	1.16
	(-0.62)	(-1.20)	(-0.26)	(-0.73)	(0.24)
1998-2009	0.73	1.01	0.55*	0.76	0.77
	(-1.03)	(0.05)	(-1.65)	(-0.83)	(-0.56)
1995-2009	0.69	1.14	0.73	0.61	2.60*
	(-1.08)	(0.38)	(-0.76)	(-1.31)	(1.69)
EU-ETS: 1999-2004	0.82	0.47	1.17	0.74	1.46
	(-0.51)	(-1.37)	(0.38)	(-0.65)	(0.79)
Extended IPC list	0.65	0.37	0.85	0.66	0.53
	(-1.05)	(-1.63)	(-0.43)	(-0.92)	(-1.13)
One-to-one matching,	1.01	0.80	1.11	1.00	1.33
with replacement	(0.03)	(-0.67)	(0.32)	(-0.02)	(0.68)
One-to-one matching,	0.87	0.94	0.71	0.88	1.04
without replacement	(-0.49)	(-0.17)	(-0.86)	(-0.42)	(0.07)
Mahalanobis distance	0.84	0.54	0.88	0.88	0.85
	(-0.49)	(-1.36)	(-0.26)	(-0.32)	(-0.22)

Robust z-statistics in parentheses

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 2.5 Effect of Ecotax on green transport patents. Summary of coefficient of interest estimated across base results (Section 2.5) and robustness tests (Section 2.6). All regressions include year and firm fixed effects, as well as controls for GDP growth and public R&D investments as a share of the GDP. egression estimated using a Poisson fixed effect model.

2.7 Discussion

Looking together at the results of the baseline analysis of Section 2.5 and of the robustness tests of Section 2.6, we can conclude that there is no evidence that the Ecotax reform had any effect on green transport technologies, a result that is consistent across a variety of specifications. The case for energy technologies is less clear, as the baseline results and some of the robustness tests indicate that small firms seem to decrease their filling of green energy patents after the introduction of the reform, while other specifications show no effect. Most importantly, the effects of the reform are not robust to small changes in the timing of the reform (to account for anticipatory effects) and of the inclusion criteria of green energy patents. This should lead us to believe that there is no underlying effect at all, or if there is, its magnitude is so small that minor variations in the data or analysis specifications fail to capture it. We should then conclude that the Ecotax reform did not have a significant effect on green innovation outcomes of firms already involved in green technology R&D.

There are some reasons that could explain why the reform did not induce any change in the green innovation outcome of German firms. First, some of the characteristics of the reform might have undermined its potential incentives to innovate. As presented in Section 2.2, the reform did not include mechanisms to update the tax rate as inflation and rising oil prices decrease the effective tax rate of the reform (OECD, 2012). This would have diminished the potential incentives derived from the tax, as the tax was imposed as an absolute increase in the unit price of electricity (2.1 cents/kWh) and fuel (15.5 cents/liter) (Görres, 2005).

Second, the reform included a number of exceptions that reduced the number of firms directly affected by the price increase. Manufacturers, and especially manufacturing firms with large energy consumption, enjoyed a reduction of 40% and 80% of the tax, respectively (Beuermann and Santarius, 2006; Umwelt Bundesamt, 2011). Many of these firms also enjoyed further rebates on their already reduced tax payments (OECD, 2012). It is important to notice that the nature of the Ecotax reform meant that large firms – who are more likely to have enough resources to undertake new R&D projects (Stucki et al., 2018) and to invest in green technologies (European Investment Bank, 2023) –, and manufacturers – who could benefit directly from the energy and fuel savings –, were shielded from most of the price increase coming from the reform. Two different groups of firms can then be found in respect to their exposure to the tax: those that faced the full tax price (small and non-manufacturing firms) and those that faced a reduced tax (large and manufacturing firms).

On the one hand, there is evidence that small firms tend to be decrease their product innovation outputs when facing new green regulation, as they must allocate their scarce resources to projects that would decrease their energy and/or fuel intensity (process innovation) and the development of new products or services (product innovation) (Stucki et al., 2018). This would explain why small firms did not increase their innovative output when the tax reform was introduced. On the other hand, there is also evidence that energy prices might not have an effect on green patenting when consumers pay the increased energy price and have incomplete information on the energy efficiency of the products they purchase – a classic agent-principal problem (Noailly, 2012). This would explain why large and manufacturing firms did not respond to the reform, as they might not be able to directly recoup the costs of the new R&D projects. This problem would be specially salient if the consumers have incomplete information of the energy and fuel efficiency of the products that they purchase (Noailly, 2012).

Lastly, reconciling these results with previous studies on the green innovation effect of the Ecotax reform (e.g. Basaglia et al., 2023) might prove less challenging than it seems at first. Firstly, note that the results of this study focus on the response at the firm level, not at the aggregate level. Given that innovation activities tend to be concentrated among a selected number of firms, it is plausible that, even if there is no response at the firm level, the responses of a small number of these firms was large enough to drive an observable effect at the national level. Secondly, the constraints of the matching presented in Section 2.4 mean that the results presented in this study only cover firms already established before 1999, and that were also involved in green technology development – a fraction of the total firms involved in green technologies after 1999. This leaves out the potential response of firms established pre-1999 that got involved in green technologies after the reform, and those new firms that might have been founded with the specific goal of developing new green technologies.

2.8 Conclusions

This study investigates the impact the Ecotax reform introduced in Germany in 1999 had on green innovation, and analyses how this effect differs depending on firms' characteristics. By using firm-level patent data and employing a matching difference-in-differences design, I present causal evidence of the effect of this reform on firms, and how this effect could depend on firms' characteristics. I find no evidence that this reform had an effect on green technology innovation performed by German firms previously involved in green patenting, neither on average, nor for firms with different sizes or working on different economic sectors.

The analysis faces some limitations. By focusing on the potential heterogeneous firm effects of the reform, some methodological constraints are not possible to be removed. In particular, this analysis does not allow to evaluate the innovation done by firms founded after the reform was introduced, neither does it enable an estimation of the effect on established firms that might have entered the green innovation market. Furthermore, this analysis focuses on the response at the firm level, so a direct interpretation of the aggregate effects of the reform is not straightforward.

This study raises questions about the role of exceptions to environmental policies. Although they might be aimed at reducing the loss of competitiveness of firms, exceptions can also reduce firms' incentives to innovate. Policy makers designing environmental regulation should try to find the right balance between short term competitiveness losses due to firms facing higher costs, and the incentives to adapt and innovate that would bring long term competitiveness gains. Getting the balance of incentives right will depend on the ultimate goals of the regulation, and on the inclusion of supporting mechanisms, such as recycling of the tax revenue (Andersen and Skou, 2010; Oueslati et al., 2017) or public R&D funding programs for SMEs (Criscuolo and Menon, 2015; Howell, 2017). Policies including these safe-guards may help to better tap into the innovation potential from small firms.

Future research is needed to better understand the distributional effects of environmental regulation on firms, especially when assessing innovation outcomes. Previous studies have established the importance of distributional effects of climate policy at individual level (e.g. Banzhaf et al., 2019) and firm level (e.g. Peñasco et al., 2021). The results of aggregate level outcomes (e.g. aus dem Moore et al., 2022) and of suggestive evidence of self-reports (e.g. European Investment Bank, 2023) should be supplemented with granular analysis of innovation outcomes to understand said distributional effects and individual firm behavior. Studying more stringent environmental policies proven to be effective in inducing green innovation may help shedding some light on the distributional aspects of said effect, and its resulting implications for market concentration.

Acknowledgments

I would like to thank Sofia Badini, Eugenie Dugoua, Marion Dumas, Andreas Lange, and Sebastian Renner, as well as seminar audiences from Hamburg, LSE, and REGIS Summer School 2024 for their helpful feedback. I am grateful to the Faculty of Business Studies and Economics of the University of Bremen for providing me access to the databases Orbis and Orbis IP during my research visit, as well as to Torben Klarl for his kind invitation.

References

Abadie, A. (2005). Semiparametric difference-in-differences estimators. *The Review of Economic Studies*, 72(1):1–19.

Abadie, A. (2021). Using synthetic controls: Feasibility, data requirements, and methodological aspects. *Journal of Economic Literature*, 59(2):391–425.

Abadie, A., Diamond, A., and Hainmueller, J. (2010). Synthetic control methods for comparative case studies: Estimating the effect of Californias tobacco control program. *Journal of the American Statistical Association*, 105(490):493–505.

Abadie, A. and Gardeazabal, J. (2003). The economic costs of conflict: A case study of the Basque Country. *American Economic Review*, 93(1):113–132.

Aghion, P., Dechezleprêtre, A., Hemous, D., Martin, R., and Van Reenen, J. (2016). Carbon taxes, path dependency, and directed technical change: Evidence from the auto industry. *Journal of Political Economy*, 124(1):1–51.

Andersen, P. and Skou, M. (2010). Europes experience with carbon-energy taxation. *SAPI EN. S. Surveys and perspectives integrating environment and society*, (3.2).

Andersson, J. J. (2019). Carbon taxes and CO2 emissions: Sweden as a case study. *American Economic Journal: Economic Policy*, 11(4):1–30.

aus dem Moore, N., Brehm, J., and Gruhl, H. (2022). Driving innovation? Carbon tax effects in the Swedish transport sector. *Working Paper*.

Banzhaf, S., Ma, L., and Timmins, C. (2019). Environmental justice: The economics of race, place, and pollution. *Journal of Economic Perspectives*, 33(1):185–208.

Basaglia, P., Behr, S. M., and Drupp, M. A. (2023). De-Fueling Externalities: Causal Effects of Fuel Taxation and Mediating Mechanisms for Delivering Climate and Health Benefits. *CESifo Working Paper*.

Beuermann, C. and Santarius, T. (2006). Ecological tax reform in Germany: handling two hot potatoes at the same time. *Energy Policy*, 34(8):917–929.

Bosch, X. (2001). Spain opts to fuel health funds with petrol sales. *BMJ*, 323(7324):1271.

Bosquet, B. (2000). Environmental tax reform: Does it work? A survey of the empirical evidence. *Ecological Economics*, 34(1):19–32.

Brunel, C. (2019). Green innovation and green imports: Links between environmental policies, innovation, and production. *Journal of Environmental Management*, 248:109290.

Brunnermeier, S. B. and Cohen, M. A. (2003). Determinants of environmental innovation in US manufacturing industries. *Journal of Environmental Economics and Management*, 45(2):278–293.

Calel, R. (2020). Adopt or innovate: Understanding technological responses to cap-and-trade. *American Economic Journal: Economic Policy*, 12(3):170–201.

Calel, R. and Dechezleprêtre, A. (2016). Environmental policy and directed technological change: evidence from the European carbon market. *Review of Economics and Statistics*, 98(1):173–191.

Conefrey, T., Fitz Gerald, J. D., Valeri, L. M., and Tol, R. S. (2013). The impact of a carbon tax on economic growth and carbon dioxide emissions in Ireland. *Journal of Environmental Planning and Management*, 56(7):934–952.

Costa-Campi, M. T., García-Quevedo, J., and Segarra, A. (2015). Energy efficiency determinants: An empirical analysis of Spanish innovative firms. *Energy Policy*, 83:229–239.

Costantini, V., Crespi, F., and Palma, A. (2017). Characterizing the policy mix and its impact on eco-innovation: A patent analysis of energy-efficient technologies. *Research Policy*, 46(4):799–819.

Criscuolo, C. and Menon, C. (2015). Environmental policies and risk finance in the green sector: Cross-country evidence. *Energy Policy*, 83:38–56.

De Marchi, V. (2012). Environmental innovation and R&D cooperation: Empirical evidence from Spanish manufacturing firms. *Research policy*, 41(3):614–623.

de Rassenfosse, G. and van Pottelsberghe de la Potterie, B. (2009). A policy insight into the R&D–patent relationship. *Research Policy*, 38(5):779–792.

DeCanio, S. J. and Watkins, W. E. (1998). Investment in energy efficiency: Do the characteristics of firms matter? *Review of Economics and Statistics*, 80(1):95–107.

Dechezleprêtre, A., Märtin, R.-P., and Mohnen, M. (2015). Knowledge spillovers from clean and dirty technologies. *Working Paper, Centre for Economic Performance*.

Dehejia, R. H. and Wahba, S. (1999). Causal effects in nonexperimental studies: Reevaluating the evaluation of training programs. *Journal of the American Statistical Association*, 94(448):1053–1062.

Dekker, T., Vollebergh, H. R., de Vries, F. P., and Withagen, C. A. (2012). Inciting protocols. *Journal of Environmental Economics and Management*, 64(1):45–67.

Dugoua, E. (2023). Induced innovation and international environmental agreements: evidence from the ozone regime. *Review of Economics and Statistics*, pages 1–45.

European Commision (2005). EU action against Climate Change: EU emissions trading an open scheme promoting global innovation. `http://bookshop.ec.europa.eu/ent/eu-emissions-trading-an-open-system-promoting-global-innovation-pbKH807426/`.

European Commision (2011). A Roadmap for Moving to a Competitive Low Carbon Economy in 2050. *EU technical report COM 112*.

European Investment Bank (2023). What drives firms investment in climate action? Evidence from the 2022-2023 EIB Investment Survey. *European Investment Bank*.

European Patent Office (2024). PATSTAT Global 2024 - Single Edition (Spring). `https://www.epo.org/en/searching-for-patents/business/patstat`.

Feenstra, R. C., Inklaar, R., and Timmer, M. P. (2015). The next generation of the Penn World Table. *American Economic Review*, 105(10):3150–3182.

Görres, A. (2005). Germanys Ecotax reform 1999-2003: Implementation, impact, future development. *Chairman Green Budget Germany, Berlin, October*, 12.

Griliches, Z. (1998). Patent statistics as economic indicators: a survey. In *R&D and productivity: the econometric evidence*, pages 287–343. University of Chicago Press.

Hagedoorn, J. and Cloodt, M. (2003). Measuring innovative performance: is there an advantage in using multiple indicators? *Research policy*, 32(8):1365–1379.

Haščič, I. (2012). Environmental innovation in Germany.

Haugland, T. (1993). *A Comparison of Carbon Taxes in Selected OECD Countries*. Number 78. Organisation for Economic Co-operation and Development.

Heckman, J. J., Ichimura, H., Smith, J. A., and Todd, P. E. (1998a). Characterizing selection bias using experimental data.

Heckman, J. J., Ichimura, H., and Todd, P. (1998b). Matching as an econometric evaluation estimator. *The review of economic studies*, 65(2):261–294.

Hicks, J. (1932). *The theory of wages*. Macmillan.

Howell, S. T. (2017). Financing innovation: Evidence from R&D grants. *American economic review*, 107(4):1136–1164.

International Energy Agency (2021). Net zero by 2050: A roadmap for the global energy sector.

Jaffe, A. B. and Palmer, K. (1997). Environmental regulation and innovation: a panel data study. *Review of economics and statistics*, 79(4):610–619.

Johnstone, N., Haščič, I., and Popp, D. (2010). Renewable energy policies and technological innovation: evidence based on patent counts. *Environmental and resource economics*, 45:133–155.

Kim, K., Heo, E., and Kim, Y. (2017). Dynamic policy impacts on a technological-change system of renewable energy: an empirical analysis. *Environmental and resource economics*, 66:205–236.

King, G. and Nielsen, R. (2019). Why propensity scores should not be used for matching. *Political analysis*, 27(4):435–454.

Knigge, M. and Görlach, B. (2005). Die Ökologische Steuerreform Auswirkungen auf Umwelt, Beschäftigung und Innovation. *Institut fr Internationale und Europche Umweltpolitik, Berlin.*

Kossoy, A., Peszko, G., Oppermann, K., Prytz, N., Klein, N., Blok, K., Lam, L., Wong, L., and Borkent, B. (2015). *State and trends of carbon pricing 2015.* World Bank Publications.

Lanjouw, J. O. and Mody, A. (1996). Innovation and the international diffusion of environmentally responsive technology. *Research policy*, 25(4):549–571.

Leuwen, E. and Sianesi, B. (2003). PSMATCH2: Stata module to perform full Mahalanobis and propensity score matching, common support graphing, and covariate imbalance testing. `http://ideas.repec.org/c/boc/bocode/s432001.html`. This version 4.0.12.

Newell, R. G., Jaffe, A. B., and Stavins, R. N. (1999). The induced innovation hypothesis and energy-saving technological change. *Quarterly Journal of Economics*, 114(3):941–975.

Noailly, J. (2012). Improving the energy efficiency of buildings: The impact of environmental policy on technological innovation. *Energy Economics*, 34(3):795–806.

OECD (2001). Environmentally related taxes in OECD countries: Issues and strategies. `https://www.oecd-ilibrary.org/environment/environmentally-related-taxes-in-oecd-countries_9789264193659-en`.

OECD (2009). OECD patent statistics manual. *OECD Publishing, France.*

OECD (2012). OECD environmental performance reviews: Germany 2012. *OECD Publishing, France.*

OECD (September 2024). Research and Development Statistics (RDS) Database. https://www.iea.org/data-and-statistics/data-product/energy-technology-rd-and-d-budget-database-2.

Osamu, K. (2012). The role of standards: The Japanese Top Runner Program for end-use efficiency., Chapter 24: Historical case studies of energy technology innovation. *The global energy assessment*.

Oueslati, W., Zipperer, V., Rousselière, D., and Dimitropoulos, A. (2017). Energy taxes, reforms and income inequality: An empirical cross-country analysis. *International Economics*, 150:80–95.

Peñasco, C., Anadón, L. D., and Verdolini, E. (2021). Systematic review of the outcomes and trade-offs of ten types of decarbonization policy instruments. *Nature Climate Change*, 11(3):257–265.

Popp, D. (2003). Pollution control innovations and the Clean Air Act of 1990. *Journal of Policy Analysis and Management*, 22(4):641–660.

Popp, D. (2006). International innovation and diffusion of air pollution control technologies: the effects of NOX and SO2 regulation in the US, Japan, and Germany. *Journal of Environmental Economics and Management*, 51(1):46–71.

Popp, D. (2010). Innovation and climate policy. *Annual Review Resource Economics*, 2(1):275–298.

Popp, D. (2019). Environmental policy and innovation: a decade of research. *NBER Working Paper*.

Popp, D., Pless, J., Hascic, I., and Johnstone, N. (2020). Innovation and entrepreneurship in the energy sector. In *The Role of Innovation and Entrepreneurship in Economic Growth*. University of Chicago Press.

Porter, M. E. and van der Linde, C. (1995). Toward a new conception of the environment-competitiveness relationship. *Journal of economic perspectives*, 9(4):97–118.

Reichardt, K. and Rogge, K. (2016). How the policy mix impacts innovation: Findings from company case studies on offshore wind in Germany. *Environmental Innovation and Societal Transitions*, 18:62–81.

Rennings, K. and Rammer, C. (2009). Increasing energy and resource efficiency through innovation-an explorative analysis using innovation survey data. *ZEW-Centre for European Economic Research Discussion*, (09-056).

Ripollone, J. E., Huybrechts, K. F., Rothman, K. J., Ferguson, R. E., and Franklin, J. M. (2018). Implications of the propensity score matching paradox in pharmacoepidemiology. *American Journal of Epidemiology*, 187(9):1951–1961.

Rogge, K. S., Schleich, J., Haussmann, P., Roser, A., and Reitze, F. (2011). The role of the regulatory framework for innovation activities: the EU ETS and the German paper industry. *International Journal of Technology, Policy and Management*, 11(3-4):250–273.

Schmidt, T. S., Schneider, M., Rogge, K. S., Schuetz, M. J., and Hoffmann, V. H. (2012). The effects of climate policy on the rate and direction of innovation: A survey of the EU ETS and the electricity sector. *Environmental Innovation and Societal Transitions*, 2:23–48.

Smith, J. A. and Todd, P. E. (2005). Does matching overcome LaLonde's critique of nonexperimental estimators? *Journal of econometrics*, 125(1-2):305–353.

Sterner, T. (2012). *Fuel taxes and the poor: the distributional effects of gasoline taxation and their implications for climate policy.* Taylor & Francis.

Stuart, E. A., Huskamp, H. A., Duckworth, K., Simmons, J., Song, Z., Chernew, M. E., and Barry, C. L. (2014). Using propensity scores in difference-in-differences models to estimate the effects of a policy change. *Health Services and Outcomes Research Methodology*, 14:166–182.

Stucki, T., Woerter, M., Arvanitis, S., Peneder, M., and Rammer, C. (2018). How different policy instruments affect green product innovation: A differentiated perspective. *Energy Policy*, 114:245–261.

Umwelt Bundesamt (2011). *Environmentally Harmful Subsidies in Germany - Update 2010.* Umwelt Bundesamt, Dessau-Roau.

Veefkind, V., Hurtado-Albir, J., Angelucci, S., Karachalios, K., and Thumm, N. (2012). A new EPO classification scheme for climate change mitigation technologies. *World Patent Information*, 34(2):106–111.

Veugelers, R. (2012). Which policy instruments to induce clean innovating? *Research policy*, 41(10):1770–1778.

Zhang, L., Cao, C., Tang, F., He, J., and Li, D. (2019). Does Chinas emissions trading system foster corporate green innovation? Evidence from regulating listed companies. *Technology Analysis & Strategic Management*, 31(2):199–212.

Appendices

Appendix 2.A: Matching

The matches between German and foreign firms were found by using the `psmatch2` function from STATA developed by Leuwen and Sianesi (2003). The matching was performed using the k-nearest neighbor method to find up to two similar foreign firms to each German firm, in order to improve the chances of finding a similar counterfactual. The distance metric used for calculating the similarity between firms was the propensity score. The matching was performed so a given German firm could only be matched to firms working on the same economic sector. A caliper of 0.01 was chosen in order to allow a good balance between the likeliness of finding a suitable match while not allowing too dissimilar matches to be found.

The covariates used for the matching were the following. For the economic sector, the 2-digits level NACE Rev. 2 code was used (to illustrate, some examples of these sectors include “Manufacture of electrical equipment”, “Manufacture of motor vehicles, trailers and semi-trailers” or “Scientific research and development”). For the company’s age, the algorithm matched directly on the year of incorporation. For the green patent record, the total number of green patents filed by a firm in the period 1990-1998 was used. The algorithm also matched firms in respect to their total number of patents granted in the period 1990-1998.

One caveat of the data gathering process is that while the green patent data comes from PATSTAT, the total number of patents of a firm comes from Orbis IP. Due to Orbis IP not having information about priority of patents, the total number of patents likely suffers from double-counting of a given technological advancement due to it being protected by more than one patent. Although not ideal, this should not translate to a problem during the matching procedure, as companies of a similar size should be similarly likely to seek protection abroad or apply for daughter patents from a parent one (among others patenting behaviors that would entail double counting). This would tend to equalize the double-counting of patents for firms with a similar size, what should minimize any bias stemming from this problem.

Before the matching was performed, four non-German firms were dropped from the dataset, as their green patent behavior post-1999 differed greatly from the rest. Three of them filled for a disproportionate number of green patents in the period post-1999 compared to the rest of the studied firms. The last outlier increased its fillings from fewer than 10 patents per year in the post-1999 period to 129 in a single year.

Appendix 2.B: Tables

Patent code	Description
Y02B 10	Integration of renewable energy sources in buildings
Y02E 10	Energy generation through renewable energy sources
Y02E 20	Combustion technologies with mitigation potential
Y02E 40	Technologies for an efficient electrical power generation, transmission or distribution
Y02E 50	Technologies for the production of fuel of non-fossil origin
Y02E 60	Enabling technologies; Technologies with a potential or indirect contribution to GHG emissions mitigation
Y02E 70	Other energy conversion or management systems reducing GHG emissions

Table 2.A.1 Green energy patents categories (EPO's Y02 class).

Patent code	Description
Y02T 10	Road transport of goods or passengers
Y02T 90	Enabling technologies or technologies with a potential or indirect contribution to GHG emissions mitigation

Table 2.A.2 Green transport patents categories (EPO's Y02 class).

Patent code	Description
E02B 9/08	Tide or wave power plant
E04D 13/18	Aspects of roofing for energy collecting devices - e.g. incl. solar panels
F03B 13	Submerged units incorporating electric generators or motors or characterised by using wave or tide energy
F03D	Wind motors
F03G 4	Devices for producing mechanical power from geothermal energy
F03G 6	Devices for producing mechanical power from solar energy
F03G 7/04-05	Ocean thermal energy conversion
F24J 2	Use of solar heat, e.g. solar heat collectors
F24J 3/08	Other production or use of heat, not derived from combustion
F26B 3/28, 30	Drying solid materials or objects by processes involving the application of heat by radiation, e.g. from the sun
H01L 27/142	Devices consisting of a plurality of semiconductor or other solid-state components formed in or on a common substrate - especially energy conversion devices
H01L 31/04-07	Semiconductor devices sensitive to infrared radiation, light adapted as photovoltaic [PV] conversion devices
H02N 6	Generators in which light radiation is directly converted into electrical energy

Table 2.A.3 Green energy patents categories (Extended IPC codes). These codes come from Johnstone et al. (2010), Dechezleprêtre et al. (2015), Aghion et al. (2016) and Popp et al. (2020).

Patent code	Description
B60K 1	Arrangement or mounting of electrical propulsion units
B60K 6	Arrangement or mounting of plural diverse prime-movers for mutual or common propulsion, e.g. hybrid propulsion systems comprising electric motors and internal combustion engines
B60L 3	Electric devices on electrically-propelled vehicles for safety purposes; Monitoring operating variables, e.g. speed, deceleration or energy consumption
B60L 7	Electrodynamic brake systems for vehicles in general
B60L 11	Electric propulsion with power supplied within the vehicle
B60L 15	Methods, circuits, or devices for controlling the traction-motor speed of electrically-propelled vehicles
B60R 16	Electric or fluid circuits specially adapted for vehicles and not otherwise provided for
B60S 5/06	Supplying batteries to, or removing batteries from, vehicles (exchanging batteries for electric propulsion of vehicles)
B60W 10/08, 24-28	Conjoint control of vehicle sub-units of different type or different function / including control of electric propulsion units, e.g. motors or generators / including control of energy storage means
B60W 20	Control systems specially adapted for hybrid vehicles
F02B 47/06	Methods of operating engines involving adding non-fuel substances or anti-knock agents to combustion air, fuel, or fuel-air mixtures of engines; the substances including non-airborne oxygen
F02D 41	Electrical control of supply of combustible mixture or its constituents
F02M 3/02-05	Idling devices for carburetors (with means for facilitating engine's idling below operational temperatures)
F02M 23	Apparatus for adding secondary air to fuel-air mixture
F02M 25	Engine-pertinent apparatus for adding non-fuel substances or small quantities of secondary fuel to combustion-air, main fuel or fuel-air mixture.
F02M 39	Arrangements of fuel-injection apparatus with respect to engines; Pump drives adapted to such arrangements
H01M 8	Fuel cells; Manufacture thereof

Table 2.A.4 Green transport patents categories (extended IPC codes list). These codes come from Johnstone et al. (2010), Dechezleprêtre et al. (2015), Aghion et al. (2016) and Popp et al. (2020).

Countries included
Australia, Canada, Chile, Colombia, Czech Republic, Estonia, France, Greece, Hungary, Iceland, Israel, South Korea, Latvia, Lithuania, Luxembourg, Mexico, New Zealand, Poland, Portugal, Slovakia, Slovenia, Switzerland, Türkiye and Unites States.

Table 2.A.5 Countries included in the donor pool.

NACE Section	Description	German	Foreign
C	Manufacturing	240	315
D	Electricity, gas, steam and air conditioning supply	12	16
E	Water supply; sewerage, waste management and remediation activities	2	1
F	Construction	11	17
G	Wholesale and retail trade; repair of motor vehicles and motorcycles	42	49
H	Transportation and storage	3	5
J	Information and communication	4	6
K	Financial and insurance activities	12	20
H	Real estate activities	8	9
M	Professional, scientific and technical activities	76	85
N	Administrative and support service activities	5	6
Q	Human health and social work activities	1	2
S	Other service activities	2	3
Total	-	418	534

Table 2.A.6 NACE Rev. 2 main section of matched German and foreign firms (at the 1-digit level) (energy).

NACE Section	Description	German	Foreign
C	Manufacturing	142	186
D	Electricity, gas, steam and air conditioning supply	5	9
E	Water supply; sewerage, waste management and remediation activities	1	2
F	Construction	3	5
G	Wholesale and retail trade; repair of motor vehicles and motorcycles	29	38
H	Transportation and storage	1	2
J	Information and communication	2	4
K	Financial and insurance activities	9	16
H	Real estate activities	2	4
M	Professional, scientific and technical activities	53	72
N	Administrative and support service activities	3	4
Q	Human health and social work activities	1	2
S	Other service activities	4	3
Total	-	255	347

Table 2.A.7 NACE Rev. 2 main section of matched German and foreign firms (at the 1-digit level) (transport).

Countries	Matched firms	Share (%)
Australia	4	0.7
Canada	12	2.2
Czech Republic	7	1.3
France	63	11.8
Greece	1	0.2
Hungary	11	2.1
Israel	8	1.5
South Korea	71	13.3
Luxembourg	4	0.7
Mexico	1	0.2
New Zealand	1	0.2
Poland	4	0.7
Slovenia	2	0.4
Switzerland	21	3.9
USA	324	60.7
Total	534	100.0

Table 2.A.8 Origin of matched foreign firms (energy).

Countries	Matched firms	Share (%)
Australia	3	0.9
Canada	7	2.0
Czech Republic	2	0.6
France	42	12.1
Hungary	6	1.7
Israel	2	0.6
South Korea	37	10.7
Lithuania	1	0.3
Luxembourg	1	0.3
Mexico	2	0.6
Poland	2	0.6
Switzerland	21	6.1
USA	221	63.7
Total	347	100.0

Table 2.A.9 Origin of matched foreign firms (transport).

	Bottom 80 %	Top 20 %	Bottom 60%	Top 40%
	(1)	(2)	(3)	(4)
$Ecotax$	0.50**	1.07	0.38**	0.98
	(-2.16)	(0.10)	(-2.29)	(-0.04)
$GDPgrowth_{t-1}$	0.99	1.00	0.97	1.00
	(-0.36)	(0.15)	(-0.74)	(0.18)
$log(EnergyRDD)_{t-1}$	1.39	2.19	1.45	2.20*
	(1.34)	(1.59)	(1.17)	(1.79)
Year FE	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Observations	9,276	2,697	6,854	5,119
Firms	624	175	466	333

Table 2.A.10 Heterogeneous effects of the Ecotax depending on firms' total patent portfolio size during 1990-1998 period. The outcome variable is the number of green energy patents filled by a firm i during year t. Regression estimated using a Poisson fixed effect model.

