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by

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Abstract

Climate change is one of the greatest market failures of our time. This thesis consists of three essays in which we study the economics of climate change using networks as a theoretical framework.

In the first essay, we discover flaws in the foundations of a recent strand of literature estimating the carbon Kuznets curve (CKC). The CKC hypothesizes that carbon dioxide emissions initially increase with economic growth but that the relationship is eventually reversed. The recent literature attempts to estimate the CKC by adding energy consumption as a control variable. Due to model misspecifications related to the econometric methodology and database definitions, the results are biased to support the existence of a CKC. Consequently, the literature underestimates the need for climate policies.

In the second essay, we study how social networks might help to explain why differences of opinion about climate change persist across segments of the lay public despite the scientific consensus. To do this, we programmed a Facebook application that collected survey data on concerns about climate change and network data on friendships. We found that respondents tend to have friends with similar concerns as their own, the unconcerned respondents have fewer friends, and any two respondents who disagreed about the seriousness of global warming were less than half as likely to be friends. The results indicate that the structure of the social network may hinder changes in opinions, explaining why opinions persist despite the scientific consensus. The results suggest that the communication of climate science could be improved by strategies that aim to overcome these network effects.

In the third essay, we study permit markets which are connected by a network of links. A link allows participants of one emissions trading system to use permits of other systems. In a linked network of markets, foreign regulators can influence domestic policy outcomes even without a direct link. We apply graph theory to study these dependencies between markets to determine who exactly can affect domestic emissions and prices. We characterize the equilibrium's dependency structure assuming perfect competition and an exogenous trading network. The results help to avoid unexpected foreign interference with domestic policy outcomes and to secure the effectiveness of climate change policies.

Tiivistelmä

Ilmastonmuutos on yksi aikamme suurimmista markkinahäiriöistä. Tämä väitöskirja koostuu johdannon lisäksi kolmesta esseestä, joissa käsitellään ilmastonmuutoksen taloustiedettä verkostojen näkökulmasta.

Ensimmäisessä esseessä kritisoidaan tutkimuksia, joissa on tarkasteltu hiilidioksidipäästöjen ja talouskasvun välistä suhdetta ja pyritty löytämään ns. hiili-Kuznets-käyrän mukainen riippuvuus. Löytö merkitsisi, että talouskasvu lisää päästöjä köyhissä maissa, mutta vähentää niitä rikkaissa. Esseessä osoitetaan matemaattinen ristiriita tutkimuksissa käytetyissä tilastollisissa menetelmissä. Lisäksi menetelmät yliarvioivat hiili-Kuznets-käyrän kaarevuutta jättäessään huomiotta energiankulutuksen ja päästöjen määritelmällisen yhteyden. Kritisoitu kirjallisuus päätyy aliarvioimaan ilmastopolitiikan tarvetta.

Toisessa esseessä tarkastellaan sosiaalisia verkostoja ja mielipiteitä ilmastonmuutoksesta. Tutkimuksessa etsitään selitystä sosiaalisten verkostojen rakenteista sille, miksi mielipide-erot ihmisryhmien välillä ovat säilyneet tieteen konsensuksesta huolimatta. Tätä varten ohjelmoitiin Facebook-sovellus, jolla kerättiin kyselytietoa mielipiteistä ja verkostodataa Facebook-kavereista. Vastaajilla havaittiin suhteellisesti enemmän samanmielisiä kavereita, ja niillä, jotka eivät pitäneet ilmastonmuutosta ongelmana, oli vähemmän kavereita. Erimielisillä vastaajilla kaverisuhteen todennäköisyys oli yli puolet pienempi samanmielisiin verrattuna. Tulokset viittaavat sosiaalisen verkoston rakentuneen tavalla, joka selittää mielipiteiden muuttumisen hitautta. Tiedeviestinnässä tulisikin pyrkiä minimoimaan viestin välittymistä hidastavien verkoston rakenteiden vaikutus.

Kolmannessa esseessä tutkitaan päästökauppaa tilanteessa, jossa paikalliset päästökauppajärjestelmät ovat linkittyneet verkostoksi. Linkittyminen tarkoittaa, että päästökauppaan osallistuvien sallitaan käyttää toisen järjestelmän päästöoikeuksia. Verkostossa toisen maan viranomainen voi vaikuttaa kotimaisen ilmastopolitiikan tuloksiin, vaikkei maiden välillä olisikaan suoraa linkkiä. Verkostorakenteesta johtuen ei ole aina ilmeistä, ketkä voivat kotimaisen politiikan tuloksiin vaikuttaa. Tutkimuksessa sovelletaan graafiteoriaa ja osoitetaan yksikäsitteisesti, ketkä voivat vaikuttaa toisiinsa. Tulokset auttavat politiikantekijöitä välttymään yllätyksiltä ja turvaamaan ilmastopolitiikan vaikuttavuuden.

Acknowledgements

This journey began with a belief that almost everything in economics is wrong. I had acquired this belief shortly after I started my studies at the University of Helsinki. At that time, I was mostly studying social sciences. Social scientists, as I remember it, were very critical towards economics, and I had managed to absorb this view.

I am glad, however, that I was also critical towards critical view of economics. Could economists really be that evil? It seemed somehow implausible that economists could truly believe in all those absurd theories I heard about. And were they really recommending all those bitter policies purely out of ignorance and spite?

In 2006, I began my undergraduate studies in economics motivated by two alternate hypotheses: either there was a lot to be done in pointing out and fixing the shortcomings of the science—or I had much to learn about economics and the phenomena it studies. Either way I would benefit.

In retrospect, the latter hypothesis seems rather obvious. I have learned a lot both about economics and about humility. And I feel much more comfortable with the idea that I am, quite possibly, still wrong about most things.

For economics itself, however, the outcome was less unfortunate. It neither received nor needed the revolution I had originally planned for it. Nevertheless, this thesis is my humble effort provide a marginal improvement to the stock of knowledge that is economics.

I am grateful to all who have helped me along the way. First of all, I would like to thank my supervisor Panu Poutvaara for all the time and effort he has invested in my thesis and in our joint research projects. I have felt lucky to have been able to benefit from his guidance. I have found him to be a very rare combination of unconstrained imagination—able to create fresh ideas—and unyielding intellectual rigour—able to sift out bad ones.

Regarding the first article of this thesis, I would like to give many thanks to Silke Friedrich, Marc Gronwald, Hannu Kivimäki, Markku Lanne, Karen Pittel, Pentti Saikkonen, and Harri Turunen for helpful comments and discussion. For the second article, the Facebook application and survey were designed and carried out together with Panu Poutvaara. This huge joint endeavour would not have been possible without his creativity and diligence. I also wish to thank Jan-Erik Lönnqvist and Markku Verkasalo for help with the survey design and Pekka Ilmakunnas, Heikki Kauppi, Anssi Kohonen, Otto Kässi, Jaakko Nelimarkka, and Aino Silvo for valuable comments on the paper. Regarding the third article, I would like to thank Klaus Kultti, Hannu Vartiainen, Pauli Murto, and Marko Terviö for helpful comments and discussion.

Professors Markku Ollikainen and Essi Eerola kindly agreed to act pre-examiners of the thesis and provided valuable comments and suggestions for revision.

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And finally, I am of course deeply grateful to my wife for her endless support. I fear, without her wisdom and sensibility, my thesis (and I) might have become (even more) detached from reality. And I would like to thank my parents for teaching me that one should not always take the easy way out (”ei aina pidä mennä siitä, mistä aita on matalin”), and to never leave till tomorrow what you can do today (”sen, minkä voi tehdä tänään, ei kannata jättää huomiseen”). Despite the fact that these ideals make no sense to an economist, they have provided a good heuristic for life.

Helsinki, March 2015
Juha V.A. Itkonen

Contents

Chapter 1

Introduction

1.1 Background

Already the ancient Greeks and Romans considered the possibility of man-made climate change (Neumann, 1985). Since ancient times, it seems, our understanding of climate change has grown at an increasing rate. It took two millennia to conceive the idea that air could trap heat, but by the end of the 19th century, Svante Arrhenius was already trying to quantify how changes in the atmosphere's levels of carbon dioxide would alter the Earth's surface temperature (IPCC, 2007). By the 1970s, many scientist at the top level were convinced that temperatures were going to rise due to man-made greenhouse gas emissions (Broecker, 1975; Wang et al., 1976). In 1988, the Intergovernmental Panel on Climate Change (IPCC) was created to assess the science on climate change and to formulate strategies to mitigate it. By 1992, the science was compelling enough to convince politicians to sign the United Nations Framework Convention on Climate Change (UNFCCC), an international environmental treaty aiming to ”stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.”