	Bottom 80 %	Top 20 %	Bottom 60%	Top 40%
	(1)	(2)	(3)	(4)
$Ecotax$	1.26	0.64	0.89	0.69
	(0.36)	(-0.83)	(-0.20)	(-0.78)
$GDPgrowth_{t-1}$	1.00	0.94	1.05	0.95
	(0.02)	(-1.34)	(0.95)	(-1.21)
$log(TransportRDD)_{t-1}$	0.66	0.73	1.08	0.67
	(-0.94)	(-0.68)	(0.18)	(-0.86)
Year FE	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Observations	6,337	1,839	4,612	3,564
Firms	423	114	311	226

Table 2.A.11 Heterogeneous effects of the Ecotax depending on firms' total patent portfolio size during 1990-1998 period. The outcome variable is the number of green transport patents filled by a firm i during year t. Regression estimated using a Poisson fixed effect model.

Appendix 2.C: Robustness checks

Appendix 2.C.1:Robustness of energy results

			Total patents		Sector of activity	
			Bottom 90%	Top 10%	Manufacturing	Other
	(1)	(2)	(3)	(4)	(5)	(6)
$Ecotax$	1.35	0.90	0.62	0.80	1.28	0.67
	(0.73)	(-0.22)	(-1.42)	(-0.33)	(0.34)	(-0.66)
$GDPgrowth_{t-1}$		0.98	0.91**	0.99	0.99	0.96
		(-0.70)	(-2.14)	(-0.20)	(-0.32)	(-0.75)
$log(EnergyRDD)_{t-1}$		2.49**	1.99*	1.72	1.59	3.83***
		(2.36)	(1.85)	(1.37)	(0.72)	(2.61)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	13,763	10,826	9,591	1,235	6,417	4,409
Firms	842	697	620	77	414	283

Robust z-statistics in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 2.A.12 Results for using 1998 as alternative starting year of reform – year of the election of the governing coalition that introduced the Ecotax. The outcome variable is the number of green energy patents filled by a firm i during year t. Regression estimated using a Poisson fixed effect model.

			Total patents		Sector of activity	
			Bottom 90%	Top 10%	Manufacturing	Other
	(1)	(2)	(3)	(4)	(5)	(6)
$Ecotax$	0.60	0.86	0.93	0.65	0.70	1.90
	(-1.51)	(-0.36)	(-0.17)	(-0.77)	(-0.75)	(1.55)
$GDPgrowth_{t-1}$		0.99	0.98	0.98	0.99	1.04
		(-0.40)	(-0.35)	(-0.89)	(-0.60)	(1.44)
$log(EnergyRDD)_{t-1}$		1.58	2.05**	1.19	1.33	2.41***
		(1.45)	(1.98)	(0.61)	(0.54)	(4.01)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	8,542	6,392	5,631	761	3,989	2,403
Firms	476	380	334	46	235	145

Robust z-statistics in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 2.A.13 Results for using 1995 as alternative starting year of reform – year when the political discussion about the Ecotax starts getting traction (Beuermann and Santarius, 2006). The outcome variable is the number of green energy patents filled by a firm i during year t. Regression estimated using a Poisson fixed effect model.

			Total patents		Sector of activity	
			Bottom 90%	Top 10%	Manufacturing	Other
	(1)	(2)	(3)	(4)	(5)	(6)
$Ecotax$	1.43	0.91	0.55*	0.73	0.79	1.22
	(0.87)	(-0.13)	(-1.74)	(-0.28)	(-0.23)	(0.42)
$GDPgrowth_{t-1}$		0.97	0.99	0.96	0.98	0.96
		(-1.00)	(-0.29)	(-0.54)	(-0.60)	(-0.80)
$log(EnergyRDD)_{t-1}$		1.71	1.38	2.56	1.64	1.66
		(0.74)	(0.91)	(0.81)	(0.46)	(0.99)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	10,252	7,892	6,940	952	4,677	3,215
Firms	952	788	700	88	469	319

Robust z-statistics in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 2.A.14 Results for using 2004 as alternative end year – the EU-ETS was introduced in 2005. The outcome variable is the number of green energy patents filled by a firm i during year t. Regression estimated using a Poisson fixed effect model.

			Total patents		Sector of activity	
			Bottom 90%	Top 10%	Manufacturing	Other
	(1)	(2)	(3)	(4)	(5)	(6)
$Ecotax$	0.71	0.84	0.52	0.74	0.80	0.94
	(-0.86)	(-0.39)	(-1.64)	(-0.47)	(-0.30)	(-0.15)
$GDPgrowth_{t-1}$		0.99	0.96	1.01	1.01	0.98
		(-0.27)	(-1.22)	(0.22)	(0.22)	(-0.70)
$log(EnergyRDD)_{t-1}$		2.18**	2.65**	1.64	2.05	2.30***
		(2.25)	(2.04)	(1.35)	(1.02)	(2.68)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	15,247	12,333	10,925	1,408	7,258	5,075
Firms	971	826	734	92	486	340

Robust z-statistics in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 2.A.15 Results for extended list of IPC codes from Table 2.A.3. The outcome variable is the number of green energy patents filled by a firm i during year t. Regression estimated using a Poisson fixed effect model.

			Total patents		Sector of activity	
			Bottom 90%	Top 10%	Manufacturing	Other
	(1)	(2)	(3)	(4)	(5)	(6)
$Ecotax$	1.75**	1.18	0.43***	1.39	1.31	1.13
	(2.31)	(0.62)	(-3.57)	(0.73)	(0.70)	(0.36)
$GDPgrowth_{t-1}$		1.00	0.98	0.99	0.98	1.01
		(-0.14)	(-0.75)	(-0.36)	(-0.70)	(0.17)
$log(EnergyRDD)_{t-1}$		1.31	1.46**	1.49	0.92	1.86**
		(1.43)	(2.28)	(1.17)	(-0.28)	(2.52)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	11,596	9,439	8,348	1,091	5,557	3,882
Firms	736	626	558	68	370	256

Robust z-statistics in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 2.A.16 Results using an alternative matching specification – matching each German firm to a foreign firm, allowing for replacement. The outcome variable is the number of green energy patents filled by a firm i during year t. The estimation include a full set of year dummies. Regression estimated using a Poisson fixed effect model.

			Total patents		Sector of activity	
			Bottom 90%	Top 10%	Manufacturing	Other
	(1)	(2)	(3)	(4)	(5)	(6)
$Ecotax$	1.53	0.92	0.69	0.78	0.78	1.16
	(1.34)	(-0.20)	(-1.24)	(-0.49)	(-0.43)	(0.40)
$GDPgrowth_{t-1}$		1.00	0.97	1.00	0.99	1.00
		(-0.13)	(-0.91)	(0.05)	(-0.24)	(-0.15)
$log(EnergyRDD)_{t-1}$		1.86*	1.12	2.25**	2.06	1.59**
		(1.85)	(0.50)	(2.25)	(1.42)	(2.21)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	12,383	9,915	8,768	1,147	5,798	4,117
Firms	786	659	586	73	386	273

Robust z-statistics in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 2.A.17 Results using an alternative matching specification – matching each German firm to a foreign firm, without replacement. The outcome variable is the number of green energy patents filled by a firm i during year t. The estimation include a full set of year dummies. Regression estimated using a Poisson fixed effect model.

			Total patents		Sector of activity	
			Bottom 90%	Top 10%	Manufacturing	Other
	(1)	(2)	(3)	(4)	(5)	(6)
$Ecotax$	1.03	0.85	0.45*	1.00	0.93	0.79
	(0.07)	(-0.40)	(-1.92)	(-0.00)	(-0.09)	(-0.58)
$GDPgrowth_{t-1}$		1.01	1.02	0.97	1.01	1.02
		(0.34)	(0.20)	(-0.89)	(0.29)	(0.26)
$log(EnergyRDD)_{t-1}$		2.86***	2.83***	3.07**	2.47	3.22***
		(3.20)	(2.80)	(2.10)	(1.34)	(4.35)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	14,484	11,455	10,101	1,354	6,602	4,853
Firms	922	766	682	84	441	325

Robust z-statistics in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 2.A.18 Results using an alternative matching specification – using Mahalanobis distance for finding matches. The outcome variable is the number of green energy patents filled by a firm i during year t. The estimation include a full set of year dummies. Regression estimated using a Poisson fixed effect model.

Appendix 2.C.2: Robustness of transport results

			Total patents		Sector of activity	
			Bottom 90%	Top 10%	Manufacturing	Other
	(1)	(2)	(3)	(4)	(5)	(6)
$Ecotax$	0.71	0.73	1.01	0.55*	0.76	0.77
	(-1.13)	(-1.03)	(0.05)	(-1.65)	(-0.83)	(-0.56)
$GDPgrowth_{t-1}$		1.00	1.03	0.98	1.01	1.00
		(0.08)	(0.64)	(-0.52)	(0.31)	(-0.02)
$log(TransportRDD)_{t-1}$		0.94	1.14	0.84	0.80*	1.25
		(-0.40)	(0.45)	(-1.01)	(-1.80)	(1.24)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	8,570	7,190	6,378	812	4,248	2,942
Firms	515	455	407	48	264	191

Robust z-statistics in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 2.A.19 Results for using 1998 as alternative starting year – year of the election of the governing coalition that introduced the Ecotax. The outcome variable is the number of green transport patents filled by a firm i during year t. Regression estimated using a Poisson fixed effect model.

			Total patents		Sector of activity	
			Bottom 90%	Top 10%	Manufacturing	Other
	(1)	(2)	(3)	(4)	(5)	(6)
Ecotax	0.66	0.69	1.14	0.73	0.61	2.60*
	(-1.12)	(-1.08)	(0.38)	(-0.76)	(-1.31)	(1.69)
$GDPgrowth_{t-1}$		1.01	1.01	1.00	1.02	0.99
		(0.57)	(0.23)	(0.03)	(1.11)	(-0.13)
$log(TransportRDD)_{t-1}$		0.71***	0.42*	0.79**	0.72***	0.81
		(-3.52)	(-1.66)	(-1.99)	(-3.79)	(-0.26)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	5,129	4,073	3,625	448	2,650	1,423
Firms	282	238	212	26	154	84

Robust z-statistics in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 2.A.20 Results for using 1995 as alternative starting year – year when the political discussion about the Ecotax starts getting traction (Beuermann and Santarius, 2006). The outcome variable is the number of green transport patents filled by a firm i during year t. Regression estimated using a Poisson fixed effect model.

			Total patents		Sector of activity	
			Bottom 90%	Top 10%	Manufacturing	Other
	(1)	(2)	(3)	(4)	(5)	(6)
Ecotax	0.93	0.82	0.47	1.17	0.74	1.46
	(-0.20)	(-0.51)	(-1.37)	(0.38)	(-0.65)	(0.79)
$GDPgrowth_{t-1}$		0.97	0.95	1.02	0.99	0.94
		(-0.86)	(-1.27)	(0.42)	(-0.31)	(-1.50)
$log(TransportRDD)_{t-1}$		0.71	0.90	0.47	0.57	1.18
		(-0.62)	(-0.19)	(-0.68)	(-0.76)	(0.27)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	6,637	5,472	4,836	636	3,022	2,450
Firms	602	533	476	57	290	243

Robust z-statistics in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 2.A.21 Results for using 2004 as alternative end year – the EU-ETS was introduced in 2005. The outcome variable is the number of green transport patents filled by a firm i during year t. Regression estimated using a Poisson fixed effect model.

			Total patents		Sector of activity	
			Bottom 90%	Top 10%	Manufacturing	Other
	(1)	(2)	(3)	(4)	(5)	(6)
$Ecotax$	0.64	0.65	0.37	0.85	0.66	0.53
	(-1.27)	(-1.05)	(-1.63)	(-0.43)	(-0.92)	(-1.13)
$GDPgrowth_{t-1}$		0.94***	0.93**	0.96	0.96*	0.92**
		(-2.61)	(-2.35)	(-1.11)	(-1.65)	(-2.20)
$log(TransportRDD)_{t-1}$		0.92	0.79	1.10	0.82	1.05
		(-0.46)	(-1.26)	(0.38)	(-0.92)	(0.20)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	12,998	10,934	9,651	1,283	6,479	4,455
Firms	816	723	645	78	423	300

Robust z-statistics in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 2.A.22 Results for extended list of IPC codes from Table 2.A.4. The outcome variable is the number of green transport patents filled by a firm i during year t. Regression estimated using a Poisson fixed effect model.

			Total patents		Sector of activity	
			Bottom 90%	Top 10%	Manufacturing	Other
	(1)	(2)	(3)	(4)	(5)	(6)
$Ecotax$	0.91	1.01	0.80	1.11	1.00	1.33
	(-0.37)	(0.03)	(-0.67)	(0.32)	(-0.02)	(0.68)
$GDPgrowth_{t-1}$		1.00	1.02	1.02	1.03	0.93*
		(0.21)	(0.59)	(0.52)	(1.47)	(-1.82)
$log(TransportRDD)_{t-1}$		0.54**	0.69	0.30**	0.44**	0.81
		(-2.42)	(-1.47)	(-2.24)	(-2.38)	(-0.85)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	7,329	6,314	5,625	689	3,503	2,811
Firms	459	415	372	43	227	188

Robust z-statistics in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 2.A.23 Results using an alternative matching specification – matching each German firm to a foreign firm, allowing for replacement. The outcome variable is the number of green transport patents filled by a firm i during year t. The estimation include a full set of year dummies. Regression estimated using a Poisson fixed effect model.

			Total patents		Sector of activity	
			Bottom 90%	Top 10%	Manufacturing	Other
	(1)	(2)	(3)	(4)	(5)	(6)
$Ecotax$	1.00	0.87	0.94	0.71	0.88	1.04
	(-0.02)	(-0.49)	(-0.17)	(-0.86)	(-0.42)	(0.07)
$GDPgrowth_{t-1}$		0.98	1.02	0.96	1.03	0.90***
		(-0.87)	(0.55)	(-1.27)	(1.13)	(-2.92)
$log(TransportRDD)_{t-1}$		1.00	0.73	1.09	0.73	1.22
		(0.02)	(-1.12)	(0.36)	(-0.84)	(0.97)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	7,925	6,809	6,053	756	3,868	2,941
Firms	494	446	399	47	250	196

Robust z-statistics in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 2.A.24 Results using an alternative matching specification – matching each German firm to a foreign firm, without replacement. The outcome variable is the number of green transport patents filled by a firm i during year t. The estimation include a full set of year dummies. Regression estimated using a Poisson fixed effect model.

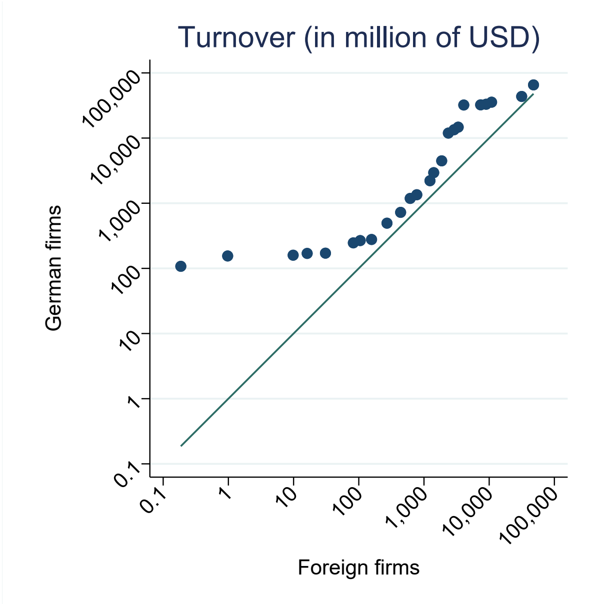
			Total patents		Sector of activity	
			Bottom 90%	Top 10%	Manufacturing	Other
	(1)	(2)	(3)	(4)	(5)	(6)
$Ecotax$	0.75	0.84	0.54	0.88	0.88	0.85
	(-0.89)	(-0.49)	(-1.36)	(-0.26)	(-0.32)	(-0.22)
$GDPgrowth_{t-1}$		0.98	1.02	0.97	0.98	1.03
		(-0.53)	(0.62)	(-0.68)	(-0.58)	(0.40)
$log(TransportRDD)_{t-1}$		0.88	0.87	0.88	0.83	0.95
		(-0.57)	(-0.44)	(-0.57)	(-0.92)	(-0.12)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	8,586	7,343	6,475	868	4,278	3,065
Firms	538	482	429	53	275	207

Robust z-statistics in parentheses

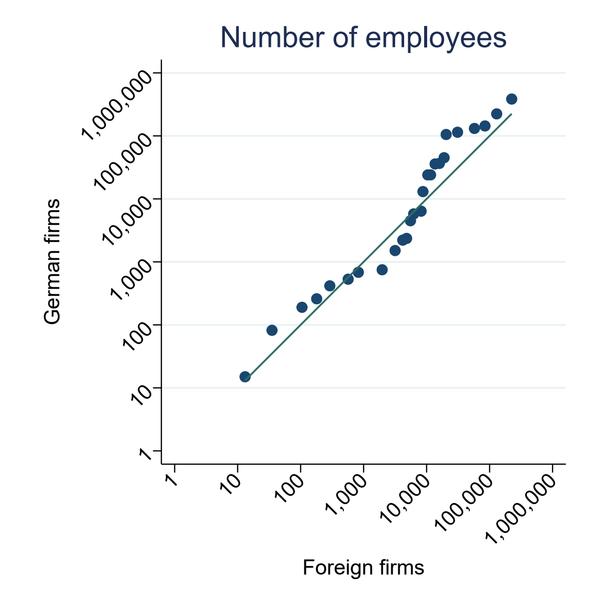
*** p<0.01, ** p<0.05, * p<0.1

Table 2.A.25 Results using an alternative matching specification – using Mahalanobis distance for finding matches. The outcome variable is the number of green transport patents filled by a firm i during year t. The estimation include a full set of year dummies. Regression estimated using a Poisson fixed effect model.

Appendix 2.D: Figures

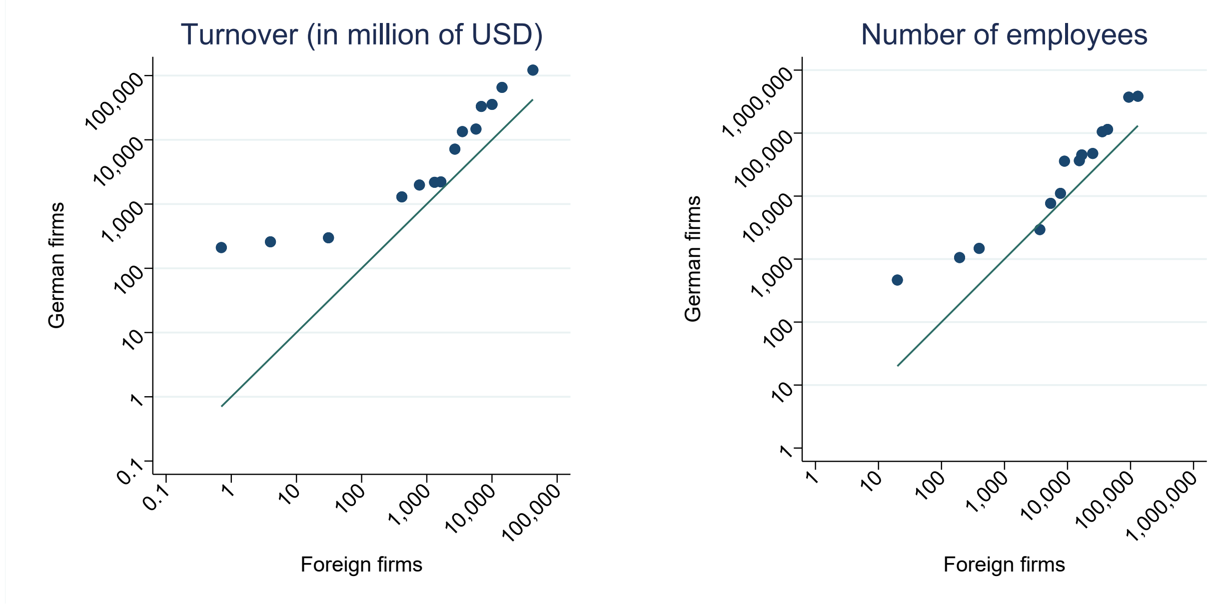


(a)



(b)

Figure 2.A.1 Comparison of unobservable variables among matched German and foreign firms working on green energy innovation. Panel (a) shows the empirical quantile-quantile plot (e-QQ plot) for the average turnover between 1995-1998, in logarithmic scale. Each dot represents a quantile of the distribution of the average turnover among German firms and non-German firms. Panel (b) shows the e-QQ plot for average number of employees between 1995-1998, in logarithmic scale.



(a) (b)

Figure 2.A.2 Comparison of unobservable variables among matched German and foreign firms working on green transport innovation. Panel (a) shows the empirical quantile-quantile plot (e-QQ plot) for the average turnover between 1995-1998, in logarithmic scale. Each dot represents a quantile of the distribution of the average turnover among German firms and non-German firms. Panel (b) shows the e-QQ plot for average number of employees between 1995-1998, in logarithmic scale.

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
06 October 2022 (06.10.2022)

WIPO | PCT

(10) International Publication Number
WO 2022/212829 A1

(51) International Patent Classification:
B29C 70/44 (2006.01) *B29C 70/54* (2006.01)
B29C 70/46 (2006.01) *B29D 99/00* (2010.01)
B29C 70/48 (2006.01)

(21) International Application Number: PCT/US2022/023031

(22) International Filing Date: 01 April 2022 (01.04.2022)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
63/170,120 02 April 2021 (02.04.2021) US

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(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, IT, JM, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK,

(54) Title: SYSTEMS AND METHODS FOR MANUFACTURING ROTOR BLADES

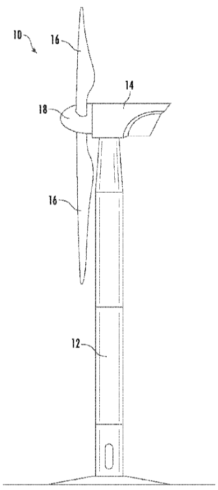


FIG. 1

(57) **Abstract:** A method for manufacturing an article includes providing a plurality of flat sheets of fiber-reinforced polymer material (102). The method also includes forming the plurality of flat sheets of the fiber-reinforced polymer material into a plurality of curved sheets of the fiber- reinforced polymer material (104). Further, the method includes assembling the plurality of curved sheets of the fiber-reinforced polymer material in a tooling device to form an outer shape of the article (106). Moreover, the method includes securing each of the plurality of curved sheets of the fiber- re info reed polymer material together to form the article (108).

WO 2022/212829 A1

[Continued on next page]

Figure 2.A.3 Example of the first page of a patent document. This particular patent was filled by a Danish company in 2022, and protects an invention related to electricity production through wind energy (CPC code Y02E10/72).

Chapter 3

Weakest links in space: on the voluntary provision of public goods in overlapping neighborhoods

Authors: Andreas Lange, and Lorenzo Romero-Fernández

Abstract

We report laboratory evidence on the voluntary provision of weakest-link public goods in a novel spatial setting. Subjects are located on a circle and interact in overlapping neighborhoods. We investigate how endowment heterogeneity and the spatial distribution of endowments affect the final provision of the public good. We find that the detrimental effects of endowment heterogeneity arise specifically when endowment types are clustered, but not when high and low types alternate. In all settings, players provide in-kind transfers only within their own neighborhood. Replacing direct transfers by an intermediary common account to overcome transfer coordination does not improve average weakest links public good provision, but can decrease inequality depending on the spatial clustering of endowments in space.

JEL classification: C91, H41, Q50
Keywords: public goods, overlapping neighborhoods, network, weakest-link, coordination, experiment

3.1 Introduction

The provision of public goods notoriously suffers from free-riding incentives. A large literature has evolved to study voluntary contributions and individual behavioral motivations (e.g., Zelmer, 2003). The largest part of the experimental literature has thereby focused on setting where the level of public good provision (i) depends on the sum of individual contributions and (ii) all players benefit from the public good. Yet, many “real-world” examples do not fit this description. Rather, it matters where public goods are provided as individual beneficiaries are typically spatially distributed, i.e. live in different locations and most public goods have some local features. Additionally, the provision of public goods may be governed by a different aggregation technology.

Prominently, the weakest-link technology has been discussed where the minimum contribution affects the provision of the public good (e.g., Hirshleifer, 1983; Vicary and Sandler, 2002; Barrett, 2016; Caparrós and Finus, 2020a,b). The recent COVID-19 pandemic has rekindled the interest in weakest-link global public good provision such as illness eradication, a topic that has been long studied for the cases of smallpox and polio (e.g Barrett, 2003, 2007).[1] Yet, the weakest link structure is vulnerable to heterogeneities of capacities to contribute to the public good.[2]

Inspired by these examples, this study provides experimental evidence on voluntary public good provision in a spatially differentiated setting. Specifically, we consider an overlapping neighborhood setting where players’ returns from the public good depend on investments in their own and their neighbors’ locations. We investigate voluntary provision in a weakest-link setting and focus on the role of endowment heterogeneity.

We trust that our study breaks novel ground: first, while the weakest-link technology has been linked to important applications like protecting against terrorism, fighting contagious diseases, or crime prevention (e.g., Hirshleifer, 1983; Vicary and Sandler, 2002; Barrett, 2016; Caparrós and Finus, 2020a,b), the literature largely ignores the spatial element,

[1] For general insights into pandemics, see Hays (2005). In general, illness eradication is a paradigmatic case of study for weakest-link global public goods (Barrett, 2009). While the economic benefits of eradicating illnesses such as smallpox, polio or measles compared to a control approach out-weigh its initial costs (Thompson and Tebbens, 2007; Barrett, 2013), the only human sickness that has been eradicated is smallpox (Henderson, 1987; Barrett, 2007), with polio being the current target of global eradication efforts (Barrett, 2003). Preference heterogeneity clearly affects the prospects of fighting such diseases. A large literature investigates the heterogeneity in preferences for vaccination (e.g., Lo and Hotez, 2017; Feemster and Szipszky, 2020; Borriello et al., 2021) and how those are shaped by peer effects (e.g., Rao et al., 2007).

[2] For example, the WHO plan for the eradication of smallpox proposed that countries suffering from endemic smallpox should pay for about 70 percent of the total expenditure required for the eradication, while international assistance would finance the remaining 30 percent, distributed by the WHO. This international assistance would consist mostly on supplying the vaccine and providing technical expertise (Barrett, 2007).

i.e. that lacking prevention measures in one location may primarily affect well-being in nearby locations and not necessarily (or only with a temporal lag) in locations at a larger distance.

Second, our paper relates to a theoretical literature on voluntary contributions to public goods in networks (e.g., Bramoullé and Kranton, 2007; Allouch, 2015) which has been experimentally tested only for public goods with summation games and homogeneous agents (e.g., Cassar, 2007; Kirchkamp and Nagel, 2007; Rosenkranz and Weitzel, 2012; Angelovski et al., 2018a,b). Specifically, we consider a spatial setting where individuals are located around a circle, thus representing a specific network structure that can be extended to different real-world scenarios. All players can make investments in all locations, and their return from the public good depends on the minimum of total investments in their own neighborhood, i.e. the weakest-link of themselves and their two direct neighbors. A similar circular, overlapping structure has been tested before (e.g. Boosey, 2017; Gallo and Yan, 2023; Zhang and He, 2021), but they all use the summation technology. We are unaware of other studies that consider such overlapping neighborhood setting with a weakest link aggregation technology in public good provision.

Third, we investigate the role of endowment heterogeneity within this spatial context. While studies focusing on summation technology have found mixed effects of such heterogeneity on public good contributions (e.g., Cherry et al., 2005; Buckley and Croson, 2006; Hofmeyr et al., 2007; Anderson et al., 2008), endowment differences can be expected to be more crucial in the weakest-link setting: if a player has a smaller income, she cannot contribute sufficiently in her own location. As such, high endowment players need to transfer (in-kind) to other locations in order to strengthen the weakest-link and be able to achieve more efficient equilibria. Yet, such transfers require effective coordination. We thus additionally study a coordinating mechanism where all players can transfer funds to an intermediary common account which then provides coordinated investments in low endowment locations.[3]

We address the following research questions. First, we study how the introduction of overlapping neighborhoods affect the provision of a public good. For this, we compare an overlapping neighborhood with a closed neighborhood setting which coincides with traditional public good settings which ignore the spatial dimension. Second, we assess how endowment heterogeneity affects the provision of the weakest link public goods in the overlapping neighborhood setting. Importantly, we investigate whether the spatial location of the differently endowed participants influences the provision decisions. We compare two different spatial distributions: one where high and low endowment partici-

[3]This intermediary common account transfer system is inspired by real-world global public good provision schemes to help in coordinating the provision efforts, for example, in the WHO smallpox eradication program (Barrett, 2007).

pants are spatially clustered vs. one where high and low endowment types' locations are alternating. Within these spatial settings, we investigate how investments in players' own locations relate to in-kind transfers to others. Third, we explore whether replacing the individual direct transfers by transfers to a common account which distributes the funds evenly to the low endowment players can overcome coordination problems.

We find that overlapping neighborhoods do not affect the investment levels and provision levels of public goods when compared to closed neighborhoods when all players have the same endowment. The impact of heterogeneity depends on the spatial distribution of endowment types: provision and payoff levels are reduced due to endowment heterogeneity when endowment types are spatially clustered. Yet, when high and low endowment players alternate in their locations, heterogeneity does not have a significant effect on payoff and provision levels. Participants tend to invest in all three locations inside of their neighborhood, and they divide their transfers rather similarly among the three of them, indicating that the neighborhood works as a strong focus point for participants' investment decisions.

Overall, we find a significant extent of in-kind transfers even in the homogeneous settings, thereby leading to substantial spatial spillovers of individual players' investments. When replacing such in-kind transfers in the heterogeneous setting by investments into a common account that distributes its contents equally to low endowment locations, we observe that participants relocate investments towards their own locations. Yet, they still invest substantial amounts into the common account, contrary to theoretical predictions as the common account introduces free-riding incentives. As the result, the average payoff levels are rather stable while inequalities tend to be reduced.

The rest of the paper is organized as follows. Section 3.2 discusses the related literature. Section 3.3 lays out the experimental design, before we discuss predictions in 3.3.1 and the experimental procedure in section 3.3.2. Section 3.4 presents the results. We conclude in section 3.5.

3.2 Literature

Our paper connects the literature on the voluntary provision of public goods, specifically in a weakest-link setting, with the literature on the provision on networks which has largely focused on summation technology.

Since the seminal work of Hirshleifer (1983), weakest-link technologies have been investigated in several settings (e.g., Vicary and Sandler, 2002; Barrett, 2016; Caparrós and Finus, 2020a,b). Problems of providing weakest link public goods particularly arise when individuals are heterogeneous (e.g Vicary, 1990; Vicary and Sandler, 2002; Lei et al., 2007; Gregor, 2011). Under heterogeneity, transfers are needed in order to achieve maximum efficiency equilibria, yet obstacles to coordination arise (Riedl et al., 2016; Cooper and Weber, 2020). The extent of inequality can also influence which type of transfer allowed, i.e. monetary or in-kind, are more beneficial towards achieving coordination (Lei et al., 2007).[4] The effectiveness of transfers crucially depends on the extent to which a group coordinates, as investments beyond the minimum are wasted. Given the initial endowment heterogeneity, this coordination may additionally be hampered if individuals follow different norms.[5]

Different mechanisms to improve coordination have been tested in the literature. For example, Weber (2006) propose adding new participants to a group to prevent coordination failures stemming from large size of groups, while Karakostas et al. (2023) find that a "team allocator" that allocates benefits of the public good might help in best-shot and linear public goods, but is ineffective in weakest-link public goods. Riedl et al. (2016) show that freedom to choose group membership might be enough to achieve fully efficient coordination and welfare improvements.

By studying the provision of public goods in a spatial setting, we connect the experimental literature with a developing theoretical literature on the provision of public goods in networks (e.g., Bramoullé and Kranton, 2007; Corazzini and Gianazza, 2008; Bramoullé et al., 2014; Allouch, 2015; Corazzini et al., 2020). Several experimental studies on voluntary provision in networks exist (e.g., Kirchkamp and Nagel, 2007; Cassar, 2007; Rosenkranz and Weitzel, 2012).[6] Rosenkranz and Weitzel (2012) and Kirchkamp and Nagel (2007) focus on the effect of the specific network on cooperation by homogeneous agents. Cassar (2007) also studies behavior within a coordination game. Angelovski et al. (2018a,b) use a circular network to study the provision to local public goods where each person is generating two separate public goods, one with the right, another with the left neighbor. Perhaps the closest study to ours are Berninghaus et al. (2002) who also assess the challenge of

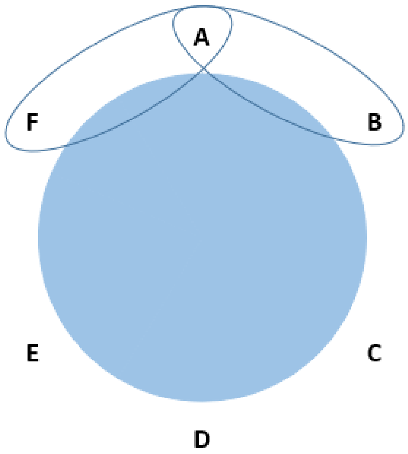
[4]More generally, the effects of heterogeneity on the voluntary provision of public goods have been examined in a prolific strand of literature, yet mostly focusing on summation technologies, thus not requiring transfers: with respect to endowment or income (e.g Zelmer, 2003; Cherry et al., 2005; Buckley and Croson, 2006; Hofmeyr et al., 2007; Anderson et al., 2008; Heap et al., 2016), productivity of the public good (Hauser et al., 2019), benefits from the public good (Kolstad, 2010; Fischbacher et al., 2014; Kölle, 2015; Nosenzo et al., 2015; Gangadharan et al., 2017). The effect of heterogeneity on the contribution and coordination has been found to be negative in the majority of studies undertaken (e.g Van Dijk et al., 2002; Cherry et al., 2005), with a few studies finding a positive effect (e.g Barrett, 2001; Waichman et al., 2021) or no effect (Hofmeyr et al., 2007).

[5]Numerous studies document this for the summation technology (e.g., Nikiforakis et al., 2012). In threshold public good games, coordination may require communication (e.g., Cavaliere, 2001; Tavoni et al., 2011; Cason et al., 2012) or some other coordinating device (Corazzini et al., 2020).

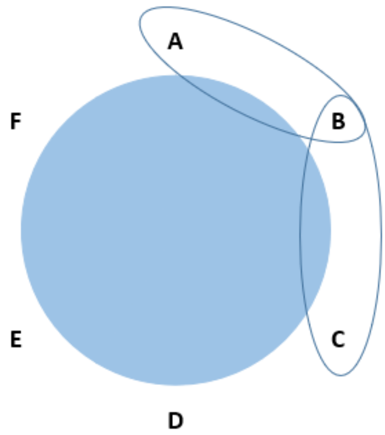
[6]Local features of public good provisions have also been studied in settings with multiple public goods, in particular local and global ones (e.g Falk et al., 2013; Fellner and Lünser, 2014). These studies find that cooperation tends to happen at the inefficient, subgroup level. Fellner and Lünser (2014) find that observing the contribution levels of the global group improve the cooperation of individuals, giving insights into the importance of feedback in the institutional design.

coordination on an circular network with overlapping neighborhoods but focus on a coordination problem similar to the battle of the sexes. Boosey (2017), Gallo and Yan (2023), and Zhang and He (2021) also use a circular structure where participants benefit from the provision of their direct neighbors, but they focus on a summation technology as the aggregation technology of the contributions and have a homogeneous endowment across participants. Yet, to our knowledge, no study on players with heterogeneous endowment or the provision within a weakest-link context in networks exists.

3.3 Experimental Design



(i)



(ii)

Figure 3.1 Illustrating the overlapping neighborhood setting. As an example, (i) shows the neighborhood of participant A, and (ii) the neighborhood of particpant B.

Our experimental design extends the classical weakest-link public good game by adding an spatial element. Subjects interact in neighborhoods, the public good is provided based on the minimal investments in any location within a neighborhood. Each subject has a neighborhood comprised by herself and her direct neighbors – in our design, the participants that are spatially closest to her. We compare closed and overlapping neighborhoods and investigate the role of endowment heterogeneity. Figure 3.1 illustrates this concept of overlapping neighborhoods.

Players interact in groups of six players, $i \in \{A, B, \ldots, F\}$, being identified by their respective location. Each player has an endowment w_i and is located within a neighborhood N_i of a total of three players – herself and her two direct neighbors. Players can invest into projects in any location $i \in \{A, B, \ldots, F\}$, the investment of player i in location j is denoted by g_{ij} ($\sum_j g_{ij} \leq w_i$). The total investments by players i in location j are added to yield the total investment level at that location G_j ($G_j = \sum_i g_{ij}$). The payoff of player

i is then given by

$$\Pi_i = w_i - \sum_j g_{ij} + h \min_{j \in N_i} G_j. \tag{3.1}$$

It comprises the initial endowment w_i minus the sum of investments by this player $\sum_j g_{ij}$ plus the returns from the public good $h \min_{j \in N_i} G_j$. The latter are given by the minimum of total investments in the player's neighborhood N_i. That is, the returns from the public investments are driven by a weakest-link technology.

Our main treatments vary (i) the way the neighborhoods are defined (closed vs. overlapping), (ii) the endowments (homogeneous vs. heterogeneous), and (iii) the spatial allocation of endowment types (clustered vs. alternating high and low endowment). The summary of these main treatments is given in Table 3.1. The different endowment conditions are illustrated in Figure 3.2.

Treatment T1 (CN_{hom}) serves as a baseline and comprises two closed neighborhoods, $N_A = N_B = N_F = \{A, B, F\}$ and $N_C = N_D = N_E = \{C, D, E\}$ (see Figure 3.2 (i)). It resembles a typical weakest-link public good setting as players investments *within* their neighbor can mutually benefit each other. Players can invest in each location, thus implicitly providing in-kind transfers to other participants.

The only difference to a classical two- to four-players weakest-link public good game (e.g., Harrison and Hirshleifer, 1989; Lei et al., 2007) is that two neighborhoods of 3 players each are assigned to the same 6 player group. Although the investments in the public good in one three-player group do not affect the other one, both groups can theoretically transfer funds between each other and have access to the information on decisions within the other group.

All other treatments reflect an overlapping neighborhood setting where each player interacts with her left- and right-neighbor, e.g. $N_A = \{F, A, B\}$, $N_B = \{A, B, C\}$, ..., $N_F = \{E, F, A\}$. As such, the investments in three locations again determine the provision of the public good for a player, yet the set of investment locations that affects a direct neighbor's location only partly overlaps. We first consider how moving to the overlapping neighborhood setting affects investment decisions by comparing T1 (CN_{hom}) with T2 (ON_{hom}) which is based on overlapping neighborhoods but keeps the homogeneous endowments (see Figure 3.2 (ii)).

Treatments T3 (ON_{alt}) and T4 (ON_{clu}) introduce endowment heterogeneity into the overlapping neighborhood setting. Here, three players have a high endowment w_H and three players have a low endowment w_L, in a ratio $w_H : w_L = 2 : 1$, i.e high endowment participants get twice as much tokens as the players with a low endowment. T3 (ON_{alt})

alternates high and low endowment types, while T4 (ON_{clu}) has endowment types clustered such that three high (low) types are located next to each other (Figure 3.2 (iii) and (iv), respectively). Our design thus allows us to study the effects of (i) overlapping neighborhoods, and (ii) of different spatial heterogeneous endowment settings.

We complement these main treatments by two additional treatments with overlapping neighborhoods and endowment heterogeneity. Instead of being able to invest in any location, subjects in Treatments T5 (ON^C_{hom}) and T6 (ON^C_{alt}) can only invest in their own location and into a common account. The total investments into this common account are then uniformly invested at all low endowment players' locations. The idea motivating this common account are calls for coordinated action among rich countries to sponsor public good investments in poorer countries (see Barrett (2007) for a real-world example and Corazzini et al. (2020) for an experimental testing of this idea). For a summary of the treatments features, see Table 3.1.

In these treatments T5 and T6, each player i can invest in his own account (g_{ii}) or into the intermediary common account (g^C_i). The payoff of a player is then given by

$$\Pi_i = w_i - g_{ii} - g^C_i + h \min_{j \in N_i} G_j. \tag{3.2}$$

where $G_i = g_{ii}$ if $w_i = w_H$ and $G_i = g_{ii} + (\sum_j g^C_j)/3$ if $w_i = w_L$.

We chose the following parameters in the experiment: $w_i = 30$ in the homogeneous treatments and $w_L = 20$ and $w_H = 40$ in the heterogeneous treatments[7]. The productivity multiplier of the public good is set to $h = 2.5$, which secures that players may have an incentive to invest in up to two locations, and also makes it efficient to coordinate on the largest investment given specific investment allocation across space (see Section 3.3.1 below).[8]

3.3.1 Theoretical guidance – predictions

The weakest-link setting leads to multiple equilibria. A payoff-maximizer player would never invest outside of her neighborhood, and given that the productivity multiplier is $h = 2.5$, she would invest in at most two locations within her neighborhood. Specifically, a player i has an incentive to invest at some location j inside of her neighborhood $j \in N_i$

[7]Note that the total tokens in a group (180) do not change between homogeneous and heterogeneous setting, so all equilibria of the homogeneous setting are accessible in the heterogeneous treatments with the right transfers.

[8]Weakest link settings are prone to coordination problems. The relatively high benefit parameter h is selected to provided sufficient incentives to strive for coordination. We also note that many real-world examples showcases considerable benefit-cost ratios for the eradication of contagious diseases (e.g Thompson and Tebbens, 2007; Barrett, 2013).

Treatments	T1 CN_{hom}	T2 ON_{hom}	T3 ON_{alt}	T4 ON_{clu}	T5 ON^C_{alt}	T6 ON^C_{clu}
Neighborhoods	CN	ON	ON	ON	ON	ON
Endowments	Hom	Hom	Het	Het	Het	Het
	$w_i = 30$		$w_L = 20, w_H = 40$			
Distribution	-	-	Alternate	Cluster	Alternate	Cluster
Investment locations	All	All	All	All	Own & common account	Own & common account
Payoffs	$\Pi_i = w_i - \sum_j g_{ij} + h \min_{j \in N_i} G_j$				$\Pi_i = w_i - g_{ii} - g_i^C + h \min_{j \in N_i} G_j$	

Table 3.1 Features of treatments 1-6. "Hom" stands for homogeneous, "Het" for heterogeneous, "CN" for closed neighborhoods and "ON" for Overlapping neighborhoods. The endowments are $w_M = 30$ in the homogeneous treatments T1 and T2, and $w_L = 20$ and $w_H = 40$ in the heterogeneous treatments T3-T6.

with $j \in \arg\max_{k \in N_i}\{G_k^{-i}\}$ in order to increase the lowest total investment in any of the neighborhood's locations.

This would result in the equalization of all total investments within the neighborhood if the endowment is sufficient to make this investment ($w_i \geq 3\max_{k \in N_i}\{G_k^{-i}\} - \sum_{j \in N_i} G_j^{-i}$). In this case:

$$g_{ij} = \max_{k \in N_i}\{G_k^{-i}\} - G_j^{-i}.$$

If the endowment is smaller, subject i is predicted to invest all her endowment. Two cases can occur: (i) If $w_i + \min_{j \in N_i} G_j^{-i} < G_k^{-i}$ for both other $k \in N_i$, player i only invests in the location where other subjects have invested the least, i.e. $g_{ik} = w_i$ for $k = \arg\min_{j \in N_i} G_j^{-i}$. In other words, player i would transfer to the location inside of her neighborhood that has the lowest investment. (ii) If the endowment is sufficient to equalize total investments in the two locations with the lowest investment,

$$g_{ij} = \frac{w_i + \sum_{k \in N_i} G_k^{-i} - \max_{k \in N_i}\{G_k^{-i}\}}{2} - G_j^{-i}$$

for $j \in N_i, j \neq \arg\max_{k \in N_i}\{G_k^{-i}\}$.

Intuitively, a player seeks to increase the weakest-link by first investing in the location in her neighborhood with the lowest investments by others. Once that level reaches the investment, she invests in both these locations up to the investment level $\max_{j \in N_i} G_j^{-i}$ or until all endowment is spent.

Within the closed neighborhood setting (T1), this logic immediately implies that total investments at all three locations *within* a neighborhood need to be equal in any equilibrium. Yet, different total investments may occur *between* the two neighborhoods (FAB vs. CDE). The most pessimistic equilibrium involves zero investments into the public good. Conversely, the equilibrium which maximizes total payoffs is obviously the one where all

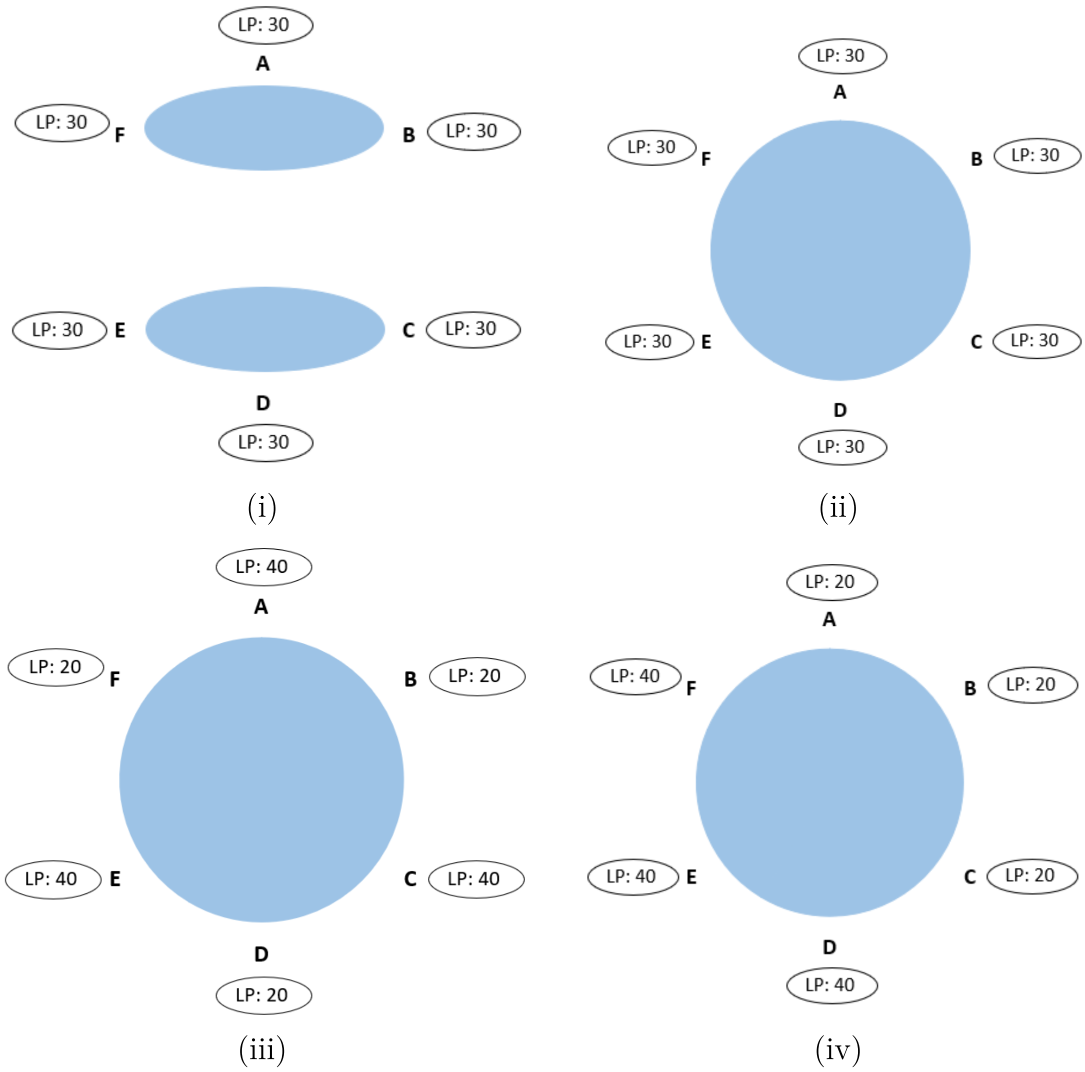


Figure 3.2 Illustration of the different treatments. Closed neighborhoods, homogeneous endowment (i) (Treatment 1), overlapping neighborhoods, homogeneous endowment (ii) (Treatment 2), heterogeneous, alternating allocation (iii) (Treatments 3 and 5), and heterogeneous, clustered allocation (iv) (Treatments 4 and 6).

players invest their full endowment and investments are evenly spread within the neighborhood. Although the focal point is that players invest in their own location only, other spatial investment patterns may result.

The overlapping neighborhood setting may generate different investment patterns in equilibrium. Yet, the investment levels are again necessarily identical in all locations in equilibrium.

In any equilibrium in the experimental weakest link game with overlapping neighborhoods, the total investment levels are identical in all locations.

The proof is given in Appendix 3.A. This statement holds true for our experimental setting of six players and the given level of heterogeneity. It relies on showing that any player who has one location within her neighborhood with a smaller total investment level than in other locations would necessarily invest all endowment in this location. This leads to a contradiction as the endowment of at least one player in such a neighborhood (i.e. a high endowment player) would have sufficient income to equalize that the total investments in her neighborhood.[9]

Proposition 3.3.1 thus implies that total investments and thus the returns from a public good will be equal in all locations. Thus, initial inequalities can only be reduced by high endowment types investing larger amounts than low endowment players.

Clearly, maximization of total payoffs requires that players invest their full endowments. In this case, payoffs are equalized in all locations in equilibrium.[10] While this can be achieved through players only investing in their own location in the homogeneous setting, endowment heterogeneity necessarily needs to involve transfers in order to secure the efficiency gains. As such, coordination on maximal or large provision levels might be more problematic.

Subjects are expected to reduce their investment in a location in response to experiencing low investment levels by others. Within the closed neighborhood setting, the two distinct neighborhoods are decoupled such that uncooperative behavior within one may not spill over to the other neighborhood. This is different in the overlapping neighborhood setting. Here, low investments by one player may lead to reduced investments by their next neighbors, thus over time spreading to neighbors' neighbors and reducing investment in the full network.

Hypothesis 1 *The overlapping neighborhood setting will decrease the average provision levels of the public good relative to the closed neighborhood setting.*

Endowment heterogeneity implies that not all members of a group have the same capacity to invest. Yet, high endowment participants may "help out" by investing in low endowment locations. However, high endowment players in equilibrium will never invest in their own *and* both (low endowment) neighbors' locations (see above) if they try to maximize

[9]For more extreme endowment heterogeneities, i.e. if $w_H < 6w_L$, this statement will no longer be true in the clustered setting. For $w_h < 6w_L$, low endowment players by investing all their endowment in the center low player location (B) would not able to equalize total investments given by $x > 3w_l$ in all other locations which can be sustained in equilibrium by the border high endowment players (D,F)) investing x in their own and their low endowment neighbor's and x in their own location, while the center high endowment player (E) invests x in his own location only.

[10]Even not allowing for non-equilibrium investment decisions, realization of maximal total payoffs still requires total investments to be equalized across all locations. Assume to the contrary that total investments are not equalized. Then consider a maximal connected set of locations with the maximal total investments, $\max_j G_j$. Let k denote the number of these locations. Now consider reducing the investment in each of these k locations by 1, and reinvesting the amount in all other locations, i.e. $k/(n-k)$ tokens in all other locations. Then, the provision of the public good, i.e. the weakest-link in the respective neighborhood is reduced by 1 in $k-2$ locations (the interior of the maximal connected set), while the provision in $n-k+2$ locations is increased by $k/(n-k)$. Thus, total payoff is increased as $-k+(n-k+2)k/(n-k) > 0$.

their own payoff. Achieving high (or maximal) total investments in equilibrium thus requires coordination not only on the level of investment by the individual players, but also on the extent and location of in-kind transfers. For the alternating endowment setting, maximal investment levels can be achieved by (i) the low endowment player investing all their endowment in their own location, and (ii) the high endowment players investing part ($g_[ii = 30$) at their own location and part ($g_{ij} = 10$) at one neighbor's location. For this to occur in equilibrium, it is necessry that *all* high endowment types coordinate to transfer in-kind to their right neighbor (alternatively all transfering to their left neighbor).

The necessary transfers to sustain maximal investments in the clustered endowment settings are even more sophisticated. Here, the center low endowment player needs to receive in-kind transfers from at least one of her neighbors (who also have low endowment). Thus, these border low endowment players have to simultaneously transfer to their poor neighbor but also receive transfers from their rich neighbor in order to achieve equilibrium investments larger than $w_L = 20$ in each location.

We thus hypothesize that the spatial allocation of types affects the propensity of players to coordinate on high investment equilibria:

Hypothesis 2 *The spatial distribution of the endowment types will affect the transfers and payoffs. When they are alternated, the provisions levels and payoffs will be larger than when endowment types are spatially clustered.*

The theoretical predictions were based on payoff-maximizing individual behavior which implied that a single player will invest in at most one location. Behaviorally, we may expect that players may invest in both their neighbors' locations, e.g. due to reciprocal preferences. Yet, also in this case, the implicit symmetry in the alternating setting makes it easier to coordinate on transfers to achieve equal investments in the different locations. For example, each player in the alternating setting could decide to invest half of her endowment in her own location and to transfer a quarter to each of her neighbors' locations. Doing so would generate maximal and equalized investments. Again, in the clustered setting the transfers would necessarily need to be more complex to achieve the same investment outcome. Thus, we find further behavioral support for hypothesis 2.

We further note that players cannot be expected to play equilibrium strategies right from the beginning. As such, we expect behavioral dynamics to evolve over time. In the overlapping neighborhood setting, all players directly or indirectly interact. As such, investment decisions by a player may not only affect her direct neighbors, but - if these react in the next period - over time affect all participants.

Similarly, convergence to equilibrium, i.e. achieving equalized total investment levels in all locations, might be problematic: players may try to increase investments in location which formed the weakest link, or reduce investments in locations where more than the weakest link was invested. As players make their transfer decisions simultaneously and without communication, cyclical investment decisions may evolve.

The final two treatments are designed to reduce these coordination challenges by introducing an intermediary common account from which funds are later invested equally into the low endowment locations. In principle, if all high endowment players transfer some funds into the common account, they would secure that all poor endowment locations equally benefit. Yet, given the productivity multiplier is $h = 2.5$, no payoff maximizing player ever has an incentive to contribute to this common account as collected funds are allocated to three locations.

On the other hand, if players are altruistic or look for efficiency, they would be inclined to make transfers to the low endowment participants. The decision of where to transfer to is not straightforward to make, as it would depend on the investment decisions of the low endowment participants and the transfers that other players make. In a setting where communication is not possible as ours, these players might be willing to transfer funds but fail to coordinate on their decisions or decide not to transfer as they cannot know where it is best to transfer. In this case, an intermediary common account could help to alleviate the coordination problem. We explore whether this mechanism helps overcoming the coordination issues arising from each player individually deciding the location of investments.

Exploratory question *How does the introduction of an intermediary common account affect the transfer and investment decision of the players?*

3.3.2 Experimental Procedures

The experiment took place at the WiSo Research Lab of the Faculty of Business, Economics and Social Sciences of the University of Hamburg from May to July 2022.[11] Participants took part on the experiment through the online tool of the WiSo Research Lab and were managed using the *hroot* software developed by Bock et al. (2014). The experiment was coded using the *o-Tree* software (Chen et al., 2016).

Participants were invited into online sessions. Upon arrival, they were shown the instructions for them to read, followed by several control questions. Subjects' questions about

[11] The experiment was preregistered at the AEA RCT Registry (Lange, Andreas and Romero-Fernández, Lorenzo. 2022. "It's a small world: effects of overlapping neighborhoods in the provision of public goods." AEA RCT Registry. June 21. `https://doi.org/10.1257/rct.9451-2.1`). Ethical approval was obtained at the Faculty of Business, Economics and Social Sciences of the University of Hamburg.

the instructions and other doubts were answered via a live chat or phone call. Participants that had not passed the control questions after a given time (15 minutes) were automatically removed from the experiment. After passing the control questions, participants were assigned to groups of six for the remainder of the experiment. At this stage, their spatial position at the group (A - F) and their endowment was also assigned and remained fixed for the remainder session. Groups of six players were allocated into one of the treatments described in Table 3.1 and played the spatial weakest-link public good game for ten periods.

At the beginning of each round, each participant was given a new batch of tokens depending on her endowment and was presented with the decision of how many tokens to invest and where, and how many to keep. After all participants in a group made their decisions, all participants were informed of the results of the round: information was given about how many tokens each participant kept in her private accounts, the total investment levels in each location, the minimum of the total investments in the neighborhood, as well as the payoff from the weakest-link public good, and the final payoff of each player in the group.

Upon conclusion of the ten rounds, participants answered a short questionnaire containing questions on their socio-demographic characteristics, field of study, risk behaviour and perception of the experiment.

The instructions and questionnaire are given in Appendix C and D.

One round out of the ten was randomly selected for payment. The tokens were converted into Euros at an exchange rate of 5 tokens per 1 Euro. Additionally, all participants received a 5 Euro show-up fee. The average total payment was 14.44 Euros. Sessions lasted between 50 and 60 minutes.

3.4 Experimental Results

We report the summary statistics on average individual decisions in Table 3.2. We report the tokens kept in the private account (*"keep"*), the total tokens invested by players (*"invest_sum"*), as well as those separated by tokens invested in the own and others' locations (*"invest_own"* and *"invest_others"*, respectively), the amount of the public good provided (*"provided"*), as well as the resulting payoff. Additionally we report a measure of wasted investments *"waste_sp"* which reflects the number of tokens investments can be reduced without changing the provision level of the public good in any location. Table 3.3 differentiates these variables by endowment type for the heterogeneous endowment treatments.[12]

Unless stated otherwise, all the comparisons discussed are the result of the Mann-Whitney rank-sum test at the group of 6 level. We remind the reader that zero investment would result in an average payoff of 30 tokens, while full and efficient investment would result in $30h = 75$ tokens per player.

VARIABLES	T1 CN_{hom}	T2 ON_{hom}	T3 ON_{alt}	T4 ON_{clu}	T5 ON^C_{alt}	T6 ON^C_{clu}
keep	8.86	9.37	10.45	13.00	11.89	13.84
	(5.39)	(4.30)	(4.84)	(4.42)	(4.56)	(3.56)
invest_sum	21.14	20.63	19.55	17.00	18.11	16.16
	(5.39)	(4.30)	(4.84)	(4.42)	(4.56)	(3.56)
invest_own	9.05	7.60	7.61	6.64	11.82	11.28
	(3.54)	(2.72)	(3.20)	(2.58)	(2.72)	(3.12)
invest_others	12.09	13.03	11.94	10.36	6.29	4.89
	(3.83)	(3.40)	(2.88)	(2.19)	(2.24)	(1.56)
provided	16.77	15.50	14.25	11.86	13.37	11.14
	(6.30)	(4.01)	(5.06)	(4.23)	(3.46)	(3.43)
waste_sp	4.37	5.13	5.29	5.14	4.74	5.02
	(1.78)	(1.63)	(1.41)	(1.71)	(1.31)	(1.18)
payoff	50.79	48.12	46.09	42.64	45.32	41.69
	(10.63)	(6.26)	(8.12)	(6.72)	(4.25)	(5.34)
Observations	12	12	11	10	11	10

Table 3.2 Summary statistics by treatment, each observation corresponds to a group of 6.

3.4.1 Effects of overlapping neighborhoods and endowment heterogeneity

In the baseline treatment of closed homogeneous neighborhoods, we observe a payoff average of 50.79 tokens (T1, Table 3.2). Introducing the spatial pattern of overlapping neighborhoods does only insignificantly reduce average payoffs (48.12 tokens in T2, $p = 0.478$). The same applies to the provision levels of the public good (16.77 in T1 vs. 15.50 in T2, $p = 0.514$). A similar comparison of other relevant variables do not show any effect: tokens kept in the private account (8.86 in T1 vs. 9.37 in T2, $p = 0.671$) and total investments (21.14 vs. 20.63, $p = 0.671$). Thus, we do not find support for Hypothesis 1.

[12] Table 3.A.1 separates these summary statistics by round 1-5 vs. rounds 6-10. There are no significant differences in the average payoff and provision level of the public good between rounds 1-5 and rounds 6-10, see section 3.4.3.

Result 1 *The introduction of the overlapping neighborhood setting does not have an effect on participants' behavior.*

	T3 ON_{alt}	T4 ON_{clu}	T5 ON^C_{alt}	T6 ON^C_{clu}
High endowment ($w_H = 40$)				
keep	15.44	20.78	15.42	20.81
	(7.47)	(8.60)	(5.76)	(6.09)
invest_sum	24.56	19.22	24.58	19.19
	(7.47)	(8.60)	(5.76)	(6.09)
invest_own	9.18	6.70	16.44	14.20
	(4.09)	(3.48)	(3.24)	(5.02)
invest_others	15.37	12.52	8.14	4.99
	(4.06)	(5.48)	(3.24)	(2.06)
provided	14.99	11.92	13.78	10.25
	(5.00)	(5.56)	(3.79)	(4.13)
payoff	52.91	50.58	49.88	46.43
	(6.12)	(7.01)	(4.58)	(5.64)
waste_sp	2.48	4.93	2.66	3.95
	(1.28)	(2.20)	(1.20)	(1.67)
Low endowment ($w_L = 20$)				
keep	5.46	5.22	8.36	6.87
	(2.73)	(2.22)	(4.32)	(2.57)
invest_sum	14.54	14.78	11.64	13.13
	(2.73)	(2.22)	(4.32)	(2.57)
invest_own	6.04	6.58	7.19	8.35
	(2.76)	(2.78)	(2.48)	(3.32)
invest_others	8.50	8.20	4.45	4.78
	(2.56)	(2.10)	(2.98)	(1.75)
provided	13.52	11.79	12.96	12.03
	(5.15)	(3.17)	(3.16)	(3.02)
payoff	39.26	34.71	40.76	36.96
	(10.57)	(7.04)	(4.52)	(6.72)
waste_sp	8.11	5.35	6.82	6.10
	(2.43)	(1.73)	(3.01)	(2.31)
Observations	11	10	11	10

Table 3.3 Summary statistics by endowment type for heterogeneous treatments (Treatments T3 - T6).