The science of climate change has not been without its controversies. But for a long time now, a vast majority of scientists working in the field of climate science have agreed with IPCC's assessment that humans are affecting the climate and that this poses a threat to us. Still, there are always those who challenge the scientific consensus (as should be). Some even deny that such a consensus exist. For this reason, the scientists have felt the need to study the scientists themselves, in order to determine how convinced they actually are about man-made global warming. A broad analysis of top climate scientists showed that over 97% of them support the conclusions of the IPCC (Anderegg et al., 2010). Another analysis of 11944 peer-reviewed articles on climate change showed that over 97% of abstracts that expressed a position on the matter endorsed the idea that humans are causing climate change (Cook et al., 2013). Also the latest IPCC assessment report (IPCC, 2013) concluded that ”it is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century.”

Economists make poor climate scientists. Economists, however, understand well the benefits of division of labour. Accordingly, it is best to leave it to the physical scientists to study the physical world.

Climate change has many economic aspects which are best studied by economists. Climate change affects the well-being of everyone on this planet, and economists have studied its implications ever since it was considered a plausible problem several decades ago. The economics literature on climate change can be roughly divided into three groups, based on the fundamental question which is being asked: (1) what are the costs and benefits of the impacts of climate change, (2) how can we slow down climate change, and (3) how can we adapt to climate change?

The Stern Review (2007) was an ambitious effort to answer all of these questions at once. And I must admit, it was my original inspiration for studying climate change. Despite its mixed reception, it managed to change the way that climate change was perceived in political discourse. It was not the first of its kind but it was extensive and compelling, and its message was clear. The review was essentially a huge cost–benefit analysis which concluded that the benefits of climate change policies would outweigh the cost of doing nothing. In other words, climate change mitigation made sense in economic terms.

Climate change is the main theme of this thesis. All three articles in this thesis relate to the second fundamental question of climate change economics, i.e. climate change mitigation.

1.2 Networks

Networks are the main tools of this thesis. The articles examine different aspect of mitigation policies, but they all employ networks in one way or another. A network is simply an object that consists two sets: a set of nodes and a set of links between these nodes. Networks exist in many forms. Because the basic concept of a network is so simple, it can be applied to a huge variety of subjects. Basically it can describe any situation where pairs of objects are attributed with a property of some kind.

Networks are used explicitly in the second and third article. In the second article, nodes represent Facebook users and links represent Facebook friendships between users. In the third article, the nodes represent emissions trading systems and the links represent possibilities to use permits of one system in another system. Even though it is not apparent, also the first article is based on networks.

In the first article, the variables of the statistical model can be viewed as nodes in a network, while links represent causal relationships between these variables. This type of networks are known as causal networks. More generally, the network in the first article can be classified as a (non-causal) Bayesian network, if the links imply merely a certain conditional dependence relation between the variables (Pearl, 2009).

Causal networks proved extremely useful in providing a rigorous analysis of the article's main argument which, in essence, relates to causality. While similar problems are often handled by less formal means, a more systematic approach was necessary because the article makes a rather strong claim: the method used in a recent strand of literature is fundamentally flawed. More specifically, the set of causal claims, implied in the criticized literature, cannot hold all at once. Proving such a proposition requires to exhaust a list of alternative cases, which would have been difficult without the formalism.

The underlying causal theory is based on the seminal work by Nobel Prize-winning economist Herbert Simon (1952). Although Simon's work on causal ordering has become a classic in artificial intelligence research, it has been practically forgotten by economists. Since causal networks are not commonly used in economics and the theory might appear rather esoteric, I saw it best to express the arguments by more conventional means. The interested reader may refer to Itkonen (2011) for the extended account.

In the end, the causal networks acted as a sort of scaffolding that could be dismantled after the work was done.

1.3 The carbon Kuznets curve

The first article considers methodological problems in a recent strand of literature which attempts to estimate the carbon Kuznets curve (CKC). The curve is related to a hypothesis that the carbon dioxide emissions of a country initially increase alongside economic growth and that the relationship is eventually reversed. In other words, the hypothesis implies an inverted U-shaped relationship between emissions and economic output. If the hypothesis were true, then, in the extreme case, the climate change problem could be solved by economic growth alone, and all the costly climate policies would be unnecessary.

The recent strand attempts to estimate the CKC, i.e. a relationship between GDP and CO_2 emissions, while including energy consumption as a control variable. The earliest studies that employ this method give little explanation for adding energy consumption to the model. A few merely mentions that energy and emissions are somehow related. And subsequent studies simply refer to the earlier ones. Anyway, this modelling choice is a really bad idea.

The relationship between CO_2 emissions and energy consumption is determined by elementary laws of chemistry. Stoichiometry is the branch of chemistry that studies the relative quantities of different substances going in and coming out from chemical reactions. Following the guidelines of IPCC (2006), these chemical laws are used to derive the estimates of CO_2 emissions based on the observations of energy consumption.

To put it simply, no direct measurements of CO_2 emissions exist. Energy consumption of a country is the only statistic which is quantified directly. The problem emerges when these studies try to analyse how CO_2 emissions change when energy consumption is assumed fixed.

To illustrate the problem, suppose a country consumes only one type of fuel, oil for example. Now, the CO_2 emissions statistic simply equals the amount of oil consumed multiplied by a specific chemical coefficient. How could CO_2 emissions increase without increasing the amount of oil burned? It simply cannot. Basic chemical equations dictate how much CO_2 is produced when a given amount of oil is burned.

Now, consider the general case where a country uses a mix of different fuel types. Each fuel type produces a different amount of carbon emissions when burned. For example, coal emits more than natural gas per energy unit. Therefore each fuel type has its own chemical coefficient which tells how much of CO_2 is produced by burning a certain amount of that fuel. Total amount CO_2 emissions produced by a country is the sum of CO_2 emissions from the various fuel types.

Suppose for a moment that a country does not change the proportions of different fuel types it consumes. In other words it does not change its fuel mix. Now a 10% increase in energy consumption would, by definition, result in a 10% increase in total CO_2 emissions. This is because each fuel type would produce 10% more emissions. When the fuel mix is fixed, CO_2 emissions cannot change unless energy consumption changes.

The only way total CO_2 emissions can increase without increasing the total energy consumption is if the fuel mix changes in a specific way. This occurs when the use of more heavily polluting fuels increases, while at the same time the use of less heavily polluting fuels decreases. This means the carbon intensity of the fuel mix increases. In other words, when total energy consumption is fixed, CO_2 emissions can increase only if carbon intensity increases.

The recent strand of literature claims to estimate the relationship between *carbon emissions* and economic output. The first article of this thesis shows that these studies are, in fact, unintentionally estimating the relationship between *carbon intensity* and economic output.

The policy implications are very different when the parameter is correctly identified as the relationship between carbon intensity and economic output. A correctly identified carbon Kuznets curve would imply that economic growth eventually leads to lower emissions levels. But an inverted U-shaped curve between carbon intensity and economic output does not lead to the same conclusion. Even if carbon intensity of energy consumption decreases with economic growth, the total amount CO_2 emissions might still grow. This is possible if energy consumption grows with economic growth—and it typically has. I show that this implies that the literature underestimates the need for climate policies.

Consequently, the main result of many of the studies of the literature, that economic growth would eventually take care of the climate change problem, is unfounded.

1.4 Social ties

The second article considers social ties and people's concern about global warming. As mentioned earlier, climate scientist seem to be rather concerned about global warming and advocate immediate action to mitigate climate change. Yet, a significant portion of the public seems unconcerned and unwilling to implement policies that scientists suggest. In democratic societies the public is responsible, in the end, for choosing the policies to mitigate climate change. But if the public does not heed the warning and take action, much of the scientific effort has been in vain.

Researcher have sought to explain this gap between public and expert concerns for global warming. Why do some members of the public see climate change as a problem, while others do not? How does the public perceive climate change and how could scientist communicate climate science more effectively? A rapidly growing body of scholarly literature aims to answer these question (Moser, 2010; Wolf and Moser, 2011).

One traditional theory is that the public simply lacks knowledge on the issue. This perspective is known as the deficit model (Irwin and Wynne, 1996). Advocates of the deficit model typically aim to overcome the problem by providing more and better information (Sturgis and Allum, 2004). To this end, researchers have tried to find ways to improve experts' ability to effectively communicate climate science (Bowman et al., 2009; Pidgeon and Fischhoff, 2011). Laymen usually have to rely on different types of heuristic techniques to assess risks related to climate change (Weber, 2006; Marx et al., 2007; Sunstein, 2006; Wolf and Moser, 2011). By understanding how people process scientific information, scientists could, it is hoped, make the evidence more compelling to non-experts.

The deficit model has been challenged by recent studies. If the lack of knowledge is the problem, then we should expect that more knowledgeable laymen are more concerned. To the contrary, Kahan et al. (2012) found that people who had better ability to understand the science were not significantly more concerned. Instead, the views of the most able were more polarized and more strongly related to political opinions. Other studies have linked political views (McCright and Dunlap, 2011; Brulle et al., 2012) and social norms (Markowitz and Shariff, 2012; Schultz et al., 2007; Allcott, 2011) to opinions about climate change. Subsequently, a prevailing view in the literature is that concern for global warming is more about social behaviour than about knowledge.

The second article studies social networks and investigates whether they can help to understand why some members of the public are less concerned about global warming than others. If the concerned and unconcerned occupy different positions in the social network, the network could operate like a filter. Information and opinions spread through social ties, so different positions receive different signals (see e.g. Bikhchandani et al., 1992; Watts, 2002). Information about climate change could reach some better than other.

If individuals are surrounded by like-minded friends, the social network can act like an echo chamber. Friends can reinforce and amplify existing opinions, while competing views are less likely to be heard. Most people find debating about climate change with friends somewhat awkward. It is often easier to ignore the science than to argue with friends (Kahan et al., 2012). This can impede the scientists' ability to convince the public.

Studying these issues was made possible by a Facebook application, which we programmed together with Panu Poutvaara. The application collected survey data on concerns about climate change, among other things, and network data on Facebook friendships.

The results showed that respondents had a disproportionate amount of friends who were similarly concerned, and that the distribution of opinions among friends was tilted towards the respondents' own opinion. The unconcerned respondents had fewer friends, which makes them less likely to receive signals through the social network. We found no difference in the level of clustering of friendships. Signals are also less likely to travel from the unconcerned to the concerned because friendships were less likely to exist between them. Two people disagreeing on the seriousness of global warming were less than half as likely to be friends, compared to like-minded people. This association was substantially stronger with climate change than with other types of environmental problems and was independent of political and social background factors.

The observed properties of the network point to a social structure which could inhibit change in opinions. The results help to explain why differences of opinion persist across segments of the lay public despite the scientific consensus. The social network makes opinions more inert.

Therefore, the communication of climate science might benefit from measures that aim to decrease social frictions. Typically, people find it easier to accept the science and support climate policies when they are not in conflict with their values. For example, if economic progress is unnecessarily stigmatized, while reporting evidence relating to the natural science, the evidence is more likely to be ignored by those who value economic progress. When the message conflicts with the values that people hold dear, it is less likely to be passed forward in the social network, and it is bound to reach fewer people. A more value-neutral message might have a better chance of reaching the masses. If these social frictions could be mitigated and the scientific knowledge had a better chance to sink in, we could expect to find more public support for the necessary policy measures.

1.5 Emissions trading and linking

The third article considers emissions trading, which has become one of the most important policy tools used to mitigate climate change (Grubb, 2012). Climate change is a global problem and the best way to solve it would be by international cooperation (Stavins, 2010). Since the creation of the UNFCCC, most countries have hoped for a broad global agreement to reduce greenhouse gases and to mitigate climate change (Newell et al., 2013). But after two decades of negotiations, the world still lacks a binding agreement. Undeterred by the sluggish progress of the international negotiations, many countries have gone ahead and set up local emissions trading systems.

The basic idea of an emissions trading systems is to create a limited amount of permits that allow firms to emit carbon dioxide. The permits are tradable so they can be bought by firms who value them the most. And similarly, firms, who find it easier to reduce emissions, can sell their permits. Trade will lower the costs of reducing emissions.

A link between emissions trading systems means that participants of one emissions trading system can use the permits of another system. This could reduce costs even further. Most national and regional emissions trading systems have been designed so they can be linked together with other systems.

But there is a problem: when emissions trading systems are linked, the outcomes of climate policies are also linked. Permit prices and the amount of emissions depend on the decisions of other regulators when systems are linked. Any regulator might unilaterally create and sell new permits. This would increase the aggregate amount of emissions. Furthermore, the rogue regulator would make an easy profit by selling the newly created permits.

Such behaviour would, of course, undermine the whole purpose of emissions trading and linking. For this reason, to prevent harmful behaviour, linking requires agreement and trust between the regulators. But in a complex network of linked emissions trading systems, it is not always obvious which foreign regulators have the ability to influence the domestic policy outcomes. Policymakers need to know who they have to trust.

The aim of the third article is to study which systems will be dependent from each other when several local emissions trading systems have been linked into a network of markets. In such a world, it is not always obvious which systems are dependent from each other. Direct links are not always necessary nor sufficient to make two systems dependent. It is not even necessary nor sufficient to have a directed path (a sequence of links oriented in the same direction) to make systems dependent.

In the article I construct a model to analyse permit markets which are connected by a network of links. Then I apply graph theory to study the dependencies between permit markets and develop a method to determine who can affect emissions and prices in other systems.

The article builds a theory to show exactly when systems are dependent and when not. The main theorem gives the necessary and sufficient condition for dependencies.

The results help to avoid unexpected interference with policy outcomes and secure the effectiveness of climate change policies.

1.6 Different perspectives

The three articles approach the subject from three very different angles.

The first article is a methodological contribution. It argues that flawed methods have been used in over a dozen of the relationship between GDP and CO_2 emissions. This, of course, is a very bold claim. To assure that no mistake has been made on my part, the rather simple argument has been presented in exhaustive length and with a determinate aim for clarity. The argumentation is based on basic theory of statistical inference. Three problems are presented in the article. The first problem is that the statistical assumptions of the model are inconsistent. The inconsistency is proved by deducing a contradiction from the set of model assumptions. The two other problems described in the article result from a misinterpretation of the parameters of interest, which is also the reason for the wrong policy implications. This is shown by augmenting the model with an accounting identity which has to hold by definition. It reflects the chemical equations that were used to calculate emissions data from energy consumption data. When taking this identity into account, the estimated parameters have a different meaning.

The second article is an empirical contribution which develops and applies new methods of data collection. The Facebook application was programmed to collect a dataset that contains both Facebook friendships and survey data. To our knowledge, such a task had not been attempted before. It required learning several new programming languages, techniques, and tools. All this it took over a half a year of work. The project has already produced two publications written in collaboration with psychologist Jan-Erik Lönnqvist and Markku Verkasalo (Lönnqvist et al., 2014; Lönnqvist and Itkonen, 2014).

The third article is a theoretical contribution. The study uses mathematical tools to analyse emissions trading. As a novel approach, it employs graph theory. Graphs give a visual representation of the underlying problem, while graph theory provides concepts and tools that help to derive the main results.

Summary of the essays

Chapter 2: Problems estimating the carbon Kuznets curve

We discover flaws in the foundations of a recent strand of literature estimating the carbon Kuznets curve (CKC). The CKC hypothesizes that carbon dioxide emissions initially increase with economic growth but that the relationship is eventually reversed. The recent literature attempts to estimate the CKC by adding energy consumption as a control variable. Due to model misspecifications related to the econometric methodology and database definitions, the results are biased to support the existence of a CKC. Consequently, the literature underestimates the need for climate policies.

Chapter 3: Social ties and concern for global warming

Recent research focusing on social factors affecting risk perceptions has suggested that social networks might help to explain why differences of opinion about climate change persist across segments of the lay public despite the scientific consensus. Even though concern for global warming in itself might seem irrelevant for most social ties, we show that it is significant enough to be reflected in the structure of social networks. To do this, we programmed a Facebook application that collected survey data on concerns and network data on friendships. We found that respondents tend to have friends with similar concerns as their own, the unconcerned respondents have fewer friends, and any two respondents who disagreed about the seriousness of global warming were less than half as likely to be friends. The results indicate that the structure of the social network may hinder changes in opinions, explaining why opinions persist despite the scientific consensus. The results suggest that the communication of climate science could be improved by strategies that aim to overcome these network effects.

Chapter 4: Emissions trading in a network of linked markets

We study permit markets which are connected by a network of links. A link allows participants of one emissions trading system to use permits of other systems. In a linked network of markets, foreign regulators can influence domestic policy outcomes even without a direct link. We apply graph theory to study these dependencies between markets to determine who exactly can affect domestic emissions and prices. We characterize the equilibrium's dependency structure assuming perfect competition and an exogenous trading network. The results help to avoid unexpected foreign interference with domestic policy outcomes and to secure the effectiveness of climate change policies.

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Chapter 2

Problems estimating the carbon Kuznets curve[1]

2.1 Introduction

As concerns for climate change and the need for global mitigation action have gained more awareness, also the long-standing debate on the environmental Kuznets curve (EKC) has heated. The EKC hypothesizes a relationship between emissions and output: at low levels of economic development growth increases emissions, but at higher levels of output the relationship is reversed. Graphically this implies emissions are an inverted U-shaped function of output. When the focus is particularly on carbon dioxide emissions, the relationship is referred to as the carbon Kuznets curve (CKC).

The issue is controversial as the advocates and the opponents of the CKC propose very different development and climate change mitigation policies. If the CKC hypothesis is true, business-as-usual economic growth would ultimately lead to the reduction of emissions, implying synergy between development and mitigation policy goals. The opponents of the CKC typically view that emissions continue to grow as output grows. This implies the need for separate climate policies. (See e.g. Brock and Taylor, 2005.)

Since its beginning (namely Grossman and Krueger, 1991, 1995) the EKC-hypothesis has generated an enormous amount of literature.[2] Various problems in estimating the EKC have lead to the use of evermore complicated econometric methods. A recent strand of literature attempts to merge the CKC literature (emissions-output-nexus) with a related topic concerning the

[1]This chapter was published in *Energy* (Itkonen, 2012).