The effects of heterogeneity depend on the spatial agglomeration of the different endowment types: while average payoff in the alternating setting (46.09, T3) does not significantly differ from the homogeneous setting case (48.12 in T2, $p = 0.347$), the clustered setting marginally reduces the payoff (42.64 in T4, $p = 0.059$ vs. T2). This effect can also be observed in the results for number of tokens kept (9.37 in T2 vs. 13.00 in T4,

$p = 0.036$), total investments in the public good (20.63 vs. 17.00, $p = 0.036$) and the level of the public good provided (15.50 vs. 11.86, $p = 0.059$).

We thus find directional support for Hypothesis 2, while acknowledging that the differences in payoffs, provision levels, total investments, investments on the participant's location and investments on others between the alternating and clustered distribution are insignificant (T3 vs. T4, respectively). Importantly, the endowment heterogeneity also results in final payoff inequality between high and low endowment types ($p < 0.01$ in both T3 and T4, Table 3.3).

Result 2 *Endowment heterogeneity has a detrimental effect on average investments and average payoffs when the participants are clustered together in respect to their endowment, but not when they are alternating.*

Table 3.2 also shows that participants transfer more than half of their total investments to other participants, a value that exceeds the investments in the own location ($p < 0.01$ in T1-T4, using the Wilcoxon signed-rank test at group of 6 level). Interestingly, this also happens in the homogeneous setting T1 and T2, contrary to our expectations that the focal point for participants would be to invest in their own locations.

VARIABLES	T1 CN_{hom}	T2 ON_{hom}	T3 ON_{alt}	T4 ON_{clu}	T5 ON^C_{alt}	T6 ON^C_{clu}
invest_neighbors	11.40	12.52	11.34	9.84	-	-
	(4.21)	(3.62)	(2.64)	(2.16)	-	-
invest_nonneighbors	0.69	0.51	0.60	0.52	-	-
	(1.13)	(0.69)	(0.61)	(0.70)	-	-
Observations	12	12	11	10	11	10

Table 3.4 Decomposing the tokens invested in others' position by transfers to the participant's two direct neighbors (*"invest_neighbors"*) vs. the three participants outside of her neighborhood (*"invest_nonneighbors"*).

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Table 3.4 shows how many tokens players invest in their direct neighbors' locations vs. outside of their own neighborhood. In line with the predictions, participants in treatments T1-T4 do not transfer a significant number of tokens outside of their own neighborhood.

Yet, players were also expected to invest in at most two locations due to the value of the productivity factor of the public good $h = 2.5$. In contrast to this prediction, the modal number of locations invested into is 3 in all treatments that allow for direct transfers (T1-T4), with the average number that a single participant invests into ranging from 2.43 (T4) to 2.71 (T2). This means that players tend to invest in their own and *both* their neighbors' locations, distributing their investments relatively equally between the three locations.

We thus obtain the following result:

Result 3 *The neighborhood works as a focal point for investments – participants coordinate by spreading their investments among the three members of their neighborhoods.*

3.4.2 Effects of the intermediary common account

We now consider the effects of the intermediary common account. Relying on the intermediary common account rather than individual in-kind transfers does not change the average payoff levels for any of the spatial locations (Table 3.2) – neither for the alternating (46.09 in T3 vs. 45.32 in T5) or for the clustered case (42.64 in T4 vs. 41.69 in T6). No statistical difference is found either for total investments (19.55 in T3 vs. 18.11 in T5; and 17.00 in T4 vs. 16.16 in T6) or level of public good provided (14.25 in T3 vs. 13.37 in T5, and 11.86 in T4 vs. 11.14 in T6). Low endowment types again obtain smaller payoffs than their high endowment counterparts ($p < 0.01$ in both T5, T6, Table 3.3).

In theory, no payoff-maximising individual should transfer to the intermediate common account as the potential gains from that investment would always be smaller than opportunity cost of keeping the tokens in their own private accounts. Regardless, Table 3.2 shows that participants make substantial transfers to this common account (see invest_others). Yet, we find that participants in both common account treatments invest more tokens in their own location when the common account transfer is introduced, for both the alternating setting (7.61 in T3 vs. 11.82 in T5, $p < 0.01$) and the clustered one (6.64 in T4 vs. 11.38 in T6, $p < 0.01$). On the other hand, they also transfer fewer tokens to other players (11.94 in T3 vs. 6.29 in T5, $p < 0.001$; 10.36 in T4 vs. 4.89 in T6, $p < 0.001$).

This effect is observed for both high and low endowment participants, although it is only statistically significant for the high type (Table 3.3). While high endowment types invest more in their own location (T5 vs. T3, $p < 0.001$; T6 vs. T4, $p < 0.01$), low endowment types only marginally change their investments in their own location (T5 vs. T3, $p = 0.308$; T6 vs. T4, $p = 0.089$). Both types invest less in other locations, i.e. transfer less tokens into the common account in T5 and T6 than they directly transfer in T3 and T4, respectively (T5 vs. T3: $p < 0.001$ for high and $p = 0.002$ for low endowment types; T6 vs. T4: $p = 0.002$ for high and $p = 0.002$ for low endowment types).

We summarize this discussion as follows:

Result 4 *The intermediary common account does not improve the coordination on providing the public good, but it changes direction of participants' investment decisions.*

Result 3 states that the common account is neither detrimental nor beneficial to in terms of coordination and welfare. This contrasts the theoretical prediction for payoff-maximizing individuals who should not have made any use of this account.

We have seen that moving to a coordinating mechanism such as an intermediate common account changes the investment patterns. We now have a more detailed look at the distributional impacts of these investment patterns.

In treatments T4 and T6, participants are clustered in regards to their endowment. This creates asymmetries among the three high endowment and among the three low endowment players, respectively. For each endowment type, we can differentiate between a central participant that only interacts with neighbors of her own endowment type and two border players who interact with one high and one low endowment participant. We discuss how this spatial location affects their decisions. Table 3.5 summarizes the payoff levels as well as the provision and investment levels for each of these types. They are also illustrated Figure 3.3. [13]

Table 3.5 shows evidence of participants interacting with the other endowment type directly, i.e. the border players, behave differently to the respective center player. In treatment T4, high endowment participants at the border ("highborder") differ from the high endowment participants at the center ("highcenter") in terms of their level of public good provided, total investments and transfers to others. In particular, "highborder" participants have larger level of public good provision, larger levels of total investments and make larger transfers to other participants than the "highcenter" ($p = 0.04$, $p = 0.032$ and $p = 0.063$, respectively, Wilcoxon signed-rank test). Here, the high endowment border players appear to try to raise the total investment level at their poor neighbors location by investing in those locations.

Low endowment participants at the border react by investing less in their own location. As a consequence, they have larger payoffs, lower total investments, lower investments in their own position and make lower transfers to others than the low participants at the center ("lowborder" vs. "lowcenter", $p = 0.023$, $p = 0.0023$, $p = 0.0008$ and $p = 0.094$, respectively). It is surprising that the low center player makes these substantial investments at her neighbors' locations instead of generating a higher investments at her own location. This indicates a coordination failure.

[13] For each group in T4 and T6, we averaged the values from all periods of participants in location D and F together (column "highborder" in Table 3.5). For the participants in location E, we averaged of the values across all periods of that participant (column "highcenter"). Each of these averages was treated as one observation. A similar procedure was performed on the low endowment players.

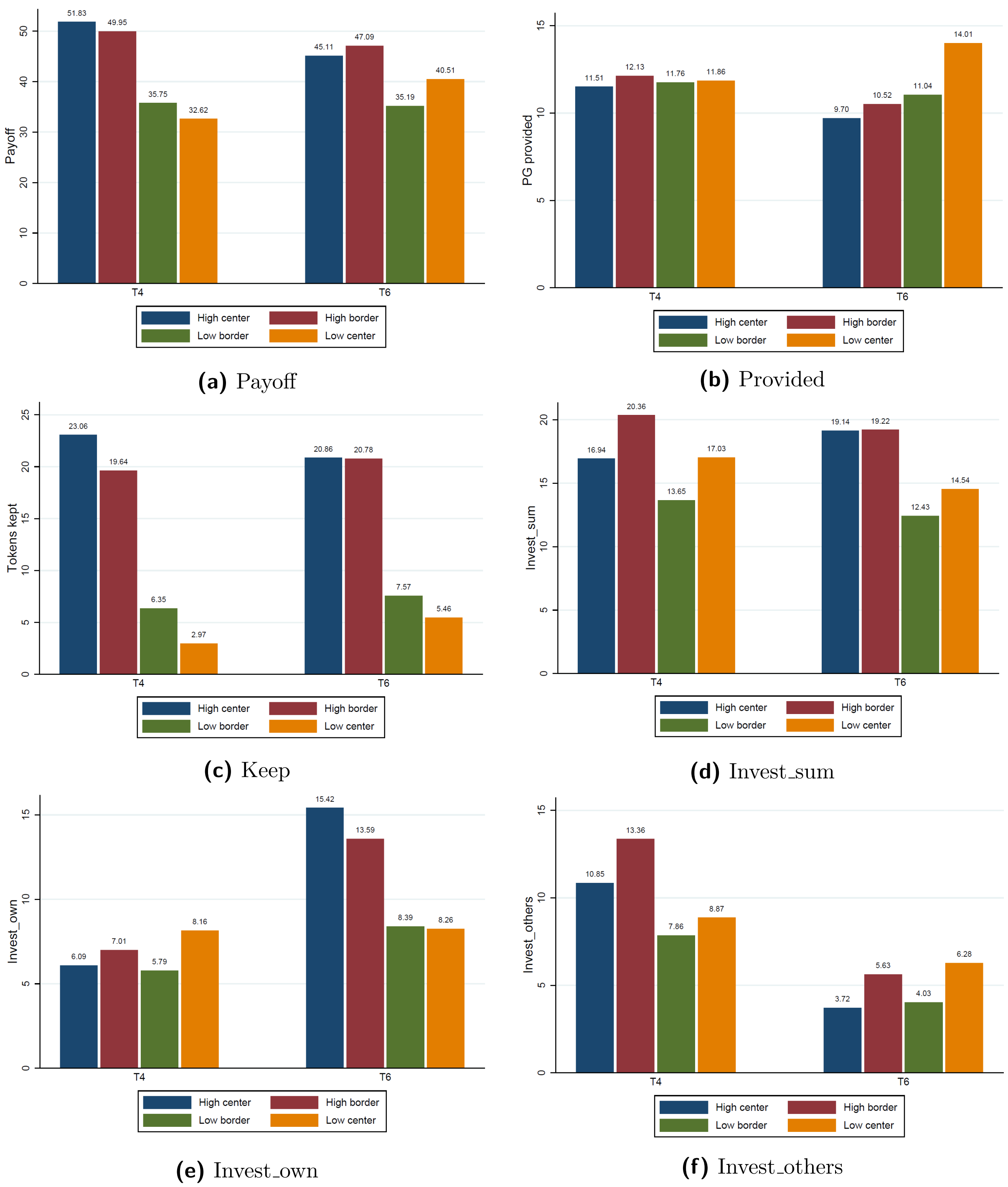
		lowborder	lowcenter	highborder	highcenter
payoff	T4	35.75	32.62	49.95	51.83
		(8.21)	(5.64)	(7.68)	(8.73)
	T6	35.19	40.50	47.09	45.11
		(7.88)	(8.14)	(5.27)	(7.57)
provided	T4	11.76	11.86	12.13	11.51
		(3.22)	(3.15)	(5.48)	(5.76)
	T6	11.04	14.01	10.52	9.70
		(3.69)	(2.94)	(4.17)	(4.22)
invest_sum	T4	13.65	17.03	20.37	16.94
		(2.77)	(3.36)	(8.24)	(11.80)
	T6	12.43	14.54	19.21	19.14
		(3.33)	(2.94)	(6.13)	(7.57)
invest_own	T4	5.79	8.16	7.01	6.09
		(2.59)	(3.85)	(3.67)	(5.54)
	T6	8.39	8.26	13.59	15.42
		(3.03)	(5.15)	(4.86)	(5.79)
invest_others	T4	7.86	8.87	13.36	10.85
		(2.57)	(2.22)	(5.08)	(7.05)
	T6	4.03	6.28	5.62	3.72
		(2.27)	(3.51)	(2.87)	(4.34)

Table 3.5 Summary statistics per participant depending on their position in treatments T4 and T6 with clustered neighborhoods: low endowment at the border ("lowborder") or the center ("lowcenter"), and high endowment at the border ("highborder") or center ("highcenter").

We now consider the impact of the common account separated by the spatial position inside of the group (see Figure 3.3). In particular, we find that the introduction of a common account (T6 vs. T4) increases the payoff of the central low endowment participant (32.62 in T4 vs. 40.50 in T6, $p = 0.0064$). None of the payoffs of other types changes significantly even though the average payoff of the high center player substantially decreases (51.83 in T4 vs. 45.11 in T6, $p = 0.14$). As a consequence, the payoff inequality is reduced by introducing the common account.

These changes are primarily driven by "lowcenter" participants reducing their total investments in the public good when the common account is introduced (17.03 in T4 vs. 14.54 in T6, $p = 0.08$), primarily by lowering the investment to others while maintaining the investment at her own position. In contrast, other player types do not significantly change their total investments, but reallocate their investments towards their own position as a response to the common account transfer system.

Result 5 *The spatial location of the participants within endowment clusters affects their investment decisions and their final payoffs. The intermediary common account improves the payoff of low endowment players in the center of the cluster and reduces inequality.*



(a) Payoff

(b) Provided

(c) Keep

(d) Invest_sum

(e) Invest_own

(f) Invest_others

Figure 3.3 Illustrating the means of variables observed for groups in treatments T4 and T6, classified by the type of participant following their location – high center, high border, low center, low border.

3.4.3 Coordination and convergence over time

Table 3.A.1 separates the main summary statistics for rounds 1-5 vs. rounds 6-10. There are no significant differences in the average payoff and provision level of the public good over time. Total investments, however, tend to decrease as the rounds go by in treatments T2 ($p = 0.002$), T3 ($p = 0.102$), T4 ($p = 0.037$), and T6 ($p < 0.01$). This already indicates

that some convergence happens over time.

In order to assess this convergence patterns, Table 3.A.2 reports three different interpretations of waste which arises from non-identical total investment levels within neighborhoods. As a consequence, a reduction in investments does not necessarily reduce the provision level of the public goods. As the aggregation technology of this public good is a weakest-link, participants might waste part of their investments in the public good. A participant i would over-invest in a position j if her investment leads to total investment in j in excess of a weakest link.

We define three different waste variables. Social planner's waste (*"waste_sp"*) defines waste as as the number of tokens by which investments in a location j can be lowered without affecting the provision level of the public good in any location. Selfish waste (*"waste_se"*) is taken from the perspective of a participant i as the number of tokens by which her investments in all positions $j \in \{A - F\}$ can be reduced without reducing her *own* level of public good provision. Altruistic waste (*"waste_al"*) is taken from the perspective of a participant i as the measure how much her own investments in all positions $j \in \{A - F\}$ can be reduced without affecting the level of public good provision for *any* of the participants in the group.[14] For all three definitions of waste, we find particularly significant reductions over time, the p-values are reported in Table 3.A.2.

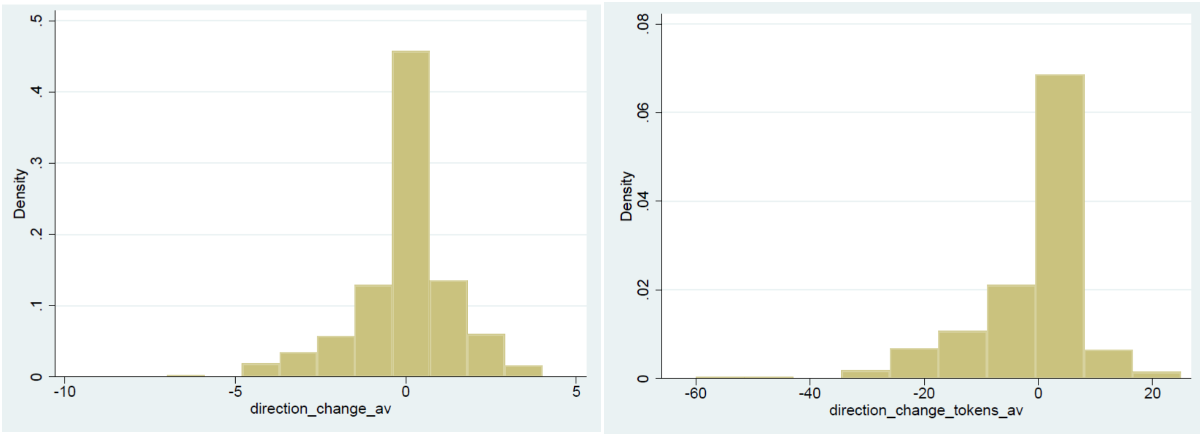
Another way to assess coordination and convergence over time is by considering the *changes* in individual investment patterns over time, i.e. the reactions of participant i in round t to the observed investments patterns in her neighborhood in round $t - 1$. Specifically, we consider whether a participant i reacts by increasing the investment in a location that created the weakest link in her neighborhood or by lowering investments in locations where previous investments were in excess of this weakest link.

For this, we create a new variable *"direction_changes_av"* that measures participant i's response in these cases.[15] A positive value of this variable indicates that participant i is more likely to increase her investments in the locations in her neighborhood that do not have the maximum total investment, and a negative value that she tends to decrease the investments made in the locations that are above the minimum total investment.

Figure 3.4 shows the distribution of the participants adjustments of investments over time. The distribution of the directional changes as defined above is closely clustered

[14] Note that the social planner's waste and the other two are not directly comparable – one token wasted in location j from the social planner's perspective could be wasted by more than one participant.

[15] For rounds 2-10, we create a variables *"direction_change2"* to *"direction_change10"* that are assigned a value of $+1$ when the participant increases her transfers to the locations below the maximum total investment, -1 if she decreases her transfers to the locations above the minimum total investment, and 0 if this two responses appear at the same time or if she does not react at all. *"direction_changes_av"* adds participant i's responses as measured by *"direction_change2"* to *"direction_change10"*.



(a) **(b)**

Figure 3.4 Average reaction of the participants in period t to the total investments in their neighborhood in period $t-1$. A positive value means that the participant i tends to increase her investments in position(s) in her neighborhood closer to the maximum total investment in her neighborhood, while a negative value means she is more likely to reduce her transfers closer to the minimum total investment in her neighborhood (weakest-link). Panel (a) considers this a a directional change variable (-1,0,1) in any period, while panel (b) accounts for the change in the number of invested tokens in the respective direction.

around 0 (see panel (a)), with 80% of the participants being in the range of -1 to 1. This indicates that participants are as likely to increase their investments in the lower-invested locations in her neighborhood as to decrease her investments in the higher-invested locations. Figure 3.4 (b) plots a related variable that accounts for the number of tokens by which investments change in the respective direction (extent of increase when participant increases investment in weakest link *plus* extent of decrease when participant decreases investments in a location not corresponding to a weakest link). These changes are clustered around 0, showing that most participants tend to increase their investments in the weakest link of their neighborhood at a similar level as they decrease investments to the location that received the largest investments.

Result 6 *When facing with an unequal total investment in the public good in their neighborhood, participants respond by reducing investments in the highest-invested location to a similar extent as by increasing investments in locations corresponding the the weakest link.*

3.5 Conclusions

In this study, we introduce a novel experimental design that incorporates an overlapping neighborhood setting to the classical weakest-link public good game. We contribute to the literature by studying the role of heterogeneity and intermediary common accounts on the provision of public goods in such a network setting.

We find that the introduction of spatial neighborhoods alone does not affect the provision of the public good as long as participants have the same endowment. Yet, endowment heterogeneity can be detrimental to the provision of the public good in overlapping neighborhoods. Its effect depends on the particular spatial distribution of high and low endowment players as only the clustered distribution has a negative effect on the payoff of the participants.

While substantial investments in the public goods occur, the coordination fails to achieve the maximal efficiency gains that are theoretically possible and supported by equilibrium strategies. This failure is largely driven by individuals dual reaction to observed investment patterns. While they tend to increase investments in locations that formed a weakest link in the previous period, they also reduce investments in locations that where total investment in excess of the weakest link occurred and thus were “wasted”.

Our study allows to investigate the spatial patterns of in-kind transfers. Participants almost exclusively invest in their own neighborhood, that is in their own location and the location of their two direct neighbors. Yet, investments are not exclusively driven by payoff maximization: contrary to the prediction, participants tend to invest in all three locations in their neighborhood and also invest in a common intermediary account when such common account to coordinate transfers replaces the option of individual in-kind transfers. Overall, the common account reduces the amounts transferred to other players and rather leads to larger investments in players’ own locations such that total investments and payoff levels are rather stable. Replacing individual in-kind transfers by a common account has a further advantage of reducing inequalities in the clustered endowment setting: here, particularly the player in the center of low endowment cluster benefits.

Our results suggest potential policy implications. First, the spatial location of individuals has an effect on their decisions of providing a public good. Clusters of wealth may backfire as individuals may only invest in their direct neighbors’ locations, i.e. if they themselves may also directly benefit from such investments. In our experimental design, parameters were chosen such that theoretically transfer regimes exist that can support large (efficient) levels of public good provision. Yet, the required set of transfers is rather sophisticated and does not materialize experimentally. Instead, mixing of neighborhoods as reflected in our alternated endowment setting tends to lead to more stable provision levels. This mixing rather than relying on clustered neighborhoods is expected to become even more important if the extent of endowment differences increases or if even larger clusters of poor neighbors exist (such that no richer neighbors can support the necessary investments in the public good).

Second, the use of an intermediary common account to overcome the transfer coordination issues does not deliver more optimistic results. While providing more equal investments in low endowment locations, investments are re-channeled towards own locations and away from others' locations. The apparent reason is that such common account essentially introduces free-riding incentives as it incorporates a public good environment with summation technology. As such, even extending such coordinated mechanism to all locations, i.e. replacing all individual direct investments, cannot be expected to lead to a better performance.

Exploring complementary ways to improve coordination towards larger provision levels of the public good thus remains a fruitful area for further research. Specifically, further investigations are needed into how such institutional design depends on the specific spatial structure of interactions between heterogeneous players. Such investigations may also prove beneficial in guiding responses regarding our motivating example of illness eradication, as our results indicate that freeriding incentives can limit the benefits from transfers schemes as introduced by the WHO (Barrett, 2007).

Acknowledgments

We would like to thank the WiSo Research Laboratory of the University of Hamburg for conducting the experimental study. We thank participants at diverse conferences and seminars for valuable comments.

Funding: Funded through personal research funds at University of Hamburg.

References

Allouch, N. (2015). On the private provision of public goods on networks. *Journal of Economic Theory*, 157:527–552.

Anderson, L. R., Mellor, J. M., and Milyo, J. (2008). Inequality and public good provision: An experimental analysis. *The Journal of Socio-Economics*, 37(3):1010–1028.

Angelovski, A., Di Cagno, D., Güth, W., Marazzi, F., and Panaccione, L. (2018a). Behavioral spillovers in local public good provision: an experimental study. *Journal of Economic Psychology*, 67:116–134.

Angelovski, A., Di Cagno, D., Güth, W., Marazzi, F., and Panaccione, L. (2018b). Does heterogeneity spoil the basket? the role of productivity and feedback information on public good provision. *Journal of Behavioral and Experimental Economics*, 77:40–49.

Barrett, S. (2001). International cooperation for sale. *European Economic Review*, 45(10):1835–1850.

Barrett, S. (2003). Global disease eradication. *Journal of the European Economic Association*, 1(2-3):591–600.

Barrett, S. (2007). The smallpox eradication game. *Public Choice*, 130(1):179–207.

Barrett, S. (2009). Polio eradication: strengthening the weakest links. *Health Affairs*, 28(4):1079–1090.

Barrett, S. (2013). Economic considerations for the eradication endgame. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 368(1623):20120149.

Barrett, S. (2016). Coordination vs. voluntarism and enforcement in sustaining international environmental cooperation. *Proceedings of the National Academy of Sciences*, 113(51):14515–14522.

Berninghaus, S. K., Ehrhart, K.-M., and Keser, C. (2002). Conventions and local interaction structures: experimental evidence. *Games and Economic Behavior*, 39(2):177–205.

Bock, O., Baetge, I., and Nicklisch, A. (2014). hroot: Hamburg registration and organization online tool. *European Economic Review*, 71:117–120.

Boosey, L. A. (2017). Conditional cooperation in network public goods experiments. *Journal of behavioral and experimental economics*, 69:108–116.

Borriello, A., Master, D., Pellegrini, A., and Rose, J. M. (2021). Preferences for a covid-19 vaccine in australia. *Vaccine*, 39(3):473–479.

Bramoullé, Y. and Kranton, R. (2007). Public goods in networks. *Journal of Economic Theory*, 135(1):478–494.

Bramoullé, Y., Kranton, R., and D'amours, M. (2014). Strategic interaction and networks. *American Economic Review*, 104(3):898–930.

Buckley, E. and Croson, R. (2006). Income and wealth heterogeneity in the voluntary provision of linear public goods. *Journal of Public Economics*, 90(4-5):935–955.

Caparrós, A. and Finus, M. (2020a). The corona-pandemic: a game-theoretic perspective on regional and global governance. *Environmental and Resource Economics*, 76(4):913–927.

Caparrós, A. and Finus, M. (2020b). Public good agreements under the weakest-link technology. *Journal of Public Economic Theory*, 22(3):555–582.

Cason, T. N., Sheremeta, R. M., and Zhang, J. (2012). Communication and efficiency in competitive coordination games. *Games and Economic Behavior*, 76(1):26–43.

Cassar, A. (2007). Coordination and cooperation in local, random and small world networks: Experimental evidence. *Games and Economic Behavior*, 58(2):209–230.

Cavaliere, A. (2001). Coordination and the provision of discrete public goods by correlated equilibria. *Journal of Public Economic Theory*, 3(3):235–255.

Chen, D. L., Schonger, M., and Wickens, C. (2016). otreean open-source platform for laboratory, online, and field experiments. *Journal of Behavioral and Experimental Finance*, 9:88–97.

Cherry, T. L., Kroll, S., and Shogren, J. F. (2005). The impact of endowment heterogeneity and origin on public good contributions: evidence from the lab. *Journal of Economic Behavior and Organization*, 57(3):357–365.

Cooper, D. J. and Weber, R. A. (2020). Recent advances in experimental coordination games. *Handbook of experimental game theory*, pages 149–183.

Corazzini, L., Cotton, C., and Reggiani, T. (2020). Delegation and coordination with multiple threshold public goods: experimental evidence. *Experimental Economics*, 23(4):1030–1068.

Corazzini, L. and Gianazza, U. (2008). Unequal contributions from symmetric agents in a local interaction model. *Journal of Public Economic Theory*, 10(3):351–370.

Falk, A., Fischbacher, U., and Gächter, S. (2013). Living in two neighborhoodssocial interaction effects in the laboratory. *Economic Inquiry*, 51(1):563–578.

Feemster, K. A. and Szipszky, C. (2020). Resurgence of measles in the united states: how did we get here? *Current Opinion in Pediatrics*, 32(1):139–144.

Fellner, G. and Lünser, G. K. (2014). Cooperation in local and global groups. *Journal of Economic Behavior and Organization*, 108:364–373.

Fischbacher, U., Schudy, S., and Teyssier, S. (2014). Heterogeneous reactions to heterogeneity in returns from public goods. *Social Choice and Welfare*, 43(1):195–217.

Gallo, E. and Yan, C. (2023). Efficiency and equilibrium in network games: An experiment. *Review of Economics and Statistics*, 105(6):1515–1529.

Gangadharan, L., Nikiforakis, N., and Villeval, M. C. (2017). Normative conflict and the limits of self-governance in heterogeneous populations. *European Economic Review*, 100:143–156.

Gregor, M. (2011). Tradeoffs of foreign assistance for the weakest-link global public goods. *International Tax and Public Finance*, 18(2):233–251.

Harrison, G. W. and Hirshleifer, J. (1989). An experimental evaluation of weakest link/best shot models of public goods. *Journal of Political Economy*, 97(1):201–225.

Hauser, O. P., Hilbe, C., Chatterjee, K., and Nowak, M. A. (2019). Social dilemmas among unequals. *Nature*, 572(7770):524–527.

Hays, J. N. (2005). *Epidemics and pandemics: their impacts on human history.* Abc-clio.

Heap, S. P. H., Ramalingam, A., and Stoddard, B. V. (2016). Endowment inequality in public goods games: A re-examination. *Economics Letters*, 146:4–7.

Henderson, D. A. (1987). Principles and lessons from the smallpox eradication programme. *Bulletin of the World Health Organization*, 65(4):535.

Hirshleifer, J. (1983). From weakest-link to best-shot: The voluntary provision of public goods. *Public Choice*, 41(3):371–386.

Hofmeyr, A., Burns, J., and Visser, M. (2007). Income inequality, reciprocity and public good provision: an experimental analysis. *South African Journal of Economics*, 75(3):508–520.

Karakostas, A., Kocher, M. G., Matzat, D., Rau, H. A., and Riewe, G. (2023). The team allocator game: Allocation power in public goods games. *Games and Economic Behavior*, 140:73–87.

Kirchkamp, O. and Nagel, R. (2007). Naive learning and cooperation in network experiments. *Games and Economic Behavior*, 58(2):269–292.

Kölle, F. (2015). Heterogeneity and cooperation: The role of capability and valuation on public goods provision. *Journal of Economic Behavior and Organization*, 109:120–134.

Kolstad, C. D. (2010). Equity, heterogeneity and international environmental agreements. *The BE Journal of Economic Analysis and Policy*, 10(2).

Lei, V., Tucker, S., and Vesely, F. (2007). Foreign aid and weakest-link international public goods: An experimental study. *European Economic Review*, 51(3):599–623.

Lo, N. C. and Hotez, P. J. (2017). Public health and economic consequences of vaccine hesitancy for measles in the united states. *JAMA pediatrics*, 171(9):887–892.

Nikiforakis, N., Noussair, C. N., and Wilkening, T. (2012). Normative conflict and feuds: The limits of self-enforcement. *Journal of Public Economics*, 96(9-10):797–807.