[2]Surveys of the vast literature are provided by, for example, Copeland and Taylor (2004), Stern (2004), Aslanidis (2009), and Kijima et al. (2010).

relationship between energy consumption and output (energy-output-nexus): in practice, energy consumption is added as a control variable to estimate the CKC. We call this combined framework the *emissions-energy-output (EEO) model*.[3]

In the past new attempts to estimate EKCs have been shortly followed by critique of the methods used. For example Copeland and Taylor (2004) and Stern (2004) survey different estimation attempts and problems in their statistical analysis. We add to this discussion by considering problems in the recent strand of literature.

We describe three problems concerning the foundations of the recent strand of literature. The first problem is related to the econometric method most commonly used to estimate the EEO model: the nonlinearity of the CKC model is incompatible with vector autoregression (VAR) models, because it creates a binding yet neglected constraint for the model, which compromises the integrity of the estimators.

Even with a proper estimation method, the second and third problem arise due to the inclusion of energy consumption as an explanatory variable.[4] The second problem arises because emissions are measured indirectly from energy use in the datasets that are used. Carbon dioxide emissions are defined

[3] In a precursory study of the new strand, Richmond and Kaufmann (2006) attempt to estimate the turning point of the CKC with various model specifications. Some of these model specifications use the consumption shares of different fuel types to explain carbon dioxide emissions levels. The influential work by Ang (2007) examines the relationship between emissions, energy consumption, and output in France using cointegration methods and a vector error-correction model (VECM). Total energy consumption is included as a regressor. Further studies have used models similar to Ang's (2007): Apergis and Payne (2009, 2010) extend and apply this method for panel data on South American countries and for the countries of the Commonwealth of Independent States. Pao and Tsai (2010) applies this to panel data on BRIC countries (Brazil, Russia, India, and China), and later add foreign direct investment as a regressor Pao and Tsai (2011b) and study Brazil alone Pao and Tsai (2011a). Pao et al. (2011) study similarly Russia. Similarly Wang et al. (2011) study a panel on China's provinces. Soytas et al. (2007) use emissions, energy consumption, and output among others variables in a vector autoregression model (VAR) for the United States. Soytas and Sari (2009) apply a similar method for Turkey and Lotfalipour et al. (2010) for Iran. Halicioglu (2009) adds foreign trade and uses an autoregressive distributed lag model (ARDL) model for Turkey. Jalil and Mahmud (2009) use an ARDL model for data on China and add foreign trade as an additional explanatory variable, while Jalil and Feridun (2011) add financial development to the equation. Acaravci and Ozturk (2010) use ARDL for European countries. Sharma (2011) investigates the determinants of emissions without adding nonlinearity to output.

[4] The articles in question only briefly comment the rationale for doing this. Some argue that it helps to tackle omitted variable bias, but, how it would solve the endogeneity problem, is left without any justification or discussion. Nevertheless, this is not a trivial matter, and it is the source of the second and third problem.

by a linear function of different fuel commodities, because the amount of emissions that each fuel commodity produces is determined by its chemical composition. As a result, controlling for the level of energy use in the model means that only the proportions of fuel types, and subsequently the ”carbon intensity” of the fuel mix, are allowed to vary. Consequently the meaning of the parameters is distorted and the relation estimated is not actually a conventional CKC. The third problem is caused by the dependence between energy use and output (energy-output-nexus). When this dependence exists, the model is biased to exaggerate the shape of a CKC.

The three problems have practical implications for climate change mitigation policy. First, the estimation problem adds uncertainty to the policy conclusions as the statistical properties of the estimators remain unknown. The second and third problem reveal that economic growth, in developing countries, increases emissions faster than anticipated and, in developed countries, reduces emissions slower if at all. Hence the EEO model can give the faulty conclusion that environmental problems could be solved simply by business-as-usual growth. This means more mitigation effort is needed both in developing and developed countries.

We discuss the problems related to the recent strand of literature by focusing on the representative one-country EEO model used for example by Ang (2007) and Pao and Tsai (2011a). Some of the articles of the strand use slightly different estimation methods and models so some of the problems manifest in different ways.[5] But they all have the common feature of controlling for energy in a CKC model which causes the second and the third problem.

In the next section we present the EEO model. In the third section we derive an accounting identity that causes one of the problems in the literature. In the fourth section we describe the aforementioned three problems. In the fifth section we conclude.

2.2 EEO model

Next we present the EEO model, introduced by Ang (2007), which has been reused and augmented in the recent strand of literature. The EEO model is

[5]For example, Ang (2007); Apergis and Payne (2009, 2010); Pao and Tsai (2011a); Wang et al. (2011) use a very similar methodology. But Richmond and Kaufmann (2006) might avoid similar complications as they explain emissions with fuel proportions, not total energy use. Sharma (2011) does not include a square of output into the model and hence avoids the first problem. Soytas et al. (2007), Soytas and Sari (2009), and Lotfalipour et al. (2010) use a time series technique known as the Toda-Yamamoto procedure, which does not explicate a long-run model, as do vector error-correction models.

described by equation

$$c_t = \beta_0 + \beta_1 e_t + \beta_2 y_t + \beta_3 y_t^2 + u_t, \tag{2.1}$$

where c_t is carbon dioxide emissions, e_t is total energy use, y_t is real GDP measured in local currency, all measured in per capita terms and converted into natural logarithms, and u_t is an error term.

As in a typical CKC-model, the square of output is included to capture the nonlinearity in the CKC. The CKC hypothesis implies that parameter β_2 is positive and β_3 is negative to form an upside-down parabola. The novel feature in the EEO model is the included regressor e_t.

Most commonly the model is estimated using cointegration and vector error-correction modelling (VECM) techniques (see e.g. Engle and Granger, 1987; Engle et al., 1989). The time series on emissions, energy use, and output may include stochastic trends. A long-run relationship between the time series may exist if stochastic trends are common to variables. A common stochastic trend implies that there is a linear combination of the time series such that the combination is stationary. In which case, the time series are said to be cointegrated.

Such a relationship is specified by equation (2.1) when u_t is stationary. This is considered as the long-run (or steady-state) model. In addition to the long-run model, we can study the dynamic causal relationship between the time series by specifying the VAR model whose corresponding error-correction representation incorporates equation (2.1). The VAR model describes how the variables vary, in the short-run, around the long-run model. (See e.g. Engle et al., 1989.)[6]

The model can be estimated using Johansen's (1988) approach, possibly correcting for small sample bias according to Reinsel and Ahn (1992).

2.3 The data and definitions

To consider the CKC literature, it is important to take into account how the carbon dioxide emissions data is produced in the datasets that are used in the literature.[7] Essentially, there are no actual measurements of carbon dioxide

[6] The long-run and short-run models are actually components of the same model. The error term of the long-run model corresponds to the error-correction term of the VECM. (Engle et al., 1989.)

[7] Most cited articles use data from the World Bank's World Development Indicators (WDI) dataset, which in turn uses carbon dioxide emission data calculated by the U.S. Department of Energy's Carbon Dioxide Information Analysis Center (CDIAC) (Boden et al., 2009). In the CDIAC dataset carbon dioxide emissions are calculated from con-

emissions. They are simply calculated from energy statistics (see 2.A).[8]

To begin we define an important concept: *Carbon intensity* A_t is the average emissions rate of total energy consumption.[9] Carbon intensity measures how much carbon dioxide emissions one unit of energy produces given the mix of different fuel types. That is, carbon intensity depends on the proportions in which different fuel types are used. 2.A gives a formal definition.

Given this knowledge, we can derive identity

$$C_t \equiv E_t A_t + X_t, \tag{2.2}$$

where C_t is carbon dioxide emissions, E_t is total energy consumption, and X_t is emissions from gas flaring and cement manufacturing, all measured per capita. 2.A shows how this identity is derived.

It is important to note, that this is simply an accounting identity derived from the definitions of the dataset, so it must be satisfied in the sample. That is, identity (2.2) holds by definition in the dataset.

We note that gas flaring and cement manufacturing amount only to a percent of total carbon emissions in the data. To derive an algebraically more convenient form, we assume, from here on, that they can be omitted, i.e. $X_t = 0$. Therefore taking a natural logarithm of equation (2.2) gives

$$c_t = e_t + a_t, \tag{2.3}$$

where the variables are the corresponding logarithms of the capital letter variables.

Next we present the three problems in the recent CKC literature.

sumed quantities of different fuel commodities and cement manufacturing. The CDIAC dataset uses energy statistics by the United Nations Statistics Division (UNSD) among others. UNSD data is used for the time period analyzed in this paper. The WDI dataset uses energy statistics compiled by the International Energy Agency (IEA). Richmond and Kaufmann (2006) use data compiled by the IEA on energy use, and calculates the carbon dioxide emissions by multiplying fuel use by the appropriate carbon content factor.

[8]It is important to note, that the data contains emissions only from domestically used energy. It does not include emissions embodied in imported goods nor does it exclude emissions from exported goods. A country's carbon footprint, which would account for the carbon content of net trade, could have a very different trend compared to domestic emissions from energy use. From this point of view, a decrease in domestic emissions of developed countries could be simply due to outsourcing heavily emitting production to developing countries. (See e.g. Ross et al. (1987); Copeland and Taylor (2004); Aichele and Felbermayr (2012).)

[9]Note that here carbon intensity refers to the ratio of carbon emissions to energy consumption. This is not to be confused with carbon intensity of output which is the ratio of carbon emissions to output.

2.4 The problems in the recent CKC literature

2.4.1 Transformations in a VAR model

The first problem relates to the estimation of the VECM and arises because of the simple functional relationship between the regressors y_t and y_t^2.[10] A system of equations entails a restriction to the model's joint distribution (Haavelmo, 1943), but this has not been fully taken into account. More specifically, the assumption of normally distributed i.i.d error terms (Johansen, 1988) is in contradiction with the VAR model's equations. A priori, the error terms can not have the assumed distribution given that the model equations hold.

The VAR model consists of equations

$$x_t = a_0 + \sum_{i=1}^{p} A_i x_{t-i} + \varepsilon_t, \qquad t = 0, \dots, T, \tag{2.4}$$

where $x_t = (c_t, e_t, y_t, y_t^2)$ is a vector of logarithms of regressors, $\varepsilon_t \in \mathbb{R}^4$ is a vector of error terms, $a_0 \in \mathbb{R}^4$ is a vector of constants, $A_i \in \mathbb{R}^{4\times4}$ is a matrix of parameters for lag i, and p is the number of lags.

The problem can be shown within a simpler setting, so without a loss to generality, we restrict to a model with only two regressors, y_t and y_t^2, and assume that $p = 1$, $a_0 = 0$, and $A_i = [a_{jk}] \in \mathbb{R}^{2\times2}$. Hence our model consists of equations

$$y_t = a_{11} y_{t-1} + a_{12} y_{t-1}^2 + \varepsilon_{1,t} \quad \text{and} \tag{2.5}$$

$$y_t^2 = a_{21} y_{t-1} + a_{22} y_{t-1}^2 + \varepsilon_{2,t}, \tag{2.6}$$

for all $t = 0, \dots, T$.

First, we show that not all error terms of the model can be normally distributed given that model equations (2.5) and (2.6) hold. Plugging y_t of equation (2.5) into equation (2.6) and rearranging gives

$$\varepsilon_{2,t} = (a_{11} y_{t-1} + a_{12} y_{t-1}^2 + \varepsilon_{1,t})^2 - a_{21} y_{t-1} - a_{22} y_{t-1}^2. \tag{2.7}$$

We notice that the lagged variables, y_{t-1}, are given at time t. Therefore equation (2.7) constrains a polynomial relationship between error terms $\varepsilon_{1,t}$ and

[10]The same source of problems, the dependency between regressors, is noted by Müller-Fürstenberger and Wagner (2007) and Wagner (2008) who conclude that a square of an unit root is not necessarily an unit root. This problem does not apply here as Johansen's (1988) estimation method does not require that all variables have an unit root (See e.g. Watson, 1994).

$\varepsilon_{2,t}$, hence they can not both be normally distributed. In other words, when the lagged variables are given and if $\varepsilon_{1,t}$ is drawn from a normal distribution, then equation (2.7) determines a non-normal distribution for $\varepsilon_{2,t}$.

Second, we show that the error terms are not independent over time. Plugging lagged equations (2.5) and (2.6) into (2.7) we get

$$\begin{aligned}\varepsilon_{2,t} =&(a_{11}(a_{11}y_{t-2} + a_{12}y_{t-2}^2 + \varepsilon_{1,t-1}) + a_{12}(a_{21}y_{t-2} + a_{22}y_{t-2}^2 + \varepsilon_{2,t-1}) + \varepsilon_{1,t})^2 \\ &- a_{21}(a_{11}y_{t-2} + a_{12}y_{t-2}^2 + \varepsilon_{1,t-1}) - a_{22}(a_{21}y_{t-2} + a_{22}y_{t-2}^2 + \varepsilon_{2,t-1})\end{aligned}$$

where again the right-hand-side regressors are given. Hence, the value of error term $\varepsilon_{2,t}$ depends on $\varepsilon_{1,t-1}$, and therefore they can not be chosen independently, which violates the model assumptions.

This means that the assumption of normally distributed i.i.d error terms, which is required by Johansen's (1988) estimation method, can not be satisfied and estimates are not reliable. We also see a much more general property: including a transformation of a regressors into a VAR model as a regressor creates an implicit constraint between error terms.

Even if the problem of estimation would be solved, there would remain other problems of misspecification. To focus on these, we temporarily set aside the aforementioned problem in the subsequent sections.

2.4.2 The interpretation of the parameters

We now turn to the second problem in the recent literature. Wrong interpretation of the parameters and resulting wrong conclusions arise from the definition of carbon emissions in the dataset (Section 2.3). It is worth emphasizing, that this problem is not about the estimation of the model, but is related to the specification of the model.

In the context of CKC, the parameter of interest is the causal effect of output on carbon emissions. That is, we want to know how output affects emissions. In model equation (2.1), the partial derivative

$$\frac{\partial c_t}{\partial y_t} = \beta_2 + 2\beta_3 y_t \tag{2.8}$$

is interpreted as the partial causal effect of y_t on c_t, i.e. it quantifies the relationship between emissions and output.[11] This would be the Marshallian ceteris paribus change that assumes other variables constant (Heckman, 2005; Heckman and Vytlacil, 2007). This term determines the shape of the carbon Kuznets curve.

[11] To be exact, we are interested in the expected conditional partial derivative, but to ease notation, we do the analysis as if it was a deterministic model.

This, however, does not take into account the conceptual dependence between energy and carbon emissions that is captured by identity (2.3). Recognizing this dependence reveals that the causal effect (2.8) has a much more narrow interpretation than intended. We give three alternative ways to reach this conclusion.

First, note that calculating the partial derivative (2.8) requires that total energy use e_t is held constant. Now, from identity (2.3) we notice that, in this case, the level of carbon dioxide emissions c_t can only change through changes in carbon intensity a_t. The causal effect (2.8) can be interpreted only as the causal effect of output y_t on emissions c_t through carbon intensity a_t. This ignores the effect of y_t on c_t through energy use e_t. As a result, the model is actually a regression analysis of carbon intensity, instead of carbon emissions.

Second, the problem can be also seen by comparing the causal effect (2.8) with the derivative of identity (2.3). Partially differentiating identity (2.3) with respect to y_t gives

$$\frac{\partial c_t}{\partial y_t} = \frac{\partial a_t}{\partial y_t} + \frac{\partial e_t}{\partial y_t}.$$

If emissions level e_t is held constant, as is required to calculate the causal effect (2.8), the second term, $\partial e_t/\partial y_t$, is omitted. This means that the causal effect (2.8), which the EEO literature investigates, is only the first term, $\partial a_t/\partial y_t$. As before, this shows that an important channel of influence is blocked.

Third, a more explicit regression equation can be formulated. Equation (2.3) can be plugged into equation (2.1) to eliminate c_t. Rearranging gives equation

$$a_t = \beta_0 + (\beta_1 - 1)e_t + \beta_2 y_t + \beta_3 y_t^2 + u_t. \tag{2.9}$$

Here we see that model equation (2.1) is equivalently a regression on carbon intensity a_t, and the functional form between a_t and output y_t is exactly the same as between carbon emissions c_t and y_t. That is, the causal effect of y_t on emissions c_t equals exactly the causal effect of y_t on carbon intensity a_t. Formally,

$$\frac{\partial c_t}{\partial y_t} = \frac{\partial a_t}{\partial y_t} = \beta_2 + 2\beta_3 y_t,$$

which brings us to the same conclusion: "parameter of interest" equals the effect of output onto carbon intensity, i.e. the cleanness of energy, not the amount of emissions, as intended.

In other words, the new and the old CKC literatures are looking at different parameters. What is missing here, is the link between energy use and

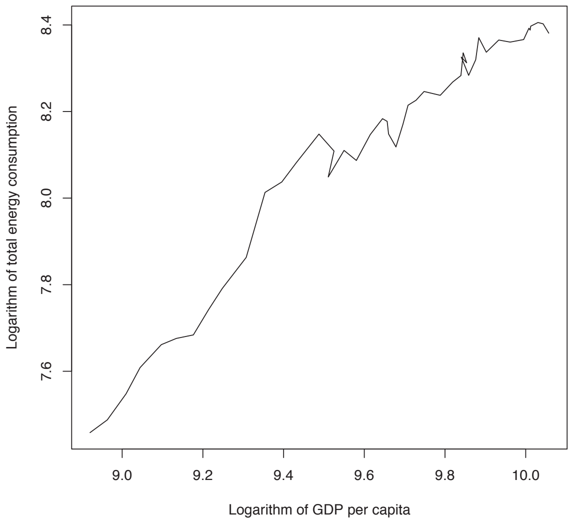

Figure 2.1: Relationship between the logarithm of total energy consumption per capita and the logarithm of per capita GDP in France, 1960-2006.

output. That is, richer economies use more energy. In the next section we consider how adding this missing link changes the picture.