Nosenzo, D., Quercia, S., and Sefton, M. (2015). Cooperation in small groups: the effect of group size. *Experimental Economics*, 18(1):4–14.

Rao, N., Mobius, M. M., and Rosenblat, T. (2007). Social networks and vaccination decisions.

Riedl, A., Rohde, I. M., and Strobel, M. (2016). Efficient coordination in weakest-link games. *The Review of Economic Studies*, 83(2):737–767.

Rosenkranz, S. and Weitzel, U. (2012). Network structure and strategic investments: An experimental analysis. *Games and Economic Behavior*, 75(2):898–920.

Tavoni, A., Dannenberg, A., Kallis, G., and Löschel, A. (2011). Inequality, communication, and the avoidance of disastrous climate change in a public goods game. *Proceedings of the National Academy of Sciences*, 108(29):11825–11829.

Thompson, K. M. and Tebbens, R. J. D. (2007). Eradication versus control for poliomyelitis: an economic analysis. *The Lancet*, 369(9570):1363–1371.

Van Dijk, F., Sonnemans, J., and Van Winden, F. (2002). Social ties in a public good experiment. *Journal of Public Economics*, 85(2):275–299.

Vicary, S. (1990). Transfers and the weakest-link: An extension of hirshleifer's analysis. *Journal of Public Economics*, 43(3):375–394.

Vicary, S. and Sandler, T. (2002). Weakest-link public goods: Giving in-kind or transferring money. *European Economic Review*, 46(8):1501–1520.

Waichman, I., Requate, T., Karde, M., and Milinski, M. (2021). Challenging conventional wisdom: Experimental evidence on heterogeneity and coordination in avoiding a collective catastrophic event. *Journal of Environmental Economics and Management*, 109:102502.

Weber, R. A. (2006). Managing growth to achieve efficient coordination in large groups. *American Economic Review*, 96(1):114–126.

Zelmer, J. (2003). Linear public goods experiments: A meta-analysis. *Experimental Economics*, 6(3):299–310.

Zhang, Y. and He, L. (2021). Theory and experiments on network games of public goods: inequality aversion and welfare preference. *Journal of Economic Behavior & Organization*, 190:326–347.

Appendices

Appendix 3.A: Proof of Proposition subsection 3.3.1

Consider a maximal connected set of locations with the maximal total investments, $\max_j G_j$, the number of locations in this set being denoted by k. For players within the interior of this set, the weakest-link is $\max_j G_j$, for players bordering lower investment locations, the minimum is given by these lower levels. For this to occur in equilibrium, these border players must have invested *all* their endowment in this neighbor's location with the lower total investment level.

First assume that $k = 3$. Here, the center player in the connected set would not have an incentive to invest in three locations. This contradicts the assumption that these three locations have a larger total investment level than the neighboring location. Second, assume $k = 4$. In both alternating and clustered settings, one corner player would have high endowment. Hence, this high endowment player would be able to bring up the total investments in the neighbor's location to $\max_j G_j$ in contradiction to the assumed investment patterns. Third, assume $k = 5$. Here, both border player in the connected set as well as the player at the lowest total investment location would have incentives to invest all endowment in this location, in contradiction to the assumption that the total investment in that location is lower than in the other locations.

Appendix 3.B: Dynamics

	T1 CN_{hom}	T2 ON_{hom}	T3 ON_{alt}	T4 ON_{clu}	T5 ON^{C}_{alt}	T6 ON^{C}_{clu}
Rounds 1-5						
keep	8.39	7.59	9.39	11.23	11.42	12.13
	(4.09)	(3.83)	(3.84)	(3.69)	(3.71)	(3.10)
invest_sum	21.61	22.41	20.61	18.77	18.58	17.87
	(4.09)	(3.83)	(3.84)	(3.69)	(3.71)	(3.10)
invest_own	9.70	8.53	8.12	7.41	12.07	11.98
	(3.02)	(2.39)	(2.73)	(2.32)	(2.03)	(2.20)
invest_others	11.92	13.88	12.49	11.36	6.51	5.89
	(3.30)	(3.48)	(2.67)	(2.03)	(2.24)	(1.88)
provided	16.27	16.51	14.47	12.49	13.23	12.56
	(5.59)	(4.08)	(4.42)	(3.94)	(2.74)	(3.67)
payoff	49.05	48.87	45.57	42.44	44.50	43.54
	(10.15)	(7.11)	(7.47)	(6.76)	(3.55)	(6.39)
Rounds 6-10						
keep	9.34	11.15	11.52	14.77	12.36	15.54
	(6.96)	(5.22)	(6.30)	(5.86)	(5.60)	(4.47)
invest_sum	20.66	18.85	18.48	15.23	17.64	14.46
	(6.96)	(5.22)	(6.30)	(5.86)	(5.60)	(4.47)
invest_own	8.40	6.67	7.10	5.87	11.57	10.57
	(4.21)	(3.38)	(3.85)	(2.95)	(3.54)	(4.33)
invest_others	12.26	12.18	11.38	9.36	6.07	3.89
	(4.92)	(3.65)	(3.60)	(3.29)	(2.51)	(1.51)
provided	17.27	14.48	14.04	11.23	13.51	9.72
	(7.42)	(4.63)	(6.46)	(5.46)	(4.45)	(3.88)
payoff	52.53	47.36	46.61	42.84	46.14	39.85
	(12.00)	(6.90)	(10.31)	(8.34)	(5.61)	(5.65)
Observations	12	12	11	10	11	10

Table 3.A.1 Dynamics of the main summary statistics over the 10 rounds, separated by their average value in the first 5 rounds (1-5) and the last 5 (6-10).

	T1	T2	T3	T4	T5	T6
	CN_{hom}	ON_{hom}	ON_{alt}	ON_{clu}	ON^C_{alt}	ON^C_{clu}
waste_sp1to5	5.35	5.90	6.14	6.29	5.36	5.31
	(2.11)	(1.99)	(1.38)	(1.77)	(1.44)	(1.39)
waste_sp6to10	3.39	4.37	4.45	4.00	4.13	4.74
	(2.00)	(1.78)	(1.93)	(1.91)	(1.32)	(1.47)
p-value	0.0005	0.0289	0.0025	0.0012	0.0397	0.3668
waste_se1to5	10.19	11.41	10.47	10.50	9.57	9.21
	(2.93)	(2.67)	(1.82)	(2.32)	(2.58)	(1.72)
waste_se6to10	7.47	8.46	7.70	6.97	8.03	7.04
	(3.94)	(2.67)	(2.82)	(3.47)	(3.02)	(2.50)
p-value	0.0000	0.0000	0.0000	0.0000	0.0031	0.0002
waste_al1to5	9.84	7.01	7.38	7.43	6.62	5.17
	(2.89)	(2.81)	(1.79)	(1.82)	(2.63)	(1.07)
waste_al6to10	6.93	5.23	4.81	4.24	4.28	3.23
	(4.08)	(2.21)	(2.26)	(2.82)	(2.70)	(1.64)
p-value	0.0000	0.0024	0.0000	0.0000	0.0001	0.0000
Observations	12	12	11	10	11	10

Table 3.A.2 Dynamics of wasted investments over the 10 rounds. The three different definitions of wasted tokens are used: from a social planner's perspective ("waste_sp"), for an altruistic player ("waste_al") and for a selfish one ("waste_se"). p-values reported from Wilcoxon signed-rank test.

Appendix 3.C: Instructions (translation from German original, treatment 4)

Welcome to our experiment!

General information

In this experiment you can earn money depending on your decisions and the decisions of the other participants.

Please read the instructions carefully to learn the rules of the experiment.

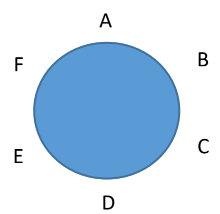
Payment during the experiment is calculated in LabPoints (LP). The exchange between LP and Euro is 5:1, i.e. 1 LP is exchanged for 0.20 €.

At the end of the experiment you will fill in a questionnaire. In total, the experiment will take about 60 minutes. Your answers will be treated anonymously. If you leave the experiment early, you will not receive any compensation.

Rules

You are in a group of 6 participants, i.e. you and 5 other people. The 6 participants take a seat at a virtual round table. Each group member faces the same decision problem. All decisions in this experiment are anonymous. To maintain anonymity, you are identified by a letter (between A and F).

The game lasts 10 separate rounds in which the same game is played. At the end, one of the 10 rounds is randomly selected and used to calculate the payouts.



Three members of the group start each round with 40 LP credited to a personal account, the other three start with 20 LP each. Specifically, players A, B and C each receive 20 LP, while players D, E and F each receive 40 LP.

Each participant decides how many LP they want to keep and how many they want to invest in projects at the respective locations A-F. That is, **each player can invest at every location**. In total, a player's investments cannot exceed his initial endowment of (40 or 20).

The total investment in a particular location is the sum of the investments made by the six players in that location. For example, the total investment in location C is the sum of the investments made in location C by all the players in the group.

Your payout at the end of the game is made up of the following parts:

- The number of LPs you still have in your personal account.
- 2.5 times **the minimum of the total investments made at your location and at the two locations of your right and left neighbours** at the round table.

That is, your payout for an initial endowment of 40 is calculated as follows:

> Payout = (Your balance (40) MINUS your total investment) PLUS 2.5 times (minimum of the total investment at your site and your two neighbouring sites).

On the other hand, if you have an initial endowment of 20, your payout is calculated as follows:

> Payout = (your balance (20) MINUS your total investment) PLUS 2.5 times (minimum investment at your site and your two neighbouring sites).

After the decision has been made by you and the other 5 members of your group, all players are informed of how much each member has in their personal account and the total investment in each location.

You are part of the same group and have the same neighbours for all ten rounds. They will also have the same letter identifier and the same initial endowment throughout the experiment. The payoff for the other participants is calculated in the same way as yours, considering the total investments in each player's location and right and left neighbours.

Remember that one of the 10 rounds is randomly selected and used to calculate the payouts. Think carefully about your choice, because each of the rounds can determine your payout.

Example of the payout

You and the other participants can use the following examples to familiarise yourself with the game.

1. You have an initial endowment of 40 LP and invest 20 LP in your own location and 10 LP in the location of your right neighbour. Assume that the total investment in your location is 20 and 10 to your left and 10 to your right. Then the minimum investment in your location and your neighbour's location is 10.

   Your payout is then (40 - 20 - 10) + 2.5 x (10) = 10 + 25 = 35

2. You have an initial endowment of 40 LP and invest 20 LP in your own location and nothing in other locations. Assume that the total investment in your site is 20 and 8 to your left and 0 to your right. Then the minimum investment in your location and your neighbours' locations is 0.

   Your payout is then (40 - 20) + 2.5 x (0) = 20 + 0 = 20

3. You have an initial endowment of 40 LP and invest 14 LP in your own site and 7 LP in your left neighbour's site. Assume that the total investments in your site are 15 and 13 to your left and 20 to your right. Then the minimum investment in your site and your neighbour's sites is 13.

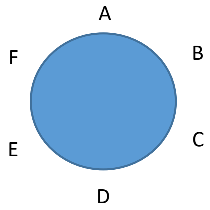
   Your payout is (40 - 14 - 7) + 2.5 x (13) = 19 + 32.5 = 51.5

The payouts to the other players depend on the investments in their respective neighbourhoods.

You can use the following examples to familiarise yourself with the rules of the game as well as the presentation of the feedback of the respective rounds.

Example 1

Here you see a hypothetical example of the decisions of 6 participants.

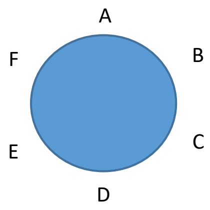


Participant	Initial endowment	Remain in private account	Total investment in the location	Minimal investment (Neighborhood)	Payout from the investment	Total payout
A	20	10	15	7 (A,B,F)	2,5 * 7 =17,5	27,5
B	20	18	7	7 (A,B,C)	2,5 * 7 =17,5	35,5
C	20	10	25	7 (B,C,D)	2,5 * 7 =17,5	27,5
D	40	30	10	10 (C,D,E)	2,5 * 10 =25	55
E	40	15	15	10 (D,E,F)	2,5 * 10 =25	40
F	40	5	20	15 (E,F,A)	2,5 * 15 =37,5	42,5

Remember that the total payout amount is calculated as follows: "Remain in own account" + "Payout from investment" = "Total payout".

Example 2

Here you see a hypothetical example of the decisions of 6 participants.



Participant	Initial endowment	Remain in private account	Total investment in the location	Minimal investment (Neighborhood)	Payout from the investment	Total payout
A	20	0	30	15 (A,B,F)	2,5 * 15=37,5	37,5
B	20	15	15	10 (A,B,C)	2,5 * 10 = 25	40
C	20	20	10	10 (B,C,D)	2,5 * 10 = 25	45
D	40	20	10	10 (C,D,E)	2,5 * 10 = 25	45
E	40	0	30	10 (D,E,F)	2,5 * 10 = 25	25

F	40	0	30	30 (E,F,A)	2,5 * 30 = 75	75

Remember that the total payout amount is calculated as follows: "Remain in own account" + "Payout from investment" = "Total payout".

Summary of instructions.

- You play 10 rounds in a group of 6 players.
- You are told which position you occupy in the round table (A to F) and what your starting endowment is (40 or 20). Players A, B, C receive 20 LP; players D, E, F receive 40 LP.
- You can invest in any location.
- In each round:
  - You and the other participants decide independently how many of the (40 or 20) tiles you invest.
  - Your payout is the sum of what you have in your account PLUS 2.5 times the minimum investment in your location and the locations of your two neighbours.
  - All players will be informed of how much each member has kept in their personal account and the total investment in each location.
- The game is repeated for a total of 10 rounds.
- Finally, you will be asked some questions about yourself.
- A random round is selected and you are paid according to your payout in that round**.**

Control questions

Please answer the following control questions.

If you have read all the instructions and have no doubts, please answer the following control questions:

Assume that the total investments at your location are 10, at your left neighbour's location are 20 and at your right neighbour's location are 15. Then what is your payout from the investments in this round? [CORRECT ANSWER B]

Note again that your payoff from the investments is 2.5 times the minimum of the investments at the three sites in your neighbourhood.

a) 12.5 b) 25 c) 37,5 d) 50

Assume that the total investments at your location are 15, at your left neighbour's location are 10 and at your right neighbour's location are 5. Then what is your payout from the investments in this round? [CORRECT ANSWER A]

Note again that your payoff from the investments is 2.5 times the minimum of the investments at the three sites in your neighbourhood.

a) 12,5 b) 25 c) 37,5 d) 50

How many members are there in a group? [CORRECT ANSWER C]

a) 4 b) 5 c) 6 d) 8

Do the members of a group change between rounds? [CORRECT ANSWER B]

a) Yes b) No

Whose site can you invest in? [CORRECT ANSWER B]

a) Only in your own location
b) In any location
c) In your location and those of your neighbours
d) Only in your neighbours' location

Are your neighbours always the same participants? [CORRECT ANSWER A]

a) Yes b) No

The experiment begins as soon as all participants have answered these questions.

Appendix 3.D: Questionnaire (translation from German original)

Finally, we would like to ask you a few questions. We would like to ask you to answer them carefully.

[QUESTIONNAIRE - QUESTIONS]

1. Please, indicate your gender:

□ Male
□ Female
□ Other

2. Please, indicate your year of birth

....

3. Please, indicate your field of studies

□ Natural sciences
□ Social sciences
□ Humanities
□ Business administration (BWL)
□ Economics (VWL)
□ Law

4. On a scale of 0 to 10, where 0 means "not at all satisfied" and 10 means "really satisfied", how satisfied are you...

	Not at all satisfied										Really satisfied
	0	1	2	3	4	5	6	7	8	0	10
... with your investment decisions?											
... with the investment decisions of your neighbors?											

5. On a scale of 0 to 10, where 0 means "not generous at all" and 10 means "very generous", how generous do you think...

	Not at all generous										Really genereous
	0	1	2	3	4	5	6	7	8	0	10
... that you were with your invesments?											
... the rest of participants were with their investments?											

6. Please tell us how risk-ready or risk-averse you are in general. *Please use the scale from 0 to 10, where 0 means: "not at all willing to take risks" and 10 "very willing to take risks". You can use the values between 0 and 10 to grade your assessment.*

.

Not at all willing to take risks										Very willing to take risks
0	1	2	3	4	5	6	7	8	0	10

7. We now ask you about your willingness to behave in a certain way in four different areas. Again, please indicate your response on a scale of 0 to 10, where 0 means you are "not at all willing" and a 10 means you are "very willing".

	Not at all willing									Very willing
	0	1	2	3	4	5	6	7	8	0	10
How willing are you to give up something that benefits you today in order to have more of it in the future?											
How willing are you to punish someone who treats you unfairly, even if it may come at a cost to you?											
How willing are you to punish someone who treats others unfairly, even if it may come at a cost to you?											
How willing are you to donate to good causes without expecting anything in return?											

8. What do you think was studied in this experiment? (Please write one or two sentences maximum)

....

Chapter 4

A good neighbor – a found treasure: on the voluntary public good provision in overlapping neighborhoods

Authors: Juliane Koch, Andreas Lange, Lorenzo Romero-Fernández

Abstract

Providing for a public good that benefits the poor might be more lucrative for the rich if they benefit likewise. This paper is inspired by ideas of policymakers advocating mixed neighborhoods and the general problem of public goods benefiting some groups relatively more than others. We investigate the role of varying spatial allocations of rich and poor for the voluntary provision of public goods. Our findings show that participants do invest in others' locations, yet mainly in a way in which they themselves benefit, i.e. in locations of their direct neighbors. In networks where rich and poor are clustered, we observe that it is the rich located at the border who trigger the redistribution to the poor cluster. Apart from equity concerns, we observe that participants are motivated by reciprocity as they reduce (increase) investments and thus punish (reward) neighbors who contributed less (more). This study highlights the importance of the spatial allocation between rich and poor in networks and suggests that making direct and indirect beneficiaries of public good provisions salient can be a way to decrease inequality.
JEL classification: C91, H41, Q50
Keywords: public good, summation technology, overlapping neighborhoods, in-kind transfer, heterogeneity.

4.1 Introduction

"It is discouraging to try to be a good neighbor in a bad neighborhood."
(William Castle)

Many public goods rely on voluntary contributions by members of communities. Yet, not all public goods are also global goods and serve everybody alike. The benefits of most public goods (or harms for public bads respectively) depend on the location of their provision relative to the location of potential beneficiaries. Reflecting this spatial structure of benefits, distributional concerns have received increased attention in both public debate and academic literature as the quality of local public goods often correlates with socio-economic status, e.g. for school quality (Avery and Pathak, 2021; Epple and Romano, 1998), or for environmental justice (Banzhaf et al., 2019).

Other examples that mirror the importance of the spatial location of public good provision range from public infrastructure and security to public bads such as pollution of air, water, soil, or noise. The exact locality of such goods or bads is crucial as for some goods geographical distance is the determining factor: The benefit of local parks or playing grounds that are located too far from users' homes becomes negligible. The contamination of water sources in specific locations is worse for those users located closest to the pollution source and decreases with distance.

Motivated by these examples, we investigate spatial patterns in an experiment on voluntary public good provision. We introduce a spatial public goods game with overlapping neighborhoods. Within this setting, which corresponds to a circular network, we investigate the role of endowment heterogeneity. Inspired by public discourse on mixed vs. segregated (income) neighborhoods (e.g., Thurber et al., 2018), we compare a mixed neighborhood setting where rich and poor alternate in space with a clustered neighborhood settings where rich and poor are spatially segregated and directly interact only at the boundaries of their respective neighborhoods. Such mixed-neighborhoods are often advocated by policymakers and scholars to address problems of social exclusion.

We consider this experimental setting as novel and empirically relevant. It allows to provide new insights into behavioral motivations for voluntary public good provision. Differently from the often studied experimental public good paradigm, the spatial structure allows players to not only choose *how much* to contribute, but – through the location of their investments – also *where* and thereby to also decide on *who* benefits from those contributions. We can thus differentiate general prosocial from distributional concerns and provide new evidence on the nature of reciprocal preferences (e.g, Rabin, 1993; Dufwenberg and Kirchsteiger, 2004).

Our results show that participants focus their investments on locations in their own neighborhood, i.e. those which generate benefits to themselves. Their investments in (direct) neighbors' locations are found to reflect both, concerns for inequality as well as reciprocity. Neither the introduction of the spatial structure of overlapping neighborhoods nor endowment heterogeneity per se affect the *average* group payoff levels. Yet, the spatial distribution of endowments matters for the payoff distribution within the group. In both, the alternating and the clustered endowment settings, investments generally result in redistribution from the rich to the poor and, thus, reduce inequality. Yet, when rich and poor players are clustered, this redistribution is primarily driven by the rich players located at the border who transfer to the poor and thereby channel most of their investments to benefit the poor and not the rich neighbor. Consequently, the rich player located in the center of the cluster who triggers redistribution to a lower extent is best off in terms of final payoffs. This is different in the alternating setting where all rich players drive redistribution to a similar extent. Apart from inequality concerns, the dynamic adjustments of contributions provide evidence for reciprocal preferences: the level and the spatial patterns of players' investments respond to investment behavior of their direct neighbors. These behavioral differences that depend on the players' spatial location can be expected to increase with the size and potentially type of the network. One should note that the network structure we look at are six-player circular networks with three rich and three poor players. At the end of the paper, we provide a discussion on potential extensions in terms of alternative network structures and their implications. Yet, our findings provide first insights that enriching the strategy space beyond the canonical public good experimental paradigm is beneficial in identifying behavioral motives.

Our experimental design is most closely related to recent studies on voluntary public good provision in networks that investigate how network structures affect cooperation (e.g., Cassar, 2007; Kirchkamp and Nagel, 2007; Rosenkranz and Weitzel, 2012; Angelovski et al., 2018a,b). Some experimental studies have also tested similar network structures, i.e. a circular network in which participants benefit from their own as well as their neighbors' provision (e.g. Boosey, 2017; Gallo and Yan, 2023; Zhang and He, 2021). Yet, none of these studies has explored the role of endowment heterogeneity nor considered the option of investing not only in one's own location, but also of providing in-kind transfers to others.[1] With this heterogeneous network setting we thereby introduce more sophisticated and realistic strategy sets that also take preferences such as inequality aversion, efficiency and reciprocity into account.

The impact of endowment heterogeneity per se has received substantial attention in typical public good experiments (e.g., Zelmer, 2003; Cherry et al., 2005; Heap et al., 2016).[2]

[1]Lange and Romero-Fernández (2023) also consider a circular network structure with heterogeneous agents, but investigate a different aggregation technology, namely a weakest link.

[2]Heterogeneities have been investigated along different dimensions, e.g. w.r.t. endowments (e.g Zelmer,

Apart from few results in which inequality can trigger cooperation (e.g Barrett, 2001; Waichman et al., 2021) or has no effect (Hofmeyr et al., 2007), most results suggest that heterogeneity leads to lower contribution and cooperation levels.[3] This also applies in settings where players can simultaneously contribute to different public goods, e.g. global and local ones (e.g., Falk et al., 2013; Fellner and Lünser, 2014; Lange et al., 2022). Under heterogeneity, decreases in contribution levels can result from a "normative conflict" as different individuals may favor different distributional norms (e.g., Nikiforakis et al., 2012; Lippert and Tremewan, 2021; Kesternich et al., 2014). That is, normative rules such as equal income or wealth do no longer correspond to equal absolute or relative contribution levels.

Especially in the theoretical literature, the voluntary contributions within certain network structures have gained attention (e.g., Bramoullé and Kranton, 2007; Bramoullé et al., 2014; Allouch, 2015). This literature demonstrates that the network structure itself affects the patterns of public good provision and that networks can lead to specialization in public good provision, where only some agents contribute, depending on their links with other agents. Our circular network structure is inherently symmetric with each player interacting with two direct neighbors, yet asymmetries are achieved through implementing different endowment patterns. While the theoretical literature largely focuses on standard preferences for private and public good consumption, our experiment relies on a linear public good setting such that any (positive) contributions to public accounts rely on behavioral motivations.

The remainder of the paper is structured as follows: section 4.2 discusses the experimental design and provides a theoretical guidance and predictions, section 4.3 reports the experimental results, before we conclude in section 4.4.

4.2 Experimental design and predictions

4.2.1 Experimental setting and treatments

We propose an experimental design that extends the classical public goods game by adding a spatial element, where the location of a player has an effect on her provision of the

2003; Cherry et al., 2005; Heap et al., 2016), marginal per capita returns on contributions (e.g. Kolstad, 2010; Fischbacher et al., 2014; Nosenzo et al., 2015; Gangadharan et al., 2017), productivity (Hauser et al., 2019), benefits from the public good (Kölle, 2015), or a symmetric or asymmetric inequality combination between income and productivity (Hauser et al., 2019).

[3] The extent to which groups suffer from this coordination failure depends on factors such as the information setting (Fellner-Röhling et al., 2020), the institutions (Kingsley, 2016), group size (Nosenzo et al., 2015) or the production function (Chan et al., 1996, 1999).

public good. Each of six participants of a group is identified with her respective location $i \in \{A,B,C,D,E,F\}$. For each player, we define a neighborhood N_i that comprises $k = 3$ participants. The public good provided to player i is calculated by the sum of all the investments made in her neighborhood, i.e. the sum of the investment in her location, plus the investments at her left- and right-hand neighbors' location.

Participants have an endowment of w_i tokens which they can invest in any of the locations. We denote g_{ij} the amount that individual i (located in i) invests in location j. Total investments in location j are thus given by $G_j = \sum_i g_{ij}$. The payoff of player i is given by

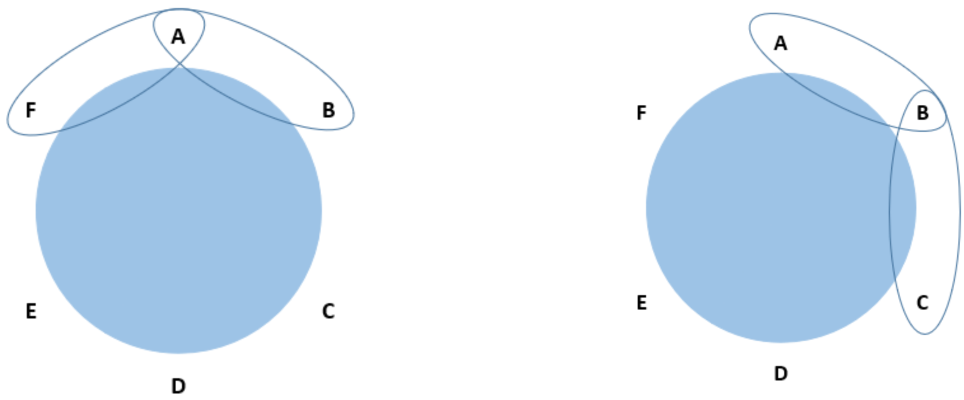
$$\Pi_i = w_i - \sum_j g_{ij} + h \sum_{j \in N_i} G_j. \tag{4.1}$$

That is, each participant benefits from all investments made in her neighborhood. The productivity multiplier of the public good is set at $h = 0.5$ and thus satisfies the typical public good properties $h < 1$ and $nh > 1$ with $n = 3$ being the size of each neighborhood.

The experimental treatments vary the structure of the spatial neighborhoods and the endowment allocation. We consider two different neighborhood settings: a closed and an overlapping neighborhood setting. First, we consider a closed setting with with two separated neighborhoods: $N_A = N_B = N_C = \{A,B,C\}$ and $N_D = N_E = N_F = \{D,E,F\}$. This structure thus corresponds to a typical three-player public goods game. The only differences with the typical public goods setup are the simultaneous presence of (and information about) another 3-persons group as well as the option to invest in any location within and outside their own neighborhood. Within this structure, we consider a treatment with homogeneous endowment (T1: CN_{hom}) and a treatment with endowment heterogeneity (T2: CN_{het}).

Second, we study overlapping neighborhoods where the neighborhood of a player is composed of her location and her two direct neighbors within a circular network. That is, $N_A = \{A,B,F\}$, $N_B = \{A,B,C\}$, $N_C = \{B,C,D\}, \ldots, N_F = \{E,F,A\}$. With this, the six neighborhoods overlap each other and any player i is part of three neighborhoods: hers and the neighborhoods of her left- and right-hand side neighbors. Hence, each participant benefits from public good investments in her location, as well as the investments made in the location of her two neighbors. Conversely, investments in any location benefit three players.
Figure 4.1 illustrates the concept of these overlapping neighborhoods.

Within this overlapping neighborhood structure, we again compare a homogeneous endowment setting (T3: ON_{hom}) with endowment heterogeneity. Importantly, the spatial distribution of endowments matters in this setting: we compare an alternating endowment setting (T4: ON_{alt}) where rich and poor individuals alternate (A, C and E having



(a) Neighborhood of A

(b) Neighborhood of B

Figure 4.1 Example of overlapping neighborhoods in Treatments T3-T5.

a low endowment; and B, D and F high endowment) and a clustered endowment setting (T5: ON_{clu}) where three direct neighbors (A, B, C) have a low endowment of w^L while the other three (D, E, F) have a high endowment w^H. Figure 4.2 provides a graphical representation of the spatial neighborhood settings in all five treatments.

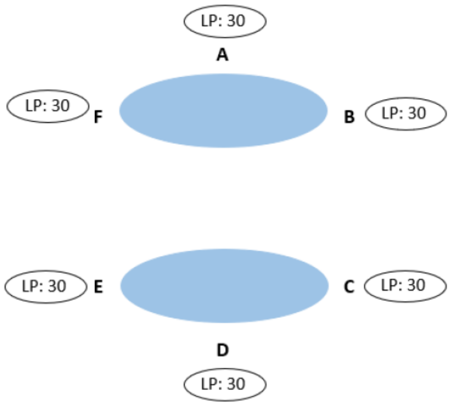
Within our experiment, the endowments are measured in tokens, and the values chosen are $w^M = 30$ for the homogeneous treatments (T1 CN_{hom} and T3 ON_{hom}), and $w^L = 20$ and $w^H = 40$ in the heterogeneous treatments (T2 CN_{het}, T4 ON_{alt} and T5 ON_{clu}). The features of all five treatments are summarized in Table 4.1.

Treatments	T1 CN_{hom}	T2 CN_{het}	T3 ON_{hom}	T4 ON_{alt}	T5 ON_{clu}
Neighborhoods	CN	CN	ON	ON	ON
Endowments	Hom	Het	Hom	Het	Het
	$w^M = 30$ (A,B,C,D,E,F)	$w^L = 20$ (B,D,F) $w^L = 40$ (A,C,E)	$w^M = 30$ (A,B,C,D,E,F)	$w^L = 20$ (B,D,F) $w^H = 40$ (A,C,E)	$w^L = 20$ (A,B,C) $w^H = 40$ (D,E,F)
Distribution	-	Alternating	-	Alternating	Clustered
Payoff	$\Pi_i = w_i - \sum_j g_{ij} + h \sum_{j \in N_i} G_j$				

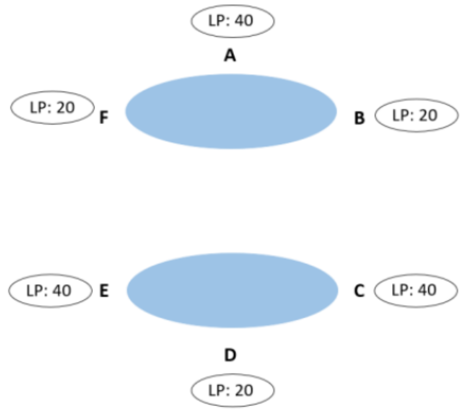
Table 4.1 Summary of features of all treatments.