2.4.3 Bias

The third problem is a misspecification bias rising from the dependence between energy use e_t and output y_t. We begin by looking at the data. First, energy use over different output levels is depicted in Figure 2.1. The apparent relationship between the variables suggests that more output requires more energy. This basic notion, the details of which are the subject of the immense energy-output-nexus literature, is actually the motivation behind the emissions-energy-output-nexus, and is essential to the CKC hypothesis. Nonetheless, it is unintentionally neglected due to the model formulation, as seen in the previous section.

Second, identity (2.2) implies that variations in both carbon intensity and energy use are essential for the CKC. This can be seen from Figure 2.2. Here the development of carbon emissions in France (curve A) has been

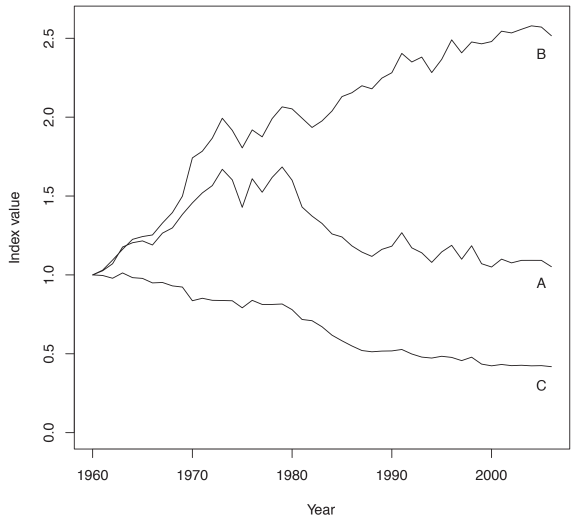

Figure 2.2: Curve A is the index of carbon emissions, B is a index energy consumption, and C is the carbon intensity. By definition $A = BC$.

decomposed in to a growing energy consumption (B) and a declining carbon intensity (C).[12] This shows that, without the growth of energy consumption, emissions in 2006 would be 60% less compared to 1960. On the other hand, without the shift to cleaner fuels, emissions would be 150% higher in 2006.[13] Clearly both factors, energy consumption and carbon intensity, need to be accounted for.

Hence, we need to consider a model where also energy use e_t depends on output y_t. To capture this dependency, we assume for simplicity that there is a linear relationship

$$e_t = \beta_e y_t + v_t, \tag{2.10}$$

where β_e a strictly positive parameter and v_t is the error term, which captures

[12]To be more specific, $A = \frac{c_t}{c_{1960}}$, $B = \frac{e_t}{e_{1960}}$, and $C = \frac{c_t}{c_{1960}} / \frac{e_t}{e_{1960}}$. That is, $A = BC$.

[13]Carbon intensity a_t has decreased in France because of a decline in the share of heavily polluting fuels like coal. They have been replaced or outgrown by the use of oil, natural gas and nuclear energy (Kaufmann, 1992). Especially in the case of France, is seems that nuclear energy has had a significant impact (see Iwata et al., 2010).

other factors affecting the relationship.[14]

The existence of another cointegration equation can not be ruled out by the cointegration test results. The tests, that are derived from Johansen (1988), reject the null hypothesis of zero cointegration equations against the alternative of one *or more* cointegration equations. In other words, the hypothesis, that there is a second cointegration equation like (2.10), is not rejected at any stage.[15] (See e.g. Lütkepohl, 2005, p. 329; Watson, 1994; Hamilton, 1994; Johansen, 1995.)

Now, instead of just model equation (2.1), we need to look at system

$$c_t = \beta_0 + \beta_1 e_t + \beta_2 y_t + \beta_3 y_t^2 + u_t \tag{2.11a}$$
$$e_t = \beta_e y_t + v_t, \tag{2.11b}$$

where the EEO model is supplemented with the link between energy and output.

This link creates a bias in the parameter of interest. To assess this, we need to calculate a causal effect for system (2.11), and compare it with the causal effect in EEO model. The magnitude of the causal effect of output y_t on carbon emissions c_t in system (2.11) can be calculated by applying the implicit function rule, as done in 2.B. The (total) causal effect is given by

$$\frac{\mathrm{d}c_t}{\mathrm{d}y_t} = (\beta_2 + 2\beta_3 y_t) + \beta_e \beta_1. \tag{2.12}$$

Now causal effect (2.12) can be compared with the biased interpretation in expression (2.8). We see clearly, that the EEO model specification is biased by the term $-\beta_e\beta_1$, which is negative in the plausible case: First, β_e is positive when a larger output implies more energy use. Second, the parameter β_1 should be also positive, as energy use has positive effect on carbon emissions. The bias equals to the causal effect of output on emissions through energy use, which was shown to be missing in EEO model.

The negative bias has two implications for the shape of the CKC.

First, the turning point of CKC is at a higher level of output when bias exists. We show this in 2.B. This means the turning point will occur later than estimated.

A second implication for the shape is that the unbiased CKC grows quicker and declines more slowly, than the biased one. This is simply because, for all levels of output y_t, the biased causal effect is smaller than the

[14]This simplified specification ignores other important factors, which might change the magnitude of the bias, but they should not affect its existence or direction, which are in focus here.

[15]Furthermore, a false negative occurs here often as the sample size is small and deterministic trends are possible (Demetrescu et al., 2009).

unbiased one. Before the turning point of the biased CKC, carbon emissions are actually growing faster. After the biased CKC has turned, emissions are actually still growing for awhile. And after the true turning point, emissions are declining, but slower then the biased CKC implies.

The unbiased shape draws a more negative picture for the CKC hypothesis. If a CKC were to be found, economic growth would benefit climate policy goals later and to a lesser extent than estimated.

2.5 Conclusions

We have shown, first, that using a transformation of a regressor as a regressor in a VAR model creates a contradiction with the statistical assumptions. In such case, the standard estimators are not reliable. Hence the reported estimates are not sound.

Second, neglecting the dataset definitions alters the interpretation of the model parameters significantly. As a result, the question answered in the recent CKC literature is not the same as in earlier CKC literature. Only the relationship between carbon intensity and output is estimated, which neglects the possible dependence through energy use. The estimated relationship is not the CKC as a whole and therefore can not be compared with earlier studies.

Third, when energy use depends on output, the model is biased. As a result, the criticized model gives an overly optimistic view of the possibility to achieve climate policy goals simply through economic growth. If there is a turning point, it occurs later than expected. Before turning, output increases emissions faster, and afterwards, emissions drop slower than anticipated.

To answer any relevant questions about the CKC hypothesis, one can not simply combine the energy-output and carbon-output nexuses into one equation, as done in the recent literature. It seems as yet another attempt to find a EKC has failed.

Appendixes

2.A Definition of carbon emissions

In this appendix we derive an identity from the definitions of the dataset. This identity is the source the second and third problem presented in Section 2.4.

First, the dataset in use (World bank's World Development Indicators, WDI) defines carbon dioxide emissions as a linear function of fossil fuel combustion and cement manufacturing. The amount of carbon dioxide emissions caused by combustion is determined by the chemical composition of the fuel. The emitted amount of carbon dioxide is calculated by multiplying the amount of fuel usage by a constant factor prescribed by the chemical properties of the fuel. Thus, the total carbon dioxide emissions C_t is a linear combination of the usage of oil E_t^{oil}, solid fuels E_t^{solid}, natural gas E_t^{gas}, and gas flaring E_t^{flare}, in addition to emissions from cement manufacturing S_t, all measured in per capita term. More formally,

$$C_t \equiv \alpha_{oil} E_t^{oil} + \alpha_{solid} E_t^{solid} + \alpha_{gas} E_t^{gas} + \alpha_{flare} E_t^{flare} + S_t, \tag{2.13}$$

where α_{oil}, α_{solid}, α_{gas}, $\alpha_{flare} > 0$ are the related ratios of emissions to fuel quantity. (See Boden et al., 2009)

Second, total energy use E_t can be defined as the sum of oil E_t^{oil}, solid fuels E_t^{solid}, natural gas E_t^{gas}, and other energy sources E_t^{other}, such as nuclear energy and renewable fuels, which do not cause emissions in the aforementioned sense.[16] Gas flaring does not result in energy production. Therefore

$$E_t \equiv E_t^{oil} + E_t^{solid} + E_t^{gas} + E_t^{other}.$$

To clarify the notation we define two sets of variable: the set of energy commodities affecting carbon dioxide emissions, $\mathfrak{C} = \{oil, solid, gas, flare\}$, and the set of energy commodities that amount to total energy use, $\mathfrak{E} = \{oil, solid, gas, other\}$.

Next let us define the proportions of fuel commodities in terms of total energy use,

$$q_t^i \equiv \frac{E_t^i}{E_t},$$

where $q_t^i \geq 0$ for all $i \in \mathfrak{E}$ and $\sum_{i \in \mathfrak{E}} q_t^i = 1$ for any t. By rearranging and plugging this into identity (2.13) to eliminate E_t^i for each i, we get

$$C_t \equiv E_t \sum_{i \in \mathfrak{C} \cap \mathfrak{E}} q_t^i \alpha_i + \alpha_{flare} E_t^{flare} + S_t.$$

By interpreting the sum term as the average emissions rate of energy consumption, we can identify it as *carbon intensity* and denote it by A_t, so that

$$C_t \equiv E_t A_t + \alpha_{flare} E_t^{flare} + S_t. \tag{2.14}$$

[16] Variable E_t^{other} does not enter equation (2.13) because possible emissions from such energy are not included in the definition of emissions in the database.

This is simply an accounting identity derived from the definitions of the dataset, so it must be satisfied by the observed values.

To derive an algebraically more convenient form, we note that gas flaring and cement manufacturing amount only to a percent of total carbon emissions in the data, therefore, for simplicity, we can omit them by setting them equal to zero. Therefore taking a natural logarithm of equation (2.14) gives

$$c_t = e_t + a_t,$$

where the variables are the corresponding logarithms of the capital letter variables.

2.B Mathematical derivations for Section 2.4.3

The magnitude of the causal effect of output y_t on carbon emissions c_t in system (2.11) can be assessed by applying the implicit function theorem to get the total derivative

$$\frac{\mathrm{d}c_t}{\mathrm{d}y_t} = -\frac{\begin{vmatrix} -(\beta_2 + 2\beta_3 y_t) & -\beta_1 \\ -\beta_e & 1 \end{vmatrix}}{\begin{vmatrix} 1 & -\beta_1 \\ 0 & 1 \end{vmatrix}}.$$

By calculating the determinants, we get a simplified expression for the (total) causal effect,

$$\frac{\mathrm{d}c_t}{\mathrm{d}y_t} = (\beta_2 + 2\beta_3 y_t) + \beta_e \beta_1. \tag{2.15}$$

Now causal effect (2.15) can be compared with the biased interpretation in expression (2.8). We see that the EEO model specification is biased by the term $-\beta_e\beta_1$, which is negative in the plausible case.

Next we show that the turning point of CKC is at a higher level of output when bias exists. In the unbiased case, the turning point y_t^* is such that the causal effect (2.12) equals zero. This is equivalent to

$$y_t^* = \frac{-\beta_2 - \beta_e\beta_1}{2\beta_3}.$$

Similarly, in the biased case, the turning point y_t^{**} satisfies

$$y_t^{**} = \frac{-\beta_2}{2\beta_3}.$$

Now, when $\beta_e\beta_1 > 0$, adding β_2 to both sides gives $\beta_2 + \beta_e\beta_1 > \beta_2$. Because β_2 is positive and β_3 is negative according to the CKC-hypothesis, we see that

$$\frac{-\beta_2 - \beta_e\beta_1}{2\beta_3} > \frac{-\beta_2}{2\beta_3}.$$

By noting the turning points, we get

$$y_t^* = \frac{-\beta_2 - \beta_e\beta_1}{2\beta_3} > \frac{-\beta_2}{2\beta_3} = y_t^{**}.$$

That is, the true turning point occurs at a higher level of output.

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Chapter 3

Social ties and concern for global warming[1]

3.1 Introduction

Why are some people concerned about global warming while others are not? As the scientific community seems to be more concerned than the public (Anderegg et al., 2010; Cook et al., 2013), researchers have tried to explain this gap between expert and public opinions. A rapidly growing body of scholarly literature has been devoted to the understanding of public perceptions of climate change and the communication of climate science (Moser, 2010; Wolf and Moser, 2011). Early studies employed a perspective known as the deficit model, which, in its simplest form, assumes that a lack of scientific knowledge could be overcome by providing more and better information (Irwin and Wynne, 1996; Sturgis and Allum, 2004). Consequently, researchers have aimed to improve experts' ability to effectively communicate climate science (Bowman et al., 2009; Pidgeon and Fischhoff, 2011). To this end, progress has been made in understanding the layman's ability to process scientific information and the public's reliance on different types of heuristic techniques to assess risks related to climate change (Weber, 2006; Marx et al., 2007; Sunstein, 2006; Wolf and Moser, 2011).

More recent studies have highlighted the role of social factors that affect public opinions and argued that the lack of concern is more than a mere consequence of the shortcomings of information processing of individuals (Kahan, 2010). Kahan et al. (2012) found that those best able to understand the science appeared more polarized and did not necessarily have opinions more similar to the experts' opinions, as would have been expected if the

[1] This chapter has been accepted for publication in *Climatic Change*.

only problem were a lack of information. To explain this, opinions about climate change have been linked to group level factors such as political views (McCright and Dunlap, 2011; Brulle et al., 2012; Kahan et al., 2012) and social norms (Schultz et al., 2007; Allcott, 2011; Markowitz and Shariff, 2012). Kahan et al. (2012) argue that individuals are motivated to adjust their interpretations of scientific issues to conform with their social surroundings, while others argue that people rely on social cues to create political and ideological filters which help to process information (Wood and Vedlitz, 2007; McCright and Dunlap, 2011; Hoffman, 2011).

Earlier research on the social aspects of science communication focused on group properties rather than the underlying network structure that connects individuals. The emergence of large online social networks has provided a new source of data to study social interaction on a large scale (Lewis et al., 2008; Wilson et al., 2012). Numerous studies have shown that online networks affect how people interact in real-life and how information spreads (Onnela et al., 2007; Aral et al., 2009; Bond et al., 2012; Senbel et al., 2014).

The social amplification of risk framework (SARF) proposes that social networks could operate as intermediate "stations" that either amplify or attenuate perceptions of risk (Kasperson et al., 1988). Contractor and DeChurch (2014) introduce a framework that explicitly aims to combine research on the psychological mechanisms of social influence with social network analysis. They emphasize that successful science communication depends on both the way that expert information is processed by individuals and how the social network is structured. Recent evidence linking concerns with social groups (McCright and Dunlap, 2011; Kahan et al., 2012) suggests that concern about climate change could also be related to the structure of the social network. If the concerned and unconcerned have different positions within the network, the network can act as a filter for concerns by percolating information and opinions through social ties (see e.g. Bikhchandani et al., 1992; Watts, 2002). When individuals are surrounded by friends who hold similar opinions, they have better access to arguments that support their existing opinion and might experience social pressure to hold it. Furthermore, a well-connected position in the centre of the network provides better access to information that flows through the network, including opposing opinions. Attitudes are less likely to converge when fewer connections exist between people with opposite opinions.

On the other hand, it would not be unreasonable to hypothesize that the structure of the social network does not reflect a concern for global warming since the issue is irrelevant for most forms of social interaction and is outweighed by numerous other reasons to form ties. Moreover, even if the social network is correlated with differences in concern for climate change, this could merely reflect the fact that the connections between individuals are determined by shared values and ideologies, which are known to correlate with concern for climate change.

In this paper we show that concern about global warming is significant enough to be observable in the structure of the extended social network. Furthermore, we argue that concern for climate change is related to the structure of the social network in a way that helps to explain why substantial differences of opinion remain across segments of the lay public, and ultimately why public concerns differ from that of the experts. To show this, we programmed a Facebook application to collect survey data on opinions and network data on friendships.

We found that respondents tended to have friends with similar levels of concern, which could result in a biased impression of the general level of concern. The unconcerned respondents had fewer friends, although there was no difference in the level clustering of friendship circles compared to the concerned. Respondents who disagreed on the seriousness of global warming had less than halve the likelihood of being friends compared to two like-minded respondents. We also found that the association with climate concerns was substantially stronger than with concerns about other types of environmental problems. The association remained strong even after controlling for political and social background factors.

The results help to explain why opinions persist despite the scientific consensus, and why it is difficult to reach and convince the unconcerned. The capacity of the social network to transfer social influences is constrained in a manner that makes opinions more inert. The results suggests that the communication of climate science could be improved by communication strategies that aim to overcome these network effects. For example, people might find it easier to absorb the scientific evidence if the message is formulated in a way that does not call into question the values that bind individuals to their social network.

3.2 Methodology

Online social networks, such as Facebook, have become an inseparable part of everyday social life for many. Facebook, with nearly a billion daily users, allows people to build friendship networks, that typically reflect the users' real-life social neighbourhoods (Hampton et al., 2011; Ellison et al., 2007). Facebook friends can be anything from family members to forgotten acquaintances, so that the network approximates the individual's social horizon. Such extended social networks, which consist of both strong and weak links, have long been an interest of theoretical work (Granovetter, 1973), and with recent online datasets, researchers have been able to confirm that they really can affect how information spreads and how people interact in real life (Bond et al., 2012; Onnela et al., 2007), and that individual characteristics affect how well the network does this (Centola, 2011; van der Leij, 2011; Golub and Jackson, 2012; Aral et al., 2009).