4.2.2 Experimental procedure

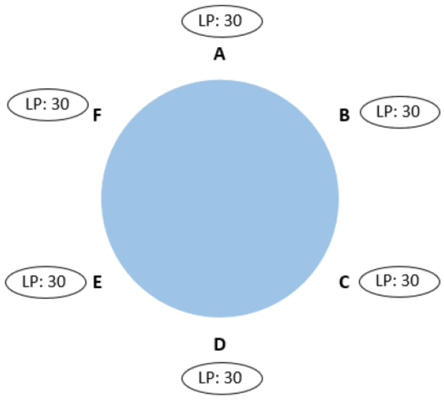
The experimental sessions took place as an in-person lab experiment in September and October 2023 at the Vienna Center for Experimental Economics of the University of Vienna. In total, we recruited 462 participants, resulting in 15 groups of 6 players in Treatments 2,3, and 4 and 16 groups of 6 players in Treatments 1 and 5. Participants



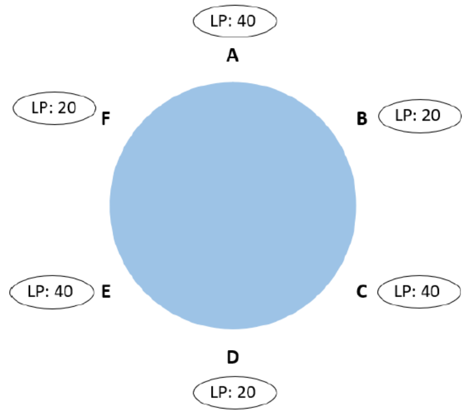
(a) Treatment T1: CN_{hom}



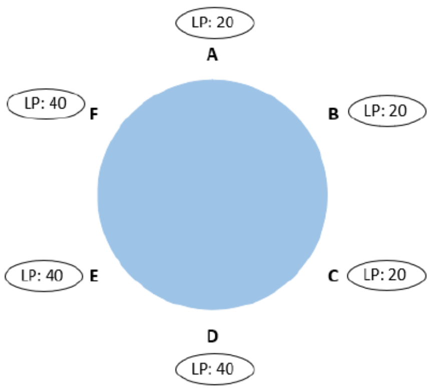
(b) Treatment T2: CN_{het}



(c) Treatment T3: ON_{hom}



(d) Treatment T4: ON_{alt}



(e) Treatment T5: ON_{clu}

Figure 4.2 Representation of the treatments T1-T5.

took part in the study by coming in person to the lab facilities of the University of Vienna and were handled via the ORSEE software (Greiner, 2015). The experiment was coded using oTree (Chen et al., 2016), was preregistered at the AEA RCT Registry (Koch et al., 2023) and got ethical approval by the Faculty of Business, Economics and Social Sciences of the University of Hamburg.[4]

[4]Initially, the experiment was planned at the WiSo Research Lab at the Faculty of Business, Economics and Social Sciences of the University of Hamburg in early 2023. Due to recruitment problems post COVID and failing to come close to the required sample size, we decided to stop this data collection and

Participants were first presented with the instructions of the experiment, which were followed by a set of control questions. After correctly answering all control questions, the participants were assigned into groups of six players, belonging to one of the five treatments. At the same time, they were also assigned a spatial location inside the group (A-F). Depending on the treatment and the position they were assigned to, their endowment w_i was determined. The group composition, spatial distribution and endowment levels were maintained during the ten rounds of the experiment. At the beginning of each round, all participants were given a new batch of tokens w_i. Afterwards, they were asked to allocate their endowment w_i in any of the locations A-F. Participants were allowed to invest in any number of locations, from none (thus keeping all tokens in their private account) to six (investing in all locations). They could freely choose the amounts invested in the respective locations as long as an individual's total investments did not exceed her token allotment w_i. [5]

After each round, participants were provided with a feedback table. This table reported how many tokens each participant kept in her private account, the total investments made in each location, the total public good level provided in each neighborhood, the payoff from the public good investments in each respective neighborhood, and the final payoff of each player in that respective round (see Appendix 4.4). At the end of the experiment, one of the ten rounds was randomly chosen for payment. After the experimental game, participants were asked to answer a short questionnaire that provided additional information regarding socio-demographics, field of studies, risk behavior and perception of the experiment. The average payment per participant was 14.65 Euros and sessions lasted around 40 minutes.

4.2.3 Experimental hypotheses

Payoff maximizers who take the investments of others as given, would evidently choose $g_{ij} = 0$ for all j as $h < 1$. In contrast, the maximization of total payoffs requires all agents to contribute their full endowment, i.e. $\sum_j g_{ij} = w_i$. A large literature has evolved that shows that positive contributions are made in linear public goods game and can be driven by, e.g., concerns for efficiency, warm-glow, reciprocity, inequality (Ashley et al., 2010; Videras and Owen, 2006).

We first note that a player i's own payoff does not depend on the specific investment

to completely restart with a new data collection at the University of Vienna. Besides the location, no changes to the experimental design were made. The otherwise-identical pre-registration from January 2023 can be found at `https://doi.org/10.1257/rct.10737-1.0`.

[5] An interactive calculator was integrated into the game and gave direct intuitive feedback to participants' on the consequences of their investment decisions, i.e. of how many tokens are created at which locations through a player's investments, before they confirmed their decisions, see Appendix 4.4.

location, i.e. as long as this investment is made at a location inside of her own neighborhood N_i, it will generate her a return of h. In contrast, investments outside one's own neighborhood are much more costly as they do not benefit the player herself. While such investments may occur due to distributional preferences, i.e. if players outside the own neighborhood are sufficiently poorer, we predict that a player confines her investments on her own neighborhood:

> **Hypothesis 1:**
> Players' investments in the public good are confined to their own neighborhood, i.e. $g_{ij} = 0$ for $j \notin N_i$.

We restrict the subsequent discussion on investment patterns on the location choices within a player's own neighborhood. Besides generating a return from the (local) public good, such investments may trigger reciprocal action by other players who benefit from these investments. Note that these may also be located *outside* of the player's neighborhood as the neighbor's neighbor benefits from investments at the neighbor's location. That is, while investments at one's own location may trigger reciprocal action by direct neighbors, investments at one's neighbors' locations may trigger investments by second-degree neighbors. Taking a concrete example considering the table structures in Figure 4.2e, player C's direct neighbors are player B and players D, while indirect or second degree neighbors are A and E (which respectively are direct neighbors of player C's direct neighbors, B and D).

Our closed neighborhood setting (Treatments 1 and 2) corresponds to the typical public good setting where players can invest into only one public account.[6] Heterogeneity in endowments may thus be expected to be detrimental to voluntary contributions (e.g., Zelmer, 2003; Cherry et al., 2005; Heap et al., 2016). With heterogeneous endowments, different equity notions may conflict, e.g. equality in final payoffs vs. equity in terms of equal gains from the provision of the public goods. Addressing such equity concerns or attending to reciprocity concerns requires changes in the amount allocated to the public good.

The overlapping neighborhood setting is designed to allow for a more nuanced strategy space: instead of only changing the *level* of the public good investment, players can also adjust the *location* of their investments. Among efficient allocations, the distribution of payoffs can widely vary as investments in the overlapping neighborhood settings can take place in different locations. In the following, we discuss the role of efficiency and equity considerations as well as reciprocity motivations in the spatial setting to guide our hypotheses for investment decisions.

[6]Even though players can in principle invest in all locations, investments outside their own neighborhood do not generate a return for them and thus are most costly.

We first show that different distributional ideals are consistent with efficiency (as defined as maximizing the total payoff, i.e. having $\sum_j g_{ij} = w_i$).

Equality consistent with efficiency

As first reference, we explore conditions that realize *equal* payoffs to all players while achieving efficiency, i.e. all players having invested all their endowments. Here, $\sum_{j \in N_i} G_j$ must be identical for all i. Simple algebra yields the following result:

Lemma 1 *For an efficient allocation to generate equal payoffs, the total investments G_j at opposing sides of the virtual table need to be identical: $G_A = G_D$, $G_B = G_E$, and $G_C = G_F$.*

Proof: see Appendix 4.A.

While equality of payoffs can thus be achieved by players investing all tokens in their own locations under endowment homogeneity (T3 ON_{hom}), equality in the treatments with endowment heterogeneity immediately requires at least some players to invest outside of their own location. The reason is that opposite ends of the table are occupied by different endowment positions in both treatments T4 ON_{alt} and T5 ON_{clu}.

The investment patterns to generate equality are not unique. Two possible transfer regimes for the alternating endowment settings are illustrated in Figure 4.3.

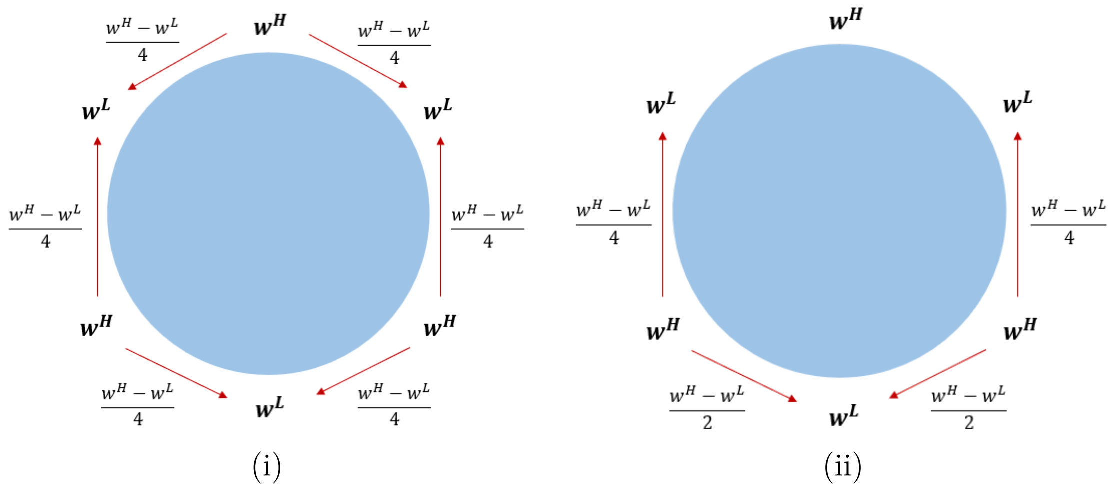


Figure 4.3 Two possible transfer regimes to obtain equality in the alternating endowment setting (T4 ON_{alt}). The arrows indicate the investments by a player in the respective neighbor's location. The remaining tokens are invested in the own location.

Importantly, as the first panel demonstrates, equality can be achieved by investment patterns where a player invests the *same* amount in both of her neighbors' locations.

This is different in the clustered setting in T5 ON_{clu}. This can easily be seen as – following Lemma 1 – the total investment in high endowment locations (D, E, F) needs to be identical to the total investments in poor locations (A, B, C). As such, equality in payoffs requires a net transfer from rich to poor locations. Two possible transfer regimes are illustrated in Figure 4.4.

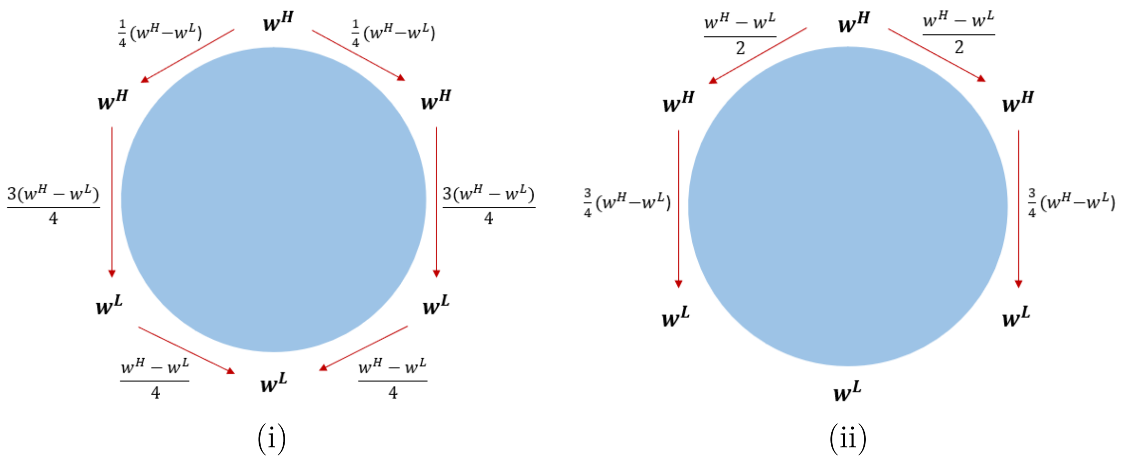


Figure 4.4 Two possible transfer regimes to obtain equality in the clustered endowment setting of T5 ON_{clu}. Option (i) is only feasibly if $w^H \leq 5w^L$.

Equity consistent with efficiency

As a second reference, we consider equitable allocation, i.e. those where the provision of public goods leads to equally sized payoff *gains* above the initial endowments. We derive the following lemma.

Lemma 2 *For an efficient allocation to generate equal payoff gains, the combined investments in the neighborhood of a rich player are given by* $G^H = ((3h+1)w^H + (3h-1)w^L)/(2h)$*, while those in the neighborhood of a poor player are given by* $G^L = ((3h-1)w^H + (3h+1)w^L)/(2h)$*. The specific investment patters are not uniquely determined, but satisfy:*
(i) in the alternating setting, the difference in total investments at opposing poor and rich players' locations is given by $G^H - G^L = (w^H - w^L)/h$*.*
(ii) in the clustered setting, the difference in total investments at the center rich position and the center poor location is given by $G_E - G_B = (w^H - w^L)/h$*. The total investments at corner players at opposing sides of the virtual table need to be identical:* $G_A = G_D$ *and* $G_C = G_F$*.*

Proof: see Appendix 4.A.

The investment patterns are again not uniquely determined. Yet, the following pattern arises in the alternating setting: investments in poor players' locations are larger than those in rich players' locations. The intuition behind this result is that the former benefit two rich and one poor players, while the latter benefit one rich and two poor. Equity thus requires the net transfers from rich to poor players to be positive. This qualitative effect is similar in the clustered setting. Comparing the rich (D, E, F) and the poor (A, B, C) cluster, the former receives larger investments than the latter, yet the difference is smaller than the total endowment of rich vs. poor players. Thus, there again needs to be a net transfer from the rich to the poor.

Figure 4.5 provides examples for possible investment patterns in the alternating and clustered setting to obtain equity in payoff gains. In the alternating setting, equity can be obtained by low endowment players investing all their tokens in their own location and the high endowment players investing a portion ($(1+h)(w^H-w^L)/(4h)$) in each of their poor neighbor's location.[7] In the clustered setting, equity requires a net transfer from the rich to the poor cluster – for our parameters $G^H - G^L = (w^H - w^L)/h < 3(w^H - w^L)$, as seen by comparing the payoffs to the respective center players.[8]

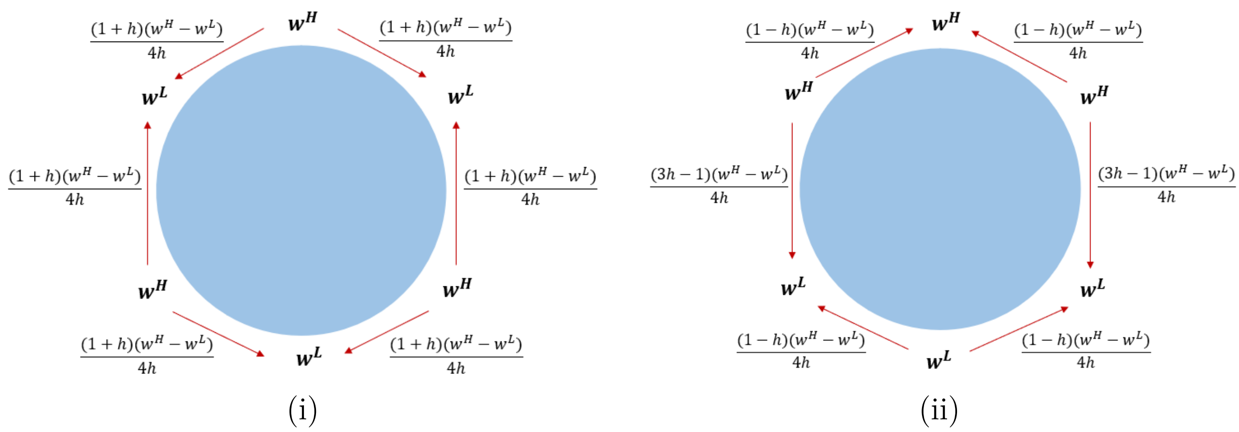


Figure 4.5 Possible transfers to obtain equal payoff gains beyond endowment (equity) in the (i) alternating (T4 ON_{alt}) and (ii) clustered setting (T5 ON_{clu}). The arrows and values describe the net transfers with the remaining tokens being invested in the own location. The settings describe the symmetric equilibria, i.e. symmetric transfers where in (i) all high endowment locations as well as all low endowment locations, respectively, receive identical total investments and in (ii) the total investments at all corner poor and rich locations are identical.

The above arguments show that allocations that reach efficiency, i.e. full investments by all players, are consistent with two extreme distributional ideals, namely payoff equality and equity as defined as equal payoff gains. We concentrate on investment patterns where each player only invests in her own neighborhood. However, as we cannot expect all players to fully contribute, the discussed investment patterns are only serving as two (likely unrealistic) reference points. We thus now turn to potential motivations of individual investment decisions.

[7]Note that even when requiring symmetry, i.e. identical investment patterns by all rich and also by all poor players, only the net transfers are uniquely determined. Total investments in each poor player's location then need to be $(w^H + w^L)/2 + (w^H - w^L)/(2h)$, while the total investments in rich locations is $(w^H + w^L)/2 - (w^H - w^L)/(2h)$.

[8]With the additional symmetry assumption that both border rich receive the same total investment which, hence, also coincides with the border poor total investment, the net transfers are uniquely determined as displayed in Figure 4.5.

Individual behavioral motivations for investment decisions

We now discuss the effects of behavioral motivations, namely inequality concerns (e.g., Charness and Rabin, 2002; Fehr and Schmidt, 1999), and reciprocity (e.g., Rabin, 1993; Dufwenberg and Kirchsteiger, 2004) on individual investment patterns.

Under endowment homogeneity, all these concerns essentially coincide in a typical public good setting (as in T1 CN_{hom}): if a player contributes more than another player, she typically receives a lower payoff. Inequality concerns as well as reciprocity considerations thus may lead to reduced contributions in response to a lower contribution of a group member. The overlapping neighborhood setting in T3, however, introduces another dimension how a player can react: instead of lowering her contributions, she can reallocate her investments away from the underperforming player, i.e. move her investments to the other neighbor who contributed more and thereby, implicitly punishing the under-performing neighbor. Based on this argument, we formulate the following prediction:

> **Hypothesis 2:**
> In the overlapping neighborhood setting under endowment homogeneity (T3 ON_{hom}) average provision levels are more stable over time than in the closed neighborhood setting (T1 CN_{hom}). Participants change their level and the location of their investments in their neighborhood in response to the (relative) contribution decisions of their neighbors.

Endowment heterogeneity in typical public good games can lower contributions (e.g., Kingsley, 2016). We thus expect a similar effect in the corresponding closed neighborhoods treatment (T2 CN_{het} vs. T1 CN_{hom}). Additionally, rich players are expected to invest more in absolute amounts, but a smaller relative share of endowments than poor players which potentially reflects different distributional ideals.

The introduction of the overlapping neighborhoods in the heterogeneous setting (T5 ON_{clu} and T4 ON_{alt} vs. T2 CN_{het}) allows participants to address distributional concerns not only by choosing their total level of investment, but also by choosing the locations of investments in their neighborhood. As long as endowment differences still persist, equality-oriented players can be expected to invest where their investments benefit the largest number of poor players. Rich players in T4 ON_{alt} thus should invest more in their own locations (thereby benefiting two poor players), while – based on the same argument – equality-oriented poor players may choose to invest a larger share in their (rich) neighbors locations than in their own. Similarly in T5 ON_{clu}, the center rich player is expected to invest a larger amount at her neighbors' locations, the border rich player can move investments to the poor neighbor, i,e. the poor border player. The poor players may move their investments primarily to the center poor player as then only poor players benefit.

Hypothesis 3:
The share of investments is larger in those locations in a player's neighborhood that benefit the largest number of poor players. Specifically, we expect to see differences between investments going to the left vs. right neighbor for border players in T5 ON_{clu}.

Players in overlapping neighborhood settings can thus address potentially different distributional ideals (e.g., equity, equality) by selecting the locations and not only the level of investments. Thus, one could also hypothesize that specifically rich players will contribute more than in the corresponding closed neighborhood setting:

Hypothesis 4:
Rich players are expected to contribute more in T4 ON_{alt} and T5 ON_{clu} than in T2 CN_{het}.

As under homogeneity, also the heterogeneous overlapping neighborhood structure allows to reciprocate on other players' investment decisions. Within our experiment, participants receive information about the number of tokens a player keeps in her account as well as on the total investments in the respective locations. As such, no direct information is given on where a player invests. We thus anticipate that players potentially reciprocate on the total contributions of other players, likely focusing on the direct neighbors. We formulate the following prediction – resembling Hypothesis 2:

Hypothesis 5:
A player's investment in a neighbor's location is positively correlated with the respective neighbor's investments in the previous period. The investments in her own location are positively correlated with total investments by both neighbors.

We note that both neighbors of a player have the same endowment in T4 ON_{alt} such that a player can directly compare the kindness of both players by considering their respective total investments. In T5 ON_{clu}, the two neighbors of border players have different endowments such that reciprocal actions may condition on the endowment of the respective neighbor.

4.3 Results

In the following, we first discuss the treatment effects on the average payoffs and their distribution, before discussing the underlying investment decisions. In doing so, we explore the underlying behavioral motivations. For our discussion, we primarily use nonparametric Wilcoxon rank-sum and Wilcoxon signed-rank tests to compare group averages, either for entire groups of six players or divided by endowment type. Those are complemented by panel regressions with individual random effects to account for the dynamics of behavior. Table 4.A.1 provides a summary statistics of the main outcome variables averaged by group for all treatments. Table 4.A.2 separates these by endowment types.[9]

4.3.1 Payoffs and distribution

The average payoffs range from 36.17 in T3 ON_{hom} to 37.51 in T5 ON_{clu} (Table 4.A.1). We find that the overlapping neighborhood structure has no effect on average payoffs when compared to the corresponding closed neighborhood public good, neither for homogeneous endowments (T3 vs. T1, p=0.1510, Wilcoxon rank-sum test), nor under endowment heterogeneity (T4 vs. T2, p=0.9674; T5 vs. T2, p=0.9845). The heterogeneity of endowments also does not lead to major changes of average payoffs in the closed-neighborhood setting (T2 vs. T1, p=0.9534) or the overlapping neighborhood treatments (T4 vs. T3, p=0.2496; T5 vs. T3, p=0.1102). We thus formulate the following result:

Result 1 *Neither the introduction of overlapping neighborhoods nor the heterogeneity of endowments affect average payoffs.*

While average payoffs do not differ, the overlapping neighborhood structure could also affect the distributional patterns under endowment heterogeneity. We first look at the effect of introducing overlapping neighborhoods (T4 ON_{alt} and T5 ON_{clu}) and compare them to the closed neighborhood treatment T3 ON_{hom}. Second, we distinguish between rich and poor in the overlapping neighborhood and compare the alternating (T4 ON_{alt}) with the clustered setting (T5 ON_{clu}). Table 4.A.2 summarizes the payoffs by endowment types.

We find that neither the introduction of overlapping neighborhoods nor the specific endowment allocation in space affect poor participants' payoffs (T4 vs. T2, p=0.6315; T5

[9] Table 4.A.3 and Table 4.A.4 separate these summary statistics by round 1-5 vs. 6-10 in order to give provide information into the dynamics of behavior. We do not find treatment differences in this dynamics and thus concentrate on discussing the effects average across all 10 periods for the most part of the paper.

vs. T2, p=0.3183; T5 vs. T4, p=0.5106). Yet, differences arise for the rich types: while the alternating setting is no different from a closed neighborhood setting (T4 vs. T2, p=0.3245), the clustered endowments benefit the rich on average (T5 vs. T2, p=0.0013). This increase in payoffs of rich participants in the clustered distribution translates to a higher payoff difference between rich and poor participants compared to the closed neighborhood treatment (T5 vs. T2, p=0.0597), while the payoff gap in the alternating endowment setting is not affected (T4 vs. T2, p=0.4363).

Result 2 *The payoff distribution is affected by spatial aspects: rich players benefit from clustered endowments relative to both alternating endowment settings and closed neighborhoods.*

The results above suggest that the spatial clustering of endowments benefits the rich, while not necessarily hurting the poor. A closer look reveals that these differences depend on the exact location of a player within the cluster. While the average payoff of rich in T5 ON_{clu} are 44.37 tokens, the center rich (location E) receives 46.44 tokens, which provides suggestive/directional evidence that they receive more than the average border rich player (43.34 tokens, p=0.1046, Wilcoxon signed rank test). The increased inequality in T5 ON_{clu} due to the endowment cluster therefore solely benefits the center rich player (p=0.0245 vs. rich players in T4), while the rich border players have essentially the same payoff as in the alternating setting (p=0.2859 vs. rich players in T4). No such differences exist for the poor. In particular, the poor center player receives 29.59 tokens in T5 ON_{clu} and not significantly less than poor players in T2 CN_{het} (p=0.1751) or T4 ON_{alt} (p=0.2475).

Result 3 *The clustering of endowment types benefits the center rich player, but does not lead to smaller payoffs to any of the poor players than they receive in alternating overlapping or in closed neighborhoods.*

We thus see that – at least in our experimental setting of 3 poor and 3 rich players – endowment clusters do not necessarily hurt the poor players, while they primarily benefit rich center participants. We now turn to considering the underlying investment patterns in more detail in order to gain insights into the behavioral motivations of the respective types.

4.3.2 Investment patterns

Table 4.A.1 summarizes the overall investment patterns, further separated by investments in a player's own location, the locations of direct neighbors, and other players outside the

neighborhood. According to Hypothesis H1, we expect the latter to be negligible as such investments would not generate a return to the player. Indeed we find that only a small, not-statistically significant fraction of one's total investment is made outside one's neighborhood.

Yet, a substantial part of investment is going towards direct neighbors' locations. In fact, the amounts transferred to neighbors' locations on average exceed the investment at one's own location but clearly are split by the two direct neighbors. This is even the case in closed neighborhood treatments, T1 CN_{hom} and T2 CN_{het}, where the place of investment inside the group of three players has no effect on the provision of the public good as all players benefit likewise from any contribution's location. Yet, on average players in a group invest 62% in T1 CN_{hom} and 64% in T2 CN_{het} of their total investments at neighbors' locations – thereby essentially splitting investments among all players in their own neighborhood (even though the location does not matter here). In overlapping neighborhoods, this share is significantly smaller in T3 (49%, p=0.0298 vs. T1) and T4 (55%, p= 0.0555 vs. T2).[10]

Result 4 *Participants invest almost exclusively in their own neighborhood with a substantial amount going into direct neighbors' locations. Yet, this share is smaller in overlapping neighborhood setting than in the closed neighborhood (where the location does not affect any player's payoff).*

In the homogeneous overlapping neighborhood treatment (T3 ON_{hom}), this result suggests a larger concentration on ones own location, potentially to generate reciprocal action by both direct neighbors. Under endowment heterogeneity, this might be driven by distributional concerns as we discuss below. We therefore now investigate more closely the determinants of investment decisions and focus on two potential drivers: The role of distributional concerns under endowment heterogeneity (T2 CN_{het}, T4 ON_{alt}, T5 ON_{clu}) and the role of reciprocity.

Distributional concerns. Generally, we observe that rich players invest a significantly larger number of tokens (in absolute terms). Investments as share of initial endowments do not significantly differ between poor and rich types in any of the heterogeneous treatments (50% for poor vs. 48% for rich in T4; 55% vs. 47% in T5). These investment patterns lead to a reduction of the initial endowment inequality (20 vs. 40 tokens) in both absolute and relative terms (see Table 4.A.2).

While the closed neighborhood setting only allows to address distributional concerns by

[10]The share is 57% in T5 ON_{clu} and thus not significantly different from the one in T2 CN_{het} or T4 ON_{alt}. Yet, the interpretation here is more difficult as the clustering of endowments leads to asymmetries in the endowments between left and right neighbors. We thus discuss investment patterns by location in more detail below.

adjusting the *level* of investments, the overlapping neighborhood setting allows to gain insights into the behavioral motivations by studying the specific *location* of investments. When endowments alternate in T4 ON_{alt}, the ratio of total investments going to direct neighbors differs between rich and poor players (61% for poor, 52% for rich players, p=0.0742, see Table 4.A.6). This is first evidence that distributional concerns matter in line with Hypothesis 3 – investing in a rich player's location would benefit most, namely two poor players. Specifically rich players invest a smaller share in their neighbors locations, thus benefiting a large share of poor players.

Table 4.A.5 summarizes the investment decisions by player types in the clustered setting. Figure 4.6 further illustrates these transfers made by a specific player position as well as the tokens received in a specific locations differentiated by endowment type. Due to the clusters, the options of players to benefit poor vs. rich players through investments in their neighborhood depend on the location of players. For example, the center rich player (in location E) can invest in her own location and benefit only rich players, or invest in a neighbor's location to benefit two rich and one poor. The border rich players (in location D and F) have the option to invest in a way to benefit only rich players (invest in E), two rich and one poor (invest in her own location), or two poor and one rich (through investing in the poor neighbor's location). Table 4.A.6 reports the shares of investments going towards the specific neighbors. It reveals that specifically the rich border players differentiate between the identity of their two neighbors (one rich, one poor) and invest more in their poor neighbor's location than in the rich neighbor's (p=0.0443), thereby benefiting two poor players and themselves, instead of investing in their rich neighbor's location which would benefit only rich players. We thus again find some evidence that concerns for equality tend to be a driver of investment decisions. In contrast, the poor border players do not differentiate their investments in their neighbors' locations by their identity, neither do any other players in the clustered network of T5 ON_{clu} differentiate transfers between their left and right neighbor (Figure 4.6).

Yet, investments might be governed by concerns for reciprocity in addition to equality concerns. As such, channeling investments primarily to the poor neighbor might affect the reciprocal action of the rich neighbor. We explore these reciprocal actions in two ways. First we compared the net transfers of public goods, i.e. how a player's investments benefit another player vs. how a player benefits through investments of the other player. Second, we have a closer look at the dynamics of investment decisions.

Figure 4.7 displays the net payoff transfers induced through public good investments in the different locations in T5 ON_{clu}. A net transfer is defined by the relation of the public good provision and its benefit, i.e. rich border players have a negative net transfer which means that they provide more than they receive – in formal terms given by $h(3\sum_j g_{ij} -$

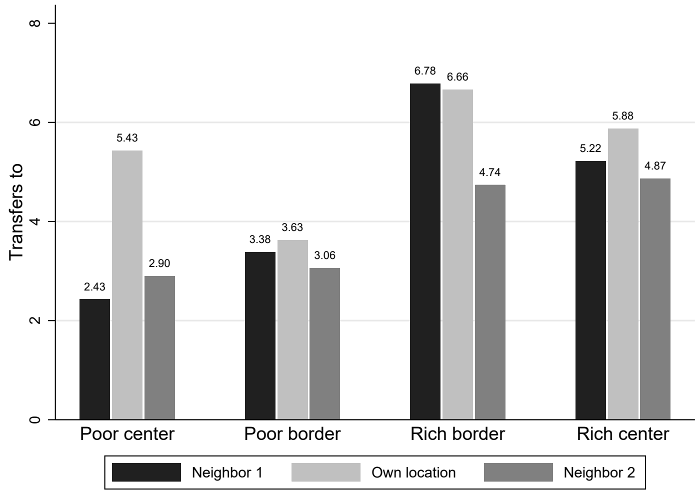


Figure 4.6 Summary of transfers made by endowment type in specific locations to (i) own location, (ii) first neighbor, and (iii) second neighbor in T5 ON_{clu}. Note that while both neighbors have the same endowment identity for the center players, the endowment identity differs between the border players' neighbors. Here, *Neighbor 1* refers to the i's poor neighbor and *Neighbor 2* to her rich neighbor.

$\sum_j \sum_{k \in N_i} g_{jk}$). [11] We see that rich players provide more tokens than they receive which leads to the reduction of inequality. Yet, this net transfer is mostly induced by the rich border players: the rich at the border transfer significantly more of their endowment in net terms compared to the rich at the center (p=0.0739), while we see no significant differences between the poor border and poor center players (p=0.3205). These investment patters form the rationale behind the payoff differences within endowment types as formulated in Result 3. Thus, the spatial structure is found to lead to inequalities within endowment types.

Result 5 *The net transfer from the rich to the poor cluster is triggered by rich participants located at the border whose transfers are significantly higher and more directed towards poor neighbors.*

Reciprocity. Apart from equality concerns, participants might be driven by reciprocal motivations when deciding *how much* and *where* to invest. We now report how individuals adapt their giving behavior depending on the actions of their direct neighbors in order to address Hypothesis H5. For this, we consider an individual's investment decision as a function of the neighbors' investment behaviors in the previous period, i.e. on how many tokens they kept. We consider the effect on both the level of the total investment as well as on the location of these investments at both direct neighbors' locations.

[11] For typical public good games which correspond to our closed neighborhood setting, this collapses to the differences in a players investments *minus* the other persons investments. In the overlapping neighborhood setting, the benefits that a player receives are governed by the location of others' investments such that the net transfer provides information beyond the simple comparison of total investment levels.

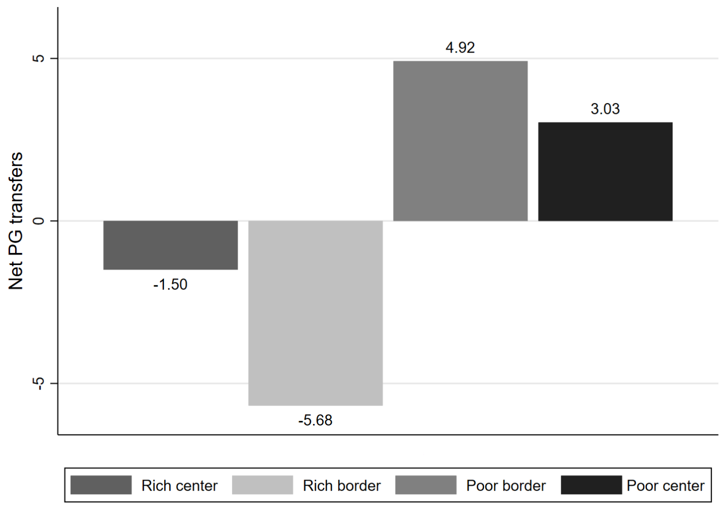


Figure 4.7 Average net transfers of participants in T5 ON_{clu}, (rounds 1-10).

Table 4.A.7, Table 4.A.8, and Table 4.A.9 report the results from panel regressions with individual random effects regressions on individual investments with the appropriate lagged variables for T3-T5 (controlling for the individual investments in the previous period as well as the total amounts kept in their respective private accounts by the left and the right neighbors).[12] We find clear evidence for reciprocal motivations. For all treatments T3- T5, the total investment level of a player are affected by how many tokens both left and right neighbors kept in their own account (column (1)). Second, investments in the left (right) neighbor's location respond negatively to the amount kept by the left (right) neighbor. Yet, they are not affected by the action of the right (left) neighbor (columns (3) and (4)). We find consistent results for the difference in investments between the right and left neighbor (column (7)). Important to note is that in T3 ON_{hom} and T4 ON_{alt}, participants decrease investments also in their own location as a consequence of a neighbor keeping more to herself. This translates into the right (left) neighbor being hurt if the left (right) neighbor keeps more to herself (see columns (5) and (6)). This suggests that individuals facing a neighbor who is less prosocial and keeps more for herself, react by reducing the investments in all locations that benefit that neighbor. Yet, they do not move investments to the other neighbor but instead reduce total investments. As a consequence and contrary to the Hypothesis 2, the overlapping neighborhood structure thus does not lead to a stronger stability of contributions over time and instead generates the typical declining trend of investments over time.[13]

Result 6 *Participants reciprocate over time on the investment decisions by their direct neighbors: when a neighbor keeps more tokens in her private account, players decrease investments (i) in their own location and (ii) in the location of the respective neighbor.*

[12] As a robustness check, we also consider these models as a function of the relative shares of their endowments that neighbors keep in their account. These are reported in Table 4.A.10, Table 4.A.11, and Table 4.A.12. The results are robust.

[13] No significant treatment differences in the time trends of average payoff levels exist.

As a consequence, both neighbors may receive less public good.

We thus find that the spatial setting allows players to exploit a much richer strategy space as the not only adjust their total *level* of investments, but also their investment *location* over time.

4.4 Conclusions

This study introduces a spatial element into a public goods experimental design. By relying on a specific network structure - namely a circular structure - we generate overlapping neighborhoods in which individuals benefit from public good investments in their own and their direct neighbors' locations. This structure is motivated by numerous examples that feature local public goods, e.g. local climate adaptation, the quality of green spaces or local security. Yet, hardly any experimental evidence exists on how heterogeneity affects voluntary contribution decisions in such spatial allocations.

The overlapping neighborhood setting provides a richer strategy space to players. Theoretically, we show that when considering spatial elements, efficiency can be consistent with different distributional ideals – such as inequality or inequity aversion. Different to the typical public goods game, in this spatial network setting, players cannot only decide *how much* but also *where* to invest. Thereby, they can choose who benefits from their investment which is particularly important under endowment heterogeneity. We compare a setting where rich and poor players alternate in space with a setting where they are clustered.

Consistent with our theory, we find that players almost exclusively invest in their own neighborhood, i.e. in locations where they themselves benefit from the public good provision. Yet, our experimental results further show that players react to past investment decisions of their neighbors, investing fewer tokens in the locations of under-performing neighbors.

Apart from reciprocity, we find that the spatial pattern of investments are driven by distributional concerns. This becomes especially evident in clustered settings where redistribution is particularly driven by the rich border players. The rich center players are better off in terms of final payoffs compared to rich players in alternating networks. This showcases a clear dependency of the poor cluster's public good on the willingness to redistribute of their direct rich neighbor.

Noteworthy, in our experiment, we focus on one specific spatial structure, namely a circular network with three rich and three poor players. If we extend these scenarios to bigger networks and for the clustered network enlarging the amount of poor players only facing other poor neighbors, the problem of the center poor being left behind becomes even more evident. In that respect, we argue that the problem of being located in a disadvantageous cluster likely also depends on the size of the cluster. Further research could also explore the role of endowment distributions in different spatial network structures. Additionally, it might be fruitful to look into an endogenous choice of neighborhoods as the quality of local public goods, e.g. the quality of public schools, often is one driver for moving decisions.

We consider our findings to provide important insights for policy makers who deal with issues of spatial allocations of wealth and public goods. We show experimentally that advocating for mixed neighborhoods instead of clusters can avoid the center of the advantaged group to become even more advantaged. Although *average* levels of wealth, pollution, etc. might be similar for advantaged and disadvantaged groups between the two settings – alternating and clustered – location-specific levels might be severely affected by the nature of the allocation structure. As inequality continues to rise, fostering cooperation and collaboration across heterogeneous individuals becomes ever more critical for public good provision, especially when wealth is spatially agglomerated.

References

Allouch, N. (2015). On the private provision of public goods on networks. *Journal of Economic Theory*, 157:527–552.

Angelovski, A., Di Cagno, D., Güth, W., Marazzi, F., and Panaccione, L. (2018a). Behavioral spillovers in local public good provision: an experimental study. *Journal of Economic Psychology*, 67:116–134.

Angelovski, A., Di Cagno, D., Güth, W., Marazzi, F., and Panaccione, L. (2018b). Does heterogeneity spoil the basket? the role of productivity and feedback information on public good provision. *Journal of Behavioral and Experimental Economics*, 77:40–49.

Ashley, R., Ball, S., and Eckel, C. (2010). Motives for giving: A reanalysis of two classic public goods experiments. *Southern Economic Journal*, 77(1):15–26.

Avery, C. and Pathak, P. A. (2021). The distributional consequences of public school choice. *The American Economic Review*, 111(1):129–152.

Banzhaf, S., Ma, L., and Timmins, C. (2019). Environmental justice: The economics of race, place, and pollution. *Journal of Economic Perspectives*, 33(1):185–208.

Barrett, S. (2001). International cooperation for sale. *European Economic Review*, 45(10):1835–1850.

Boosey, L. A. (2017). Conditional cooperation in network public goods experiments. *Journal of behavioral and experimental economics*, 69:108–116.

Bramoullé, Y. and Kranton, R. (2007). Public goods in networks. *Journal of Economic theory*, 135(1):478–494.

Bramoullé, Y., Kranton, R., and D'amours, M. (2014). Strategic interaction and networks. *The American Economic Review*, 104(3):898–930.

Cassar, A. (2007). Coordination and cooperation in local, random and small world networks: Experimental evidence. *Games and Economic Behavior*, 58(2):209–230.

Chan, K. S., Mestelman, S., Moir, R., and Muller, R. A. (1996). The voluntary provision of public goods under varying income distributions. *Canadian Journal of Economics*, 29(1):54–69.

Chan, K. S., Mestelman, S., Moir, R., and Muller, R. A. (1999). Heterogeneity and the voluntary provision of public goods. *Experimental Economics*, 2(1):5–30.

Charness, G. and Rabin, M. (2002). Understanding social preferences with simple tests. *The Quarterly Journal of Economics*, 117(3):817–869.

Chen, D. L., Schonger, M., and Wickens, C. (2016). otreean open-source platform for laboratory, online, and field experiments. *Journal of Behavioral and Experimental Finance*, 9:88–97.

Cherry, T. L., Kroll, S., and Shogren, J. F. (2005). The impact of endowment heterogeneity and origin on public good contributions: evidence from the lab. *Journal of Economic Behavior and Organization*, 57(3):357–365.

Dufwenberg, M. and Kirchsteiger, G. (2004). A theory of sequential reciprocity. *Games and Economic Behavior*, 47(2):268–298.

Epple, D. and Romano, R. E. (1998). Competition between private and public schools, vouchers, and peer-group effects. *The American Economic Review*, 88(1):33–62.

Falk, A., Fischbacher, U., and Gächter, S. (2013). Living in two neighborhoodssocial interaction effects in the laboratory. *Economic Inquiry*, 51(1):563–578.

Fehr, E. and Schmidt, K. M. (1999). A theory of fairness, competition, and cooperation. *The Quarterly Journal of Economics*, 114(3):817–868.

Fellner, G. and Lünser, G. K. (2014). Cooperation in local and global groups. *Journal of Economic Behavior and Organization*, 108:364–373.

Fellner-Röhling, G., Kröger, S., and Seki, E. (2020). Public good production in heterogeneous groups: An experimental analysis on the relation between external return and information. *Journal of Behavioral and Experimental Economics*, 84:101481.

Fischbacher, U., Schudy, S., and Teyssier, S. (2014). Heterogeneous reactions to heterogeneity in returns from public goods. *Social Choice and Welfare*, 43(1):195–217.

Gallo, E. and Yan, C. (2023). Efficiency and equilibrium in network games: An experiment. *Review of Economics and Statistics*, 105(6):1515–1529.

Gangadharan, L., Nikiforakis, N., and Villeval, M. C. (2017). Normative conflict and the limits of self-governance in heterogeneous populations. *European Economic Review*, 100:143–156.

Greiner, B. (2015). Subject pool recruitment procedures: organizing experiments with orsee. *Journal of the Economic Science Association*, 1(1):114–125.

Hauser, O. P., Hilbe, C., Chatterjee, K., and Nowak, M. A. (2019). Social dilemmas among unequals. *Nature*, 572(7770):524–527.

Heap, S. P. H., Ramalingam, A., and Stoddard, B. V. (2016). Endowment inequality in public goods games: A re-examination. *Economics Letters*, 146:4–7.

Hofmeyr, A., Burns, J., and Visser, M. (2007). Income inequality, reciprocity and public good provision: an experimental analysis. *South African Journal of Economics*, 75(3):508–520.

Kesternich, M., Lange, A., and Sturm, B. (2014). The impact of burden sharing rules on the voluntary provision of public goods. *Journal of Economic Behavior & Organization*, 105:107–123.

Kingsley, D. C. (2016). Endowment heterogeneity and peer punishment in a public good experiment: cooperation and normative conflict. *Journal of Behavioral and Experimental Economics*, 60:49–61.

Kirchkamp, O. and Nagel, R. (2007). Naive learning and cooperation in network experiments. *Games and Economic Behavior*, 58(2):269–292.

Koch, J., Lange, A., and Romero-Fernández, L. (2023). Public good provision in overlapping neighborhoods. AEA RCT Registry `https://doi.org/10.1257/rct.12179-1.0`.

Kölle, F. (2015). Heterogeneity and cooperation: The role of capability and valuation on public goods provision. *Journal of Economic Behavior and Organization*, 109:120–134.

Kolstad, C. D. (2010). Equity, heterogeneity and international environmental agreements. *The BE Journal of Economic Analysis and Policy*, 10(2).

Lange, A. and Romero-Fernández, L. (2023). Weakest links in space: on the voluntary provision of public goods in overlapping neighborhoods. *Working paper*.

Lange, A., Schmitz, J., and Schwirplies, C. (2022). Inequality, role reversal and cooperation in multiple group membership settings. *Experimental Economics*, 25(1):68–110.

Lippert, S. and Tremewan, J. (2021). Pledge-and-review in the laboratory. *Games and Economic Behavior*, 130:179–195.

Nikiforakis, N., Noussair, C. N., and Wilkening, T. (2012). Normative conflict and feuds: The limits of self-enforcement. *Journal of Public Economics*, 96(9-10):797–807.

Nosenzo, D., Quercia, S., and Sefton, M. (2015). Cooperation in small groups: the effect of group size. *Experimental Economics*, 18(1):4–14.

Rabin, M. (1993). Incorporating fairness into game theory and economics. *The American economic review*, pages 1281–1302.

Rosenkranz, S. and Weitzel, U. (2012). Network structure and strategic investments: An experimental analysis. *Games and Economic Behavior*, 75(2):898–920.

Thurber, A., Bohmann, C. R., and Heflinger, C. A. (2018). Spatially integrated and socially segregated: The effects of mixed-income neighbourhoods on social well-being. *Urban Studies*, 55(9):1859–1874.

Videras, J. R. and Owen, A. L. (2006). Public goods provision and well-being: empirical evidence consistent with the warm glow theory. *Contributions in Economic Analysis & Policy*, 5(1).

Waichman, I., Requate, T., Karde, M., and Milinski, M. (2021). Challenging conventional wisdom: Experimental evidence on heterogeneity and coordination in avoiding a collective catastrophic event. *Journal of Environmental Economics and Management*, 109:102502.

Zelmer, J. (2003). Linear public goods experiments: A meta-analysis. *Experimental Economics*, 6(3):299–310.

Zhang, Y. and He, L. (2021). Theory and experiments on network games of public goods: inequality aversion and welfare preference. *Journal of Economic Behavior & Organization*, 190:326–347.

Appendices

Appendix 4.A Proofs

Proof of Lemma 1:

Equal payoffs require that total investments in a neighborhood of any player are identical and thus given by $3(w^H + w^L)/2$ in any efficient situation as all endowment is invested. We thus have $G_A + G_B + G_C = G_B + G_C + G_D$ and thus $G_A = G_D$. The same argument can be used to show that opposing sides always have the same investment.

Proof of Lemma 2:

Denoting the total investments in a neighborhood of a poor (rich) player by G^L (G^H), equal payoff gains require $h(G^H - G^L) = w^H - w^L$. As $G^H + G^L = 3(w^H + w^L)$, we obtain $G^H = ((3h+1)w^H + (3h-1)w^L)/(2h)$ and $G^L = ((3h-1)w^H + (3h+1)w^L)/(2h)$.

(i) In the alternating setting, $G^L = G_A + G_B + G_C = G_C + G_D + G_E = G_E + G_F + G_A$ and $G^H = G_B + G_C + G_D = G_D + G_E + G_F = G_F + G_A + G_B$. Thus, we obtain $G^H - G^L = G_D - G_A = G_F - G_C = G_B - G_E$ and $G_C = G_F$.

(ii) In the clustered setting, $G^L = G_A + G_B + G_C = G_B + G_C + G_D = G_F + G_A + G_B$ and $G^H = G_C + G_D + G_E = G_D + G_E + G_F = G_E + G_F + G_A$. Thus, we obtain $G_A = G_D$ and $G_C = G_F$.

Equal gains requires $G^H - G^L = (w^H - w^L)/h$ which immediately implies that $G_F - G_B = (w^H - w^L)/h$.

Appendix 4.B Tables

VARIABLES	T1 CN_{hom}	T2 CN_{het}	T3 ON_{hom}	T4 ON_{alt}	T5 ON_{clu}
Payoff	37.29	37.15	36.17	37.30	37.51
	(2.73)	(3.09)	(2.83)	(2.87)	(2.65)
Tokens kept	15.41	15.70	17.67	15.40	14.97
	(5.45)	(6.18)	(5.67)	(5.73)	(5.31)
Tokens invested	14.59	14.30	12.33	14.60	15.03
	(5.45)	(6.18)	(5.67)	(5.73)	(5.31)
- in own location	4.09	4.37	5.14	5.01	5.31
	(2.17)	(2.96)	(3.24)	(3.63)	(3.21)
- in neighbors' location	8.85	9.07	6.08	7.80	8.56
	(3.47)	(4.41)	(2.92)	(2.49)	(3.41)
- outside of neighborhood	1.65	0.86	1.11	1.79	1.16
	(1.82)	(0.93)	(1.17)	(1.41)	(0.74)
Observations	16	15	15	15	16

Table 4.A.1 Summary statistics for treatments T1 - T5 (averaged by group).

Poor	T2 (sd)	T4 (sd)	T5 (sd)
Payoff	32.50	31.93	30.66
	(5.93)	(6.08)	(4.92)
Tokens kept	11.24	9.94	8.91
	(4.01)	(3.96)	(4.21)
Tokens invested	8.76	10.06	11.09
	(4.01)	(3.96)	(4.21)
- in own location	2.91	3.37	4.23
	(1.82)	(2.94)	(2.87)
- in neighbors' location	5.56	5.87	6.07
	(3.11)	(2.14)	(2.31)
- outside of neighborhood	0.28	0.82	0.79
	(0.46)	(1.19)	(1.08)

Rich	T2	T4	T5
Payoff	41.80	42.66	44.37
	(1.66)	(2.71)	(2.08)
Tokens kept	20.16	20.86	21.03
	(9.12)	(8.59)	(8.58)
Tokens invested	19.84	19.14	18.97
	(9.12)	(8.59)	(8.58)
-in own location	5.84	6.65	6.40
	(4.60)	(4.95)	(4.31)
- in neighbors' location	12.57	9.73	11.05
	(6.82)	(4.44)	6.13)
- outside of neighborhood	1.44	2.76	1.53
	(1.91)	(3.10)	1.28)
Difference of payoff	9.26	10.73	13.72
	(6.14)	(7.47)	(5.38)
Observations	15	15	16

Table 4.A.2 Summary statistics for treatments T2 CN_{het}, T4 ON_{alt} and T5 ON_{clu}, separated by endowment type (averaged by group).

Rounds 1-5	T1 CN_{hom}	T2 CN_{het}	T3 ON_{hom}	T4 ON_{alt}	T5 ON_{clu}
PG provided	49.98	47.85	44.38	49.24	52.48
	(14.47)	(18.77)	(15.67)	(15.10)	(13.79)
Payoff	38.33	37.97	37.40	38.21	38.75
	(2.41)	(3.13)	(2.61)	(2.52)	(2.30)
Tokens kept	13.34	14.05	15.21	13.59	12.51
	(4.82)	(6.26)	(5.22)	(5.03)	(4.60)
Tokens invested	16.66	15.95	14.79	16.41	17.49
	(4.82)	(6.26)	(5.22)	(5.03)	(4.60)
-in own location	4.77	4.94	6.04	5.32	6.24
	(2.30)	(3.13)	(3.12)	(3.06)	(3.12)
-in neighbors' locations	9.86	9.95	7.49	9.25	10.12
	(3.14)	(4.65)	(3.45)	(2.72)	(3.37)
-outside of neighborhood	2.02	1.05	1.26	1.84	1.13
	(2.00)	(1.14)	(1.15)	(1.26)	(0.79)
Rounds 6-10	T1	T2	T3	T4	T5
PG provided	37.55	37.95	29.61	38.35	37.69
	(19.36)	(19.48)	(19.58)	(20.01)	(19.42)
Payoff	36.26	36.33	34.94	36.39	36.28
	(3.23)	(3.25)	(3.26)	(3.33)	(3.24)
Tokens kept	17.48	17.35	20.13	17.22	17.44
	(6.45)	(6.49)	(6.53)	(6.67)	(6.47)
Tokens invested	12.52	12.65	9.87	12.78	12.56
	(6.45)	(6.49)	(6.53)	(6.67)	(6.47)
-in own location	3.40	3.80	4.24	4.70	4.38
	(2.25)	(3.01)	(3.59)	(4.54)	(3.77)
-in neighbors' locations	7.85	8.18	4.66	6.35	7.00
	(4.25)	(4.43)	(3.08)	(2.47)	(3.90)
-outside of neighborhood	1.27	0.67	0.97	1.73	1.18
	(1.71)	(0.77)	(1.35)	(1.62)	(0.98)
Observations	16	15	15	15	16

Table 4.A.3 Summary of outcomes variables for each treatment, grouped at the group of 6 level. Separated by average value for rounds 1-5 and rounds 6-10.

VARIABLES	T2 (Rich) CN_{het}	T2 (Poor) CN_{het}	T4 (Rich) ON_{alt}	T4 (Poor) ON_{alt}	T5 (Rich) ON_{clu}	T5 (Poor) ON_{clu}
Payoff	42.06	33.88	43.50	32.91	45.52	31.97
	(2.22)	(6.38)	(2.22)	(5.48)	(2.48)	(5.26)
Tokens kept	18.15	9.95	18.91	8.26	17.97	7.04
	(9.12)	(4.62)	(7.64)	(3.44)	(8.16)	(3.81)
Tokens invested	21.85	10.05	21.09	11.74	22.03	12.96
	(9.12)	(4.62)	(7.64)	(3.44)	(8.16)	(3.81)
- in own location	6.60	3.28	7.05	3.60	7.51	4.98
	(4.48)	(2.58)	(4.36)	(2.47)	(4.85)	(2.63)
- in neighbors' locations	13.48	6.43	11.33	7.16	13.02	7.22
	(7.01)	(3.28)	(4.36)	(2.25)	(6.22)	(3.26)
- outside of neighborhood	1.77	0.33	2.71	0.97	1.50	0.76
	(2.26)	(0.51)	(2.82)	(1.25)	(1.32)	(0.99)

VARIABLES	T2 (Rich) CN_{het}	T2 (Poor) CN_{het}	T4 (Rich) ON_{alt}	T4 (Poor) ON_{alt}	T5 (Rich) ON_{clu}	T5 (Poor) ON_{clu}
Payoff	41.53	31.12	41.82	30.96	43.22	29.34
	(1.66)	(5.95)	(3.62)	(7.07)	(2.78)	(5.29)
Tokens kept	22.17	12.52	22.81	11.63	24.08	10.79
	(9.72)	(3.97)	(9.95)	(4.87)	(9.84)	(5.13)
Tokens invested	17.83	7.48	17.19	8.37	15.92	9.21
	(9.72)	(3.97)	(9.95)	(4.87)	(9.84)	(5.13)
- in own location	5.07	2.54	6.26	3.15	5.29	3.48
	(5.08)	(1.82)	(6.07)	(3.76)	(4.76)	(3.34)
- in neighbors' locations	11.66	4.70	8.13	4.57	9.07	4.93
	(7.12)	(3.07)	(4.73)	(2.55)	(6.88)	(2.10)
- outside of neighborhood	1.10	0.24	2.80	0.66	1.55	0.81
	(1.63)	(0.47)	(3.48)	(1.19)	(1.69)	(1.28)
Observations	15	15	15	15	16	16

Table 4.A.4 Comparing rich and poor participants' outcomes over time - separated in rounds 1-5 and 6-10.

VARIABLES	Rich Center	Rich Border	Poor Border	Poor Center
Payoff	46.44	43.34	31.19	29.59
	(5.02)	(3.14)	(6.00)	(5.48)
Tokens kept	22.64	20.22	9.22	8.31
	(11.25)	(7.97)	(4.06)	(6.58)
Tokens invested	17.36	19.78	10.78	11.69
	(11.25)	(7.97)	(4.06)	(6.58)
- in own location	5.88	6.66	3.63	5.43
	(3.72)	(5.08)	(2.07)	(6.26)
- in neighbors' locations	10.09	11.52	6.44	5.33
	(8.44)	(6.06)	(2.98)	(4.56)
- outside of neighborhood	1.40	1.59	0.71	0.93
	(2.22)	(1.79)	(1.15)	(2.44)
Endowment	20	20	40	40
Observations	16	16	16	16

Table 4.A.5 Summary statistics of treatment T5 ON_{clu} by location type.

	Share of investments going to ...				
	own location	neighbors' locations	poor neighbor	rich neighbor	diff p-value
T4 ON_{alt}					
Poor	0.30	0.61			
	(0.16)	(0.16)			
Rich	0.33	0.52			
	(0.14)	(0.15)			
T5 ON_{clu}					
Rich center	0.42	0.51			
	(0.30)	(0.28)			
Rich border	0.31	0.61	0.37	0.24	0.0443
	(0.21)	(0.23)	(0.20)	(0.08)	
Poor border	0.35	0.64	0.36	0.28	0.2979
	(0.14)	(0.24)	(0.22)	(0.10)	
Poor center	0.44	0.50			
	(0.33)	(0.32)			

Table 4.A.6 Share of total investments in own vs. neighbors' positions. For rich border and poor border types in T5 ON_{clu}, the investments at neighbors' positions are further differentiated by the identity of the neighbor, i.e. if targeting more poor or more rich players. For all other types, the two neighbors are symmetric such that we refrain from differentiating. Note that the shares do not add up to one due to the small (but negligible) transfers directed to locations outside of the neighborhood.

VARIABLES	(1) invest_t (total)	(2) invest_t (own)	(3) invest_t (left)	(4) invest_t (right)	(5) invest_t (own+left)	(6) invest_t (own+right)	(7) invest_t (right-left)
invest_{t-1} (own)	0.53***	0.54***	0.06	0.07*	0.60***	0.61***	0.02
	(5.42)	(5.69)	(1.25)	(1.68)	(9.77)	(9.72)	(0.70)
invest_{t-1} (right)	0.24*	0.10	0.10**	0.41***	0.20***	0.52***	0.32***
	(1.77)	(1.44)	(2.56)	(4.00)	(2.72)	(8.78)	(3.26)
invest_{t-1} (left)	0.34***	0.23***	0.35***	0.06	0.57***	0.28***	-0.29***
	(6.12)	(2.84)	(6.57)	(1.31)	(7.38)	(3.04)	(-5.67)
keep_{t-1} (left)	-0.17***	-0.06*	-0.03**	0.01	-0.09***	-0.06**	-0.01
	(-3.90)	(-1.79)	(-2.54)	(0.31)	(-2.63)	(-2.28)	(-0.52)
keep_{t-1} (right)	-0.21***	-0.03	-0.02	-0.06***	-0.04**	-0.09***	
	(-6.92)	(-1.51)	(-1.24)	(-2.99)	(-2.30)	(-3.75)	
keep_{t-1} (right-left)							-0.05**
							(-2.21)
round	-0.21**	0.03	-0.06	-0.07	-0.02	-0.03	-0.01
	(-2.24)	(0.54)	(-1.27)	(-1.23)	(-0.35)	(-0.64)	(-0.16)
Constant	15.02***	2.30***	2.29***	2.47***	4.59***	4.77***	0.18
	(10.74)	(2.65)	(2.80)	(3.69)	(4.50)	(4.50)	(0.46)
n	90	90	90	90	90	90	90

Robust z-statistics in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 4.A.7 Determinants of investments patterns of player_i as a response to the investment levels of her neighbors (left and right) in the previous round, $_{t-1}$, for T3 ON_{hom}. Panel model with individual random effects, standard errors clustered at group level.

VARIABLES	(1) invest$_t$ (total)	(2) invest$_t$ (own)	(3) invest$_t$ (left)	(4) invest$_t$ (right)	(5) invest$_t$ (own+left)	(6) invest$_t$ (own+right)	(7) invest$_t$ (right-left)
invest$_{t-1}$ (own)	0.25***	0.53***	0.03	0.05**	0.56***	0.58***	0.02
	(2.74)	(6.26)	(0.81)	(2.48)	(10.49)	(7.50)	(0.54)
invest$_{t-1}$ (right)	0.19**	0.16**	0.07	0.44***	0.23***	0.59***	0.37***
	(1.99)	(2.10)	(1.39)	(6.43)	(3.58)	(6.01)	(5.80)
invest$_{t-1}$ (left)	0.01	-0.01	0.42***	0.12	0.40***	0.11	-0.30***
	(0.16)	(-0.14)	(9.12)	(1.47)	(5.67)	(0.99)	(-3.52)
keep$_{t-1}$ (left)	-0.13***	-0.06***	-0.05***	0.00	-0.11***	-0.05**	0.01
	(-2.89)	(-2.61)	(-3.02)	(0.04)	(-3.23)	(-2.01)	(0.31)
keep$_{t-1}$ (right)	-0.13***	-0.07***	0.00	-0.04***	-0.07***	-0.12***	
	(-3.48)	(-4.24)	(0.18)	(-2.91)	(-3.11)	(-5.58)	
keep$_{t-1}$ (right-left)							-0.04**
							(-2.18)
round	-0.60***	0.02	-0.20***	-0.16**	-0.18**	-0.15*	0.03
	(-5.24)	(0.26)	(-5.73)	(-2.46)	(-2.34)	(-1.80)	(0.52)
Constant	19.68***	3.44***	3.41***	2.98***	6.85***	6.42***	-0.43
	(10.22)	(3.41)	(7.79)	(3.62)	(5.86)	(5.29)	(-0.69)
n	90	90	90	90	90	90	90

Robust z-statistics in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 4.A.8 Determinants of investments patterns of player$_i$ as a response to the investment levels of her neighbors (left and right) in the previous round, $_{t-1}$, for T4 ON_{alt}. Panel model with individual random effects, standard errors clustered at group level.

VARIABLES	(1) invest$_t$ (total)	(2) invest$_t$ (own)	(3) invest$_t$ (left)	(4) invest$_t$ (right)	(5) invest$_t$ (own+left)	(6) invest$_t$ (own+left)	(7) invest$_t$ (right-left)
invest$_{t-1}$ (own)	0.51***	0.56***	0.05**	0.07***	0.61***	0.63***	0.02
	(11.17)	(13.52)	(2.29)	(2.58)	(12.33)	(11.22)	(0.79)
invest$_{t-1}$ (right)	0.21**	0.14*	0.12***	0.44***	0.26***	0.58***	0.32***
	(2.55)	(1.81)	(3.32)	(10.69)	(3.28)	(6.18)	(5.29)
invest$_{t-1}$ (left)	0.32***	0.11	0.55***	0.18***	0.66***	0.29***	-0.37***
	(3.60)	(1.57)	(5.73)	(5.61)	(8.31)	(4.07)	(-3.90)
keep$_{t-1}$ (left)	-0.22***	-0.06**	-0.04***	0.02	-0.09***	-0.03	0.01
	(-5.04)	(-2.00)	(-4.01)	(1.38)	(-3.58)	(-1.39)	(0.66)
keep$_{t-1}$ (right)	-0.15***	-0.02	-0.01	-0.05***	-0.02	-0.07***	
	(-6.60)	(-0.93)	(-0.68)	(-4.20)	(-1.33)	(-3.06)	
keep$_{t-1}$ (right-left)							-0.04***
							(-2.91)
round	-0.36***	-0.12**	-0.01	-0.07	-0.13*	-0.18***	-0.06
	(-3.88)	(-2.18)	(-0.15)	(-1.13)	(-1.77)	(-3.13)	(-0.78)
Constant	16.95***	2.92***	1.52**	1.81***	4.44***	4.73***	0.29
	(16.00)	(5.67)	(2.31)	(2.66)	(5.14)	(4.93)	(0.46)
n	96	96	96	96	96	96	96

Robust z-statistics in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 4.A.9 Determinants of investments patterns of player$_i$ as a response to the investment levels of her neighbors (left and right) in the previous round, $_{t-1}$, for T5 ON_{clu}. Panel model with individual random effects, standard errors clustered at group level.

VARIABLES	(1) invest$_t$ (total)	(2) invest$_t$ (own)	(3) invest$_t$ (left)	(4) invest$_t$ (right)	(5) invest$_t$ (own+left)	(6) invest$_t$ (own+right)	(7) invest$_t$ (right-left)
invest$_{t-1}$ (own)	0.53***	0.54***	0.06	0.07*	0.60***	0.61***	0.02
	(5.42)	(5.69)	(1.25)	(1.68)	(9.77)	(9.72)	(0.70)
invest$_{t-1}$ (right)	0.24*	0.10	0.10**	0.41***	0.20***	0.52***	0.32***
	(1.77)	(1.44)	(2.56)	(4.00)	(2.72)	(8.78)	(3.26)
invest$_{t-1}$ (left)	0.34***	0.23***	0.35***	0.06	0.57***	0.28***	-0.29***
	(6.12)	(2.84)	(6.57)	(1.31)	(7.38)	(3.04)	(-5.67)
keep_share$_{t-1}$ (left)	-5.22***	-1.84*	-1.00**	0.18	-2.84***	-1.66**	-0.21
	(-3.90)	(-1.79)	(-2.54)	(0.31)	(-2.63)	(-2.28)	(-0.52)
keep_share$_{t-1}$ (right)	-6.30***	-0.79	-0.51	-1.90***	-1.30**	-2.69***	
	(-6.92)	(-1.51)	(-1.24)	(-2.99)	(-2.30)	(-3.75)	
keep_share$_{t-1}$ (right-left)							-1.39**
							(-2.21)
round	-0.21**	0.03	-0.06	-0.07	-0.02	-0.03	-0.01
	(-2.24)	(0.54)	(-1.27)	(-1.23)	(-0.35)	(-0.64)	(-0.16)
Constant	15.02***	2.30***	2.29***	2.47***	4.59***	4.77***	0.18
	(10.74)	(2.65)	(2.80)	(3.69)	(4.50)	(4.50)	(0.46)
	90	90	90	90	90	90	90

Robust z-statistics in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 4.A.10 Determinants of investments patterns in T3 ON_{hom}. Panel model with individual random effects, standard errors clustered at group level.. *keep_share* variables are coded as rate of tokens kept of the original endowment.

VARIABLES	(1) $invest_t$ (total)	(2) $invest_t$ (own)	(3) $invest_t$ (left)	(4) $invest_t$ (right)	(5) $invest_t$ (own+left)	(6) $invest_t$ (own+right)	(7) $invest_t$ (right-left)
$invest_{t-1}$ (own)	0.28***	0.54***	0.04	0.06***	0.58***	0.60***	0.02
	(3.13)	(6.63)	(1.00)	(3.08)	(11.75)	(7.92)	(0.56)
$invest_{t-1}$ (right)	0.20**	0.17**	0.07	0.45***	0.24***	0.61***	0.37***
	(2.19)	(2.16)	(1.49)	(6.83)	(3.70)	(6.51)	(5.89)
$invest_{t-1}$ (left)	0.03	0.01	0.43***	0.12	0.44***	0.13	-0.31***
	(0.32)	(0.07)	(9.53)	(1.52)	(6.04)	(1.24)	(-3.58)
keep_share$_{t-1}$ (left)	-4.80***	-2.04***	-1.18***	-0.06	-3.22***	-2.10**	0.22
	(-3.33)	(-3.28)	(-2.59)	(-0.14)	(-4.13)	(-2.52)	(0.46)
keep_share$_{t-1}$ (right)	-4.72***	-2.72***	-0.04	-0.94**	-2.75***	-3.66***	
	(-4.66)	(-4.78)	(-0.07)	(-2.05)	(-3.30)	(-5.76)	
keep_share$_{t-1}$ (right-left)							-0.91
							(-1.38)
round	-0.53***	0.06	-0.19***	-0.16**	-0.13*	-0.10	0.03
	(-4.60)	(0.95)	(-4.88)	(-2.30)	(-1.73)	(-1.25)	(0.47)
Constant	19.80***	3.42***	3.18***	2.76***	6.60***	6.18***	-0.42
	(11.68)	(3.58)	(8.34)	(4.09)	(6.40)	(5.82)	(-0.85)
n	90	90	90	90	90	90	90

Robust z-statistics in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 4.A.11 Determinants of investments patterns in T4 ON_{alt}. Panel model with individual random effects, standard errors clustered at group level. *keep_share* variables are coded as rate of tokens kept of the original endowment.

VARIABLES	(1) invest$_t$ (total)	(2) invest$_t$ (own)	(3) invest$_t$ (left)	(4) invest$_t$ (right)	(5) invest$_t$ (own+left)	(6) invest$_t$ (own+right)	(7) invest$_t$ (right-left)
invest$_{t-1}$ (own)	0.51***	0.56***	0.04**	0.07**	0.60***	0.63***	0.03
	(11.23)	(13.67)	(2.07)	(2.56)	(11.87)	(11.35)	(0.95)
invest$_{t-1}$ (right)	0.20**	0.13*	0.11***	0.45***	0.24***	0.58***	0.34***
	(2.45)	(1.82)	(3.13)	(10.66)	(3.11)	(6.37)	(5.49)
invest$_{t-1}$ (left)	0.33***	0.11*	0.55***	0.17***	0.66***	0.28***	-0.38***
	(3.73)	(1.65)	(5.62)	(5.47)	(8.02)	(3.98)	(-3.87)
keep_share$_{t-1}$ (left)	-6.76***	-2.22**	-0.95**	0.38	-3.17***	-1.83**	0.32
	(-4.07)	(-2.39)	(-2.39)	(0.84)	(-3.64)	(-2.05)	(0.48)
keep_share$_{t-1}$ (right)	-4.41***	-0.35	-0.48	-1.48***	-0.83	-1.84**	
	(-4.94)	(-0.59)	(-1.13)	(-3.22)	(-1.22)	(-2.40)	
keep_share$_{t-1}$ (right-left)							-1.01
							(-1.55)
round	-0.34***	-0.11**	-0.00	-0.06	-0.11	-0.16***	-0.05
	(-3.46)	(-2.03)	(-0.07)	(-1.02)	(-1.55)	(-2.79)	(-0.74)
Constant	16.82***	3.03***	1.59**	1.85***	4.62***	4.88***	0.26
	(15.27)	(5.31)	(2.27)	(2.74)	(5.00)	(5.03)	(0.39)
n	96	96	96	96	96	96	96

Robust z-statistics in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 4.A.12 Determinants of investments patterns in T5 ON_{clu}. Panel model with individual random effects, standard errors clustered at group level. *keep_share* variables are coded as rate of tokens kept of the original endowment.

Rich	Group FAB 2 poor, 1 rich (sd)	Group CDE 2 rich, 1 poor (sd)
Payoff	39.05	43.17
	(7.68)	(3.70)
Tokens kept	18.15	21.17
	(12.56)	(11.06)
Tokens invested	21.85	18.83
	(12.56)	(11.06)
- in own location	7.41	5.05
	(7.32)	(3.82)
- in neighbors' location	12.86	12.42
	(11.05)	(8.63)
- outside of neighborhood	1.57	1.37
	(3.15)	(2.76)
Observations	15	15
	Group FAB	Group CDE
Poor	2 poor, 1 rich	2 rich, 1 poor
Payoff	31.71	34.09
	(7.10)	(8.54)
Tokens kept	10.82	12.08
	(5.01)	(5.59)
Tokens invested	9.18	7.92
	(5.01)	(5.59)
- in own location	2.97	2.79
	(2.59)	(2.71)
- in neighbors' locations	6.10	4.49
	(3.80)	(4.31)
- outside of neighborhood	0.11	0.63
	(0.21)	(1.42)
Observations	15	15

Table 4.A.13 Average outcomes of rich and poor participants, separated by the subgroup that they belong to – group FAB (2 poor, and 1 rich participant) and group BCE 2 rich, and 1 poor participant).

Appendix 4.C Experiment Instructions (translation from German original, Treatment T4 ON_{alt})

Welcome to our experiment!

General information

In this experiment you can earn money depending on your decisions and the decisions of the other participants.

Please read the instructions carefully to understand the rules of the experiment.

Payment during the experiment is calculated in LabPoints (LP). The exchange between LP and Euro is 2,5:1, i.e. 1 LP is exchanged for 0.40 €.

At the end of the experiment you will fill in a questionnaire. In total, the experiment will take about 60 minutes. Your answers will be treated anonymously. If you leave the experiment early, you will not receive any compensation.

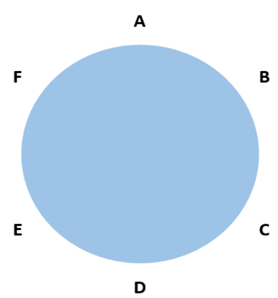
Rules

Locations and neighbourhoods

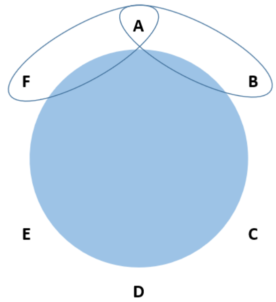
You play in a group of 6 participants in total, i.e. you and 5 other people. The 6 participants take a seat at a virtual round table, with each participant having his or her fixed location. Each group member faces the same decision problem. All decisions in this experiment are anonymous.

They play a game that is played over 10 separate and independent rounds. At the end, one of the 10 rounds is randomly selected and used to calculate the payoffs.

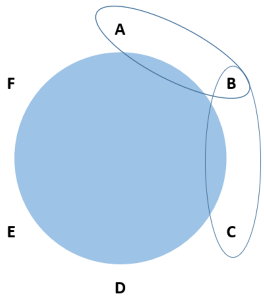
To maintain anonymity, you, i.e. your location at the virtual table, are identified by a letter (between A and F) that remains constant over all rounds:



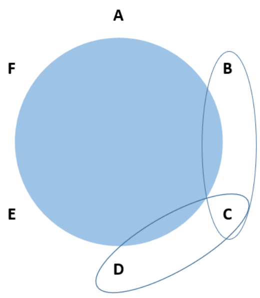
Depending on the location, the participants have different neighbours. For example, the neighbourhood of the player at location A is F-A-B:



The neighbourhood of the player at location B is A-B-C:

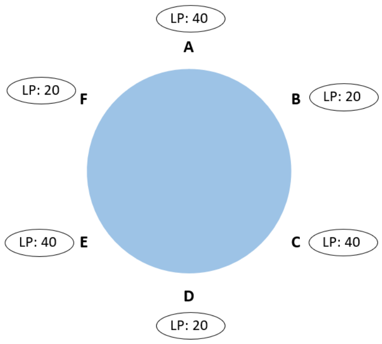


The neighbourhood of the player at location C is B-C-D (etc.):



Equipment and investments

Three players in the group start each round with 40 LP credited to their private account, while the other three start with 20 LP each. Specifically, players A, C and E each receive 40 LP, while players B, D and F each receive 20 LP.



Each player decides individually how many LP they want to keep on their private account and how many they want to invest in locations A, B, C, D, E or F. **Each player can thus invest in all locations A to F.**

The sum of a player's investments may not exceed his initial endowment of (40 or 20).

The investments of all players are added up. The total investment at a location is thus the sum of the investments made by the six players at that location.

The total investments at each location have different effects on the payout of the players.

The total investment at a location generates a payout for the player at that location as well as the respective two neighbours. This means that a player at one location benefits from the total investments at his own location as well as the locations of the two neighbours. Investments in other locations do not generate a payout for that player.

Payout

Your payout at the end of the game is made up of the following parts:

- the number of LP you still have in your private account.
- 0.5 times the total investments made at your location.
- 0.5 times the total investments made at your right-hand neighbour's location,
- 0.5 times the total investments at the location of your left-hand neighbour,

Calculation: Private account balance + investment payout (0.5 x sum of investments in neighbourhood)

A player's payout is thus determined by 0.5 times (50%) the investments in the player's neighbourhood (at his location and at the locations of the respective two neighbours). Conversely, each LP invested in a location thus generates a total payout of 1.5LP: 0.5LP each for the player of the location, as well as the respective left and right neighbour.

For example, let us assume that 40LP has been invested at location D and 20LP and 40LP at the two neighbouring locations C and E respectively. Then the sum of the total investment of the neighbourhood C-D-E is equal to 20+40+40=100. Player D receives 50% of the total investment at his location, as well as 50% of the total investment at the location of his two neighbours, i.e. a payout of 0.5 times (20+40+40) = 0.5 times 100LP = 50LP. Added to this is the payout of the remaining LP on his private account. The payout of all players is calculated analogously, i.e. depending on the remaining amount on the respective private account, investments at one's own location and investments at the locations of the respective two neighbours.

More payout examples

Use the following examples to familiarise yourself further with the calculation of the payout of the game. Your understanding of this will be tested in the knowledge questions.

1. You have an initial endowment of 40LP and invest nothing in your own location and nothing in other locations. Assume that the total investment in your location is 10 (someone else has invested in your location), in your right neighbour's location is 20LP and in your right neighbour's location is 20LP. Then the total investment in your neighbourhood is 50LP.

   Your payout is therefore (40 - 0) + 0.5 x 50 = 40 + 25 = 65 LP.

2. You have an initial endowment of 20 LP and invest 15 LP in your own location and 5 LP in your left neighbour's location. Assume that the total investment in your location is 30, that in your left neighbour's location is 20 and that in your right neighbour's location is 40. Then the total investment in your neighbourhood is 90LP.

   Your payout is therefore (20 - 20) + 0.5 x 90 = 0 + 45 = 45 LP.

Feedback

After each round in which you and your 5 group members decide at the same time, all players will be informed about how much each player has in his personal account and about the total investment at each location. You will be shown the following exemplary feedback table of the respective rounds:

Participant Location	Initial equipment	Remains in private account	Total investments in location	Sum of investments in the neighborhood	Payoff from investment *(0.5*Sum of investment in neighbourhood)*	Total payout location
A	40	15	15	55 (A,B,F)	27,5	42,5
B	20	10	15	40 (A,B,C)	20	30
C	40	30	10	32 (B,C,D)	16	46
D	20	18	7	42 (C,D,E)	21	39
E	40	0	25	57 (D,E,F)	28,5	28,5
F	20	10	25	65 (E,F,A)	32,5	42,5

Remember that the total payout amount is calculated as follows:

"Total payout" = "Remaining LP in private account" + 0.5 x "Sum of investments at your site and your neighbours' two sites. ".

Summary of instructions

- You play 10 rounds in a group of 6 players.
- You are told which location you have (A to F), accordingly which are your two neighbours and what the initial equipment of all players per round is (40 or 20). Players A, C, E receive 40 LP; players B, D, F receive 20 LP. This remains constant throughout the game.
- In each round
    - You and the other players decide simultaneously and independently of each other how many of your (40 or 20) LP you will invest in which locations.
    - All players are informed about how much each player has kept in his private account and what the total investment at the locations is.
    - Your payout is the sum of what you have kept in your private account PLUS 0.5 times the sum of your neighbour's investment, i.e. the sum of the total investment in your location plus the locations of your two neighbours.
- The game is repeated for a total of 10 rounds and at the end one round is randomly drawn for the payout.
- Finally, you will be asked some questions about yourself.

Control questions

If you have read all the instructions and have no doubts, please answer the following control questions:

1) If you retain 10LP in your private account and the total investment in your location is 10LP and in your left and right neighbour's locations is 20LP and 15LP respectively, what is your payout in this round? (CORRECT ANSWER C)

Calculation: Remaining private account + payout investment (0.5 x sum of investments in neighbourhood)

a) 12,5 b) 22,5 c) 32,5 d) 50

2) If you retain 0LP in your private account and the total investment in your location is 40 and in your left and right neighbour's locations is 0 and 0 respectively, what is your payout this round? [CORRECT ANSWER B]

Calculation: Remaining private account + payout investment (0.5 x sum of investments in neighbourhood)

a) 12,5 b) 20 c) 37,5 d) 50

3) How many players form a neighbourhood? [CORRECT ANSWER B]

a) 4 b) 3 c) 6 d) 8

4) Do the neighbours of a group change between rounds? [CORRECT ANSWER B]

a) Yes b) No

5) Which locations can you invest in? [CORRECT ANSWER B]

a) Only at your own site

b) At each site

c) At your site and those of your neighbours

d) Only at your neighbours' site

6) Who benefits from an investment in your location? [CORRECT ANSWER D]

a) Nobody

b) Only you

c) Everybody

d) You and your two neighbours

7) From which investment do you benefit more: 10LP in your location or 10LP in your left neighbour's location? You profited: [CORRECT ANSWER A]

a) Equally

b) More by investing in your location

c) More by investing in my left neighbour's location

8) Assuming you are player A, what changes if you invest in the location of your right-hand neighbour, player F, instead of your location? [CORRECT ANSWER C]

a) Nothing

b) You profit less

c) Now your other right neighbour (player B) no longer profits but the other neighbour of player F (player E)

d) Player F profits more

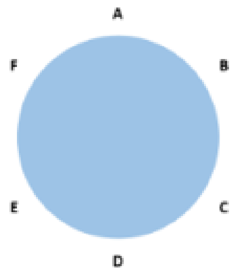
The experiment begins as soon as all participants have answered these questions.

Appendix 4.D Screenshots of Original Experiment - Decision and Feedback Page, Treatment T4 ON_{alt})

Decision Page

ENTSCHEIDUNGSBILDSCHIRM RUNDE 1:

Sie sind Spieler C.



Die Ausstattung der Spieler A, C und E beträgt 40. Die Ausstattungen der Spieler B, D und F betragen 20.

Ihr Standort ist C. Ihre Anfangsausstattung ist 40.

Denken Sie daran, dass sich Ihre Auszahlung aus der Summe folgender Werte ergibt

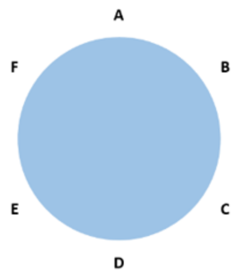
- *Die Anzahl der LP, die auf Ihrem persönlichen Konto verbleiben.*
- *Dem 0,5-fachen der Summe der Investitionen an Ihrem Standort und den Standorten Ihres linken und rechten Nachbarn.*

Wie viele LPs von Ihrem persönlichen Konto möchten Sie in dieser Runde an den jeweiligen Standorten investieren? (Die Summe darf Ihre Anfangsausstattung (40) nicht überschreiten.)

Standort	Ausstattung des Spielers am Standort	Nachbarschaft	Meine Investition in den Standort	Auszahlung an Spieler an den Standorten aufgrund meiner Investitionen
A	40			5
B	20	**Nachbar**	10	15
C	40	**Sie**	20	20
D	20	**Nachbar**	10	15
E	40			5
F	20			0
		Gesamtinvestitionen diese Runde:	40	
		Verbleib auf Ihrem Privatkonto:	0	

Feedback Page (with hypothetical numbers inserted)

ZUSAMMENFASSUNG BILDSCHIRM RUNDE 1



Teilnehmer-Standort	Anfangs-ausstattung	Verbleib auf Privatkonto	Gesamt-investition am Standort	Summe Investition Nachbarschaft	Auszahlung Investition *(0,5*Summe Investition Nachbarschaft)*	Gesamt-auszahlung Standort
A	40	40	10	20 (F,A,B)	10,0	50,0
B	20	20	10	40 (A,B,C)	20,0	40,0
C	40	0	20	40 (B,C,D)	20,0	20,0
D	20	20	10	80 (C,D,E)	40,0	60,0
E	40	0	50	60 (D,E,F)	30,0	30,0
F	20	0	0	60 (E,F,A)	30,0	30,0

Weiter

Appendix to the dissertation

List of publications derived from this dissertation

Chapter 2:

Status: not published - planned submission Q1, 2025.

Chapter 3:

Status: under review at “Games and Economic Behavior”.

Chapter 4:

Status: not published - planned submission Q1, 2025.

Abstract

This dissertation contains three different essays that study the provision of public goods. These three studies share the common overarching theme of how the nature of the public good can be expected to have a negative effect on its provision (development of climate mitigation technologies in Chapter 2, and local public goods in Chapter 3 and 4). These three studies also use empirical approaches that aim to find causal relationships, although the methodologies differ – Chapter 2 uses a quasi-experimental design, while Chapters 3 and 4 use laboratory experimental settings. Lastly, two of the chapters also study how this provision can be improved, by setting new environmental regulations (Chapter 2) or new transfer mechanisms (Chapter 3).

Chapter 2 examines how environmental regulation can spur green innovation. By studying a tax reform introduced in Germany in 1999, this study analysis whether firms responded by developing new green technologies. By matching German firms with similar, foreign companies and using a difference-in-differences design, this chapter estimates causal effects of this reform. This study finds no evidence of an effect of the reform on green transport innovation, while small firms decrease the number of green energy technologies developed after the introduction of the reform, although this result is not robust to different specifications. Finally, some potential reasons for this null effect are discussed, such as exemptions and reductions in the tax rate.

Chapter 3 and Chapter 4 investigate the role of networks in public good provision. Chapter 3 studies the provision of a weakest link public good in a circular network, where the provision of the good is calculated at a local level – formed by a participant's direct connections in the network. The treatments vary (i) the endowment of participants, whether it is homogeneous or heterogeneous, (ii) in the case of heterogeneous endowment, how it is spatially distributed – alternating or clustered together – and (iii) whether participants can transfer funds freely to each other or through an intermediary common account. This chapter finds that participants tend to transfer a sizable part of their endowment to their direct neighbors. Endowment heterogeneity is detrimental to poorer participants, but only when they are clustered together, showing that spatial distribution matters for final payoff inequality. Using an intermediary account does not improve average provision, but it decreases inequality when participants are clustered together.

Chapter 4 analyses the provision of local public goods in networks. In this setting, participants benefit directly from the investments in the public good done in their own location, as well as in the location of their direct neighbors. The treatments vary in terms of the (i) participants' endowment – homogeneous or heterogeneous –, (ii) and in the case of heterogeneous endowment, whether participants with the same endowment are alternating

or clustered together. This chapter finds that participants tend to invest a large share of their endowments on their direct neighbors' locations. When participants are clustered together regarding their endowment, there is a net transfer from rich to poor participants, facilitated by the rich participants at the border of the cluster. Participants also show a reward (punishment) behavior, where they increase (reduce) the investments to their (un)cooperative neighbor.

Zusammenfasssung

Diese Dissertation enthält drei verschiedene Aufsätze, die sich mit der Bereitstellung öffentlicher Güter befassen. Diese drei Studien haben das gemeinsame übergreifende Thema, wie sich die Art des öffentlichen Gutes negativ auf dessen Bereitstellung auswirken kann (Entwicklung von Technologien zur Eindämmung des Klimawandels in Kapitel 2 und lokale öffentliche Güter in Kapitel 3 und 4). Diese drei Studien verwenden ebenfalls empirische Ansätze, die darauf abzielen, kausale Zusammenhänge zu finden, obwohl sich die Methoden unterscheiden - Kapitel 2 verwendet ein quasi-experimentelles Design, während in den Kapiteln 3 und 4 Laborexperimente eingesetzt werden. Schließlich wird in zwei der Kapitel auch untersucht, wie diese Bereitstellung verbessert werden kann, indem neue Umweltvorschriften (Kapitel 2) oder neue Transfermechanismen (Kapitel 3) festgelegt werden.

In Kapitel 2 wird untersucht, wie Umweltvorschriften grüne Innovationen anregen können. Anhand einer 1999 in Deutschland eingeführten Steuerreform wird untersucht, ob Unternehmen darauf mit der Entwicklung neuer grüner Technologien reagierten. Indem deutsche Unternehmen mit ähnlichen ausländischen Unternehmen verglichen werden und ein Differenz-von-Differenzen-Design verwendet wird, schätzt dieses Kapitel die kausalen Auswirkungen dieser Reform. Die Studie findet keine Hinweise auf eine Auswirkung der Reform auf umweltfreundliche Verkehrsinnovationen, während kleine Unternehmen die Anzahl der entwickelten umweltfreundlichen Energietechnologien nach der Einführung der Reform verringern, obwohl dieses Ergebnis nicht robust gegenüber verschiedenen Spezifikationen ist. Abschließend werden einige mögliche Gründe für diesen Nulleffekt erörtert, wie z. B. Ausnahmeregelungen und Senkungen des Steuersatzes.

In Kapitel 3 und Kapitel 4 wird die Rolle von Netzwerken bei der Bereitstellung öffentlicher Güter untersucht. In Kapitel 3 wird die Bereitstellung eines öffentlichen Gutes mit dem schwächsten Glied in einem zirkulären Netzwerk untersucht, wobei die Bereitstellung des Gutes auf lokaler Ebene berechnet wird, die durch die direkten Verbindungen eines Teilnehmers im Netzwerk gebildet wird. Die Behandlungen variieren (i) die Ausstattung der Teilnehmer, ob sie homogen oder heterogen ist, (ii) im Falle einer heterogenen Ausstattung, wie sie räumlich verteilt ist - abwechselnd oder gebündelt - und (iii) ob die Teilnehmer Gelder frei zueinander oder über ein gemeinsames Zwischenkonto überweisen können. In diesem Kapitel wird festgestellt, dass die Teilnehmer dazu neigen, einen beträchtlichen Teil ihrer Ausstattung an ihre direkten Nachbarn zu übertragen. Die Heterogenität der Ausstattung wirkt sich nachteilig auf ärmere Teilnehmer aus, allerdings nur dann, wenn sie sich in einer Gruppe befinden, was zeigt, dass die räumliche Verteilung für die Ungleichheit der Endauszahlungen von Bedeutung ist. Die Nutzung eines Vermittlungskontos verbessert die durchschnittliche Versorgung nicht, verringert aber die

Ungleichheit, wenn die Teilnehmer in einer Gruppe zusammenleben.

Kapitel 4 analysiert die Bereitstellung lokaler öffentlicher Güter in Netzwerken. In diesem Rahmen profitieren die Teilnehmer direkt von den Investitionen in das öffentliche Gut, die an ihrem eigenen Standort sowie an den Standorten ihrer direkten Nachbarn getätigt werden. Die Behandlungen unterscheiden sich in Bezug auf (i) die Ausstattung der Teilnehmer - homogen oder heterogen -, (ii) und im Falle einer heterogenen Ausstattung, ob die Teilnehmer mit der gleichen Ausstattung sich abwechseln oder in Gruppen zusammengeschlossen sind. In diesem Kapitel wird festgestellt, dass die Teilnehmer dazu neigen, einen großen Teil ihrer Ausstattung an den Standorten ihrer direkten Nachbarn zu investieren. Wenn die Teilnehmer in Bezug auf ihre Ausstattung in einem Cluster zusammengefasst sind, kommt es zu einem Nettotransfer von reichen zu armen Teilnehmern, der durch die reichen Teilnehmer am Rande des Clusters erleichtert wird. Die Teilnehmer zeigen auch ein Belohnungs- (Bestrafungs-) Verhalten, indem sie die Investitionen für ihren (un)kooperativen Nachbarn erhöhen (reduzieren).