To study how a concern for global warming relates to social ties, we programmed a Facebook application that operates as an online survey and collected a complete list of each participant's friends and other basic information. An invitation to participate in the survey was sent to students and staff at the University of Helsinki, the university's Facebook page, and students at Aalto University, and participants were allowed to invite their friends. Also, the Finnish public broadcasting company YLE published a story about the survey with a link attached. All links to the survey's website were tagged to identify the participant's origin in order to check whether there results are consistent across participants recruited from different sources. The data were collected between May 2012 and May 2013.

Potential participants were directed to a web page which asked the participant to join our survey and asked for permission to access personal information on Facebook. Authentication and permission sharing was done with dialogues provided by Facebook's application programming interface. When given permission, our web application collected a complete list of the user's Facebook friends along with other basic information (such as gender and home town, if available), after which the application directed the user to the survey questionnaire. The questionnaire was provided in Finnish, Swedish, English, and German. The network and survey data were stored on our secure database server. After completing the questionnaire, the user was given a chance to share our link on the user's Facebook page and to send private requests to selected friends. Information on private requests was stored to check for possible sample selection caused by the snowball sampling method. Later, consecutive raffles for an iPad and a 500 Euro Amazon gift card were added as incentives. Participants got extra raffle tickets for each friend that joined the survey. Finally, participants received a personal value profile based on Schwartz's Portrait Values Questionnaire (Schwartz et al., 2001).

The analysis was limited to Finnish nationals who gave their answers in Finnish, Swedish, or English (n = 5205, 78.0% of the full sample). In the selected sample, 97.1% of respondents answered the question about the concern for global warming. We observed 23534 friendships between the respondents. The respondents had on average 9.3 friends who also answered the questionnaire (standard deviation 12.1). The mean age of the respondents was 33.0 years (standard deviation 10.9), and 63.9% of the respondents were women. As for employment status, 44.2% reported being employed full-time (30 hours a week or more), 13.0% were employed part-time, and 22.9% were students.[2]

Using the tags in our invitations' links, respondents were identified as University of Helsinki students (18.6% of the sample) and staff members (7.7%), university's Facebook fans (0.5%), YLE news readers (7.1%), or Aalto University students (4.1%). It is possible that some of the invited respondents may have found the survey website by other means. Most of the remaining respondents (62.0%) accessed the website through a shared link or a personal request from another user.

Social network services are used more often by younger people and slightly more often by women, according to a representative sample of the Finnish population (OSF, 2014). This was also reflected in our sample where younger age groups and women were overrepresented compared to the Finnish population (WVS, 2009). Consequently, also part-time employed and students were overrepresented while pensioners were underrepresented. The sample had an overrepresentation of respondents who placed themselves left on the political spectrum.[3] Rainie and Smith (2012) found similar biases among American adults. We used these variables as controls in the regression analyses to avoid sample selection bias.

We measured environmental concerns by asking how serious the respondent considers various environmental problems to be. The questionnaire listed four environmental problems: "Poor air quality where I live", "Global warming or the greenhouse effect", "Loss of plant or animal species or biodiversity globally", and "Pollution of rivers, lakes and oceans globally". The respondent had the option of answering "very serious", "somewhat serious", "not very serious" or "not serious at all".[4] The four-point scale was coded from 0 to 3, where 0 indicates "not serious at all" and 3 indicates "very serious".

[2]The employment question was adapted from the World Value Survey (WVS, 2009) allowing the respondent to choose one from a list of options.

[3]The question asking the respondent to choose a position on a left–right scale was adapted from the World Value Survey (WVS, 2009), to enable comparison.

[4]The question was adapted from the World Value Survey (WVS, 2009), to enable comparison with a representative sample of the Finnish population.

3.3 Results

3.3.1 Distribution of friends

First, we investigated the distribution of concern for global warming in our sample, and how friends' concerns are distributed given the respondent's own level of concern (Table 3.1). We found that 53% of respondents think global warming is a very serious environmental problem (compared to 51% in a representative sample of the Finnish population (WVS, 2009)). But among those very concerned, 67% of friends were also very concerned, while among those not at all concerned, only 47% of friends were very concerned.

The results show that the distribution of friends' opinions tilt towards the respondent's own opinion, which motivates us to investigate further the association between social ties and concern for global warming. In principle, the association could be explained by a preference for like-minded friends (homophily), friends influencing each other (diffusion), or other factors influencing both friendship formation and concern for global warming (e.g. Kossinets and Watts, 2009; Wimmer and Lewis, 2010; Shalizi and Thomas, 2011). Separating these effects would require dynamic network data and is beyond the scope of this study.

However, our focus is on network capacity, i.e. the network's ability to transfer knowledge, opinions, or concerns via friendships. For this purpose, static network data is sufficient. Relative amounts of connections between the concerned and the unconcerned reported in Table 3.1 approximate the network's capacity to transmit information between people that have different opinions.

Having more like-minded friends increases the chance of receiving echoed signals. In part, this could emphasize the false consensus effect, i.e. the tendency to overestimate the commonness of one's own opinion, which Leviston et al. (2013) found to be particularly strong in the case of climate change. Furthermore, when an individual is surrounded by like-minded friends, changing opinion could result in disagreement with friends, which could put existing ties at risk (Burt, 2000; Rainie and Smith, 2012) and complicate making new ties (Mcpherson et al., 2001).[5] Such mechanisms of social pressure could sustain relatively self-contained pockets of unconcerned people, and considering the communication of climate science, these pockets

[5] We found a small but significant negative correlation between the respondent's distance from the friends' average and the number of friends ($\rho = -0.053$, $t = -3.72$, degrees of freedom 4825, p-value < 0.001). This means that people who deviate from the average opinion of their friends tend to have fewer friends. The friends' average was estimated by the average among friends who participated in the survey.

could become increasingly difficult to reach if opinions polarize further.

It is important to note that even the unconcerned have a majority of concerned friends (Table 3.1). But given the relative scarcity of unconcerned people in the population, an unconcerned individual would need to exert some extra effort to build a network with a majority of like-minded friends. Social network literature on similarity distinguishes between *baseline homophily*, i.e. the similarity of friends that arises mechanically due to the availability of similar individuals, and *inbreeding homophily*, which measures similarity beyond that which is implied by the population distribution (Mcpherson et al., 2001; Currarini et al., 2009, 2010). So even in the absence of social mechanisms that lead to friends being similar, we would expect to find mostly concerned people among the friends of the concerned (baseline homophily) as well as the unconcerned (baseline heterophily). However, our observation means that respondents tend to have more friends who are similar than would be expected if friendships were made at random (inbreeding homophily).

	Distribution of concern			
	not serious at all	not very serious	somewhat serious	very serious
Our sample	2%	10%	36%	53%
Representative sample	1%	9%	39%	51%
	Distribution of friends' concern			
Own answer	not serious at all	not very serious	somewhat serious	very serious
not serious at all	5%	11%	37%	47%
not very serious	2%	12%	36%	50%
somewhat serious	1%	8%	34%	57%
very serious	1%	5%	27%	67%

Table 3.1: Distribution of friends' opinions about the seriousness of global warming. We observed 5205 answers and 23534 friendships between those who answered. The representative sample is based on World Value Survey 2005 of 1006 Finns (WVS, 2009).

3.3.2 Centrality and clustering

Second, we investigated how the concerned and unconcerned are positioned within the network, to better understand differences in their ability to obtain or distribute information through the network. We looked at sociality, measured by the number of friends, and density of friendship circles, measured by the local clustering coefficient (Watts and Strogatz (1998); Appendix 3.A describes the measure for sampled networks). Table 3.2 gives linear regression results for the number of friends and clustering coefficient.[6]

The *degree centrality* of an individual, in this case simply the number of friends, can be interpreted as a measure for the likelihood of receiving information, opinions, or attitudes flowing through the network (Borgatti, 2005). This likelihood is amplified by two common features of social networks: preferential attachment (Barabási and Albert, 1999) and assortative mixing by degree (Newman, 2003), i.e. the tendency of individuals with many connection to make new friends easily and to have friends with many connections. Due to higher connectedness, information is more likely to reach the central individuals, and they are typically better positioned to influence others (see e.g. Kitsak et al., 2010; Banerjee et al., 2013; Contractor and DeChurch, 2014).

The average number of friends was 262 (median 217, standard deviation 182). We found that concern for global warming is positively related to the number of friends when controlling for age and gender (Model 1). This relationship continued to exist even after adding controls for background variables, including relationship type, size of residential area, education level, social class, and position on left–right and liberal–conservative axes (Model 2). The model predicted that the most concerned respondents would have 52 more friends than did the least concerned.[7] To some extent, the lower friend count of the unconcerned could be explained by their minority position, as they have fewer friends to choose from, if like-minded friends are preferred (Currarini et al., 2009, 2010). In any case, the results indicate that the unconcerned occupy less central positions in the network and are at a disadvantage when it comes to sending or receiving information through the network.

The *local clustering coefficient* is the probability that two of the respondent's friends are also friends with each other. It can be described as a measure of how tightly knit the respondent's friendship circle is (see Jackson and Rogers, 2007; Jackson, 2012). The measure is between 0% and 100%, where 0% means that none of the respondent's friends are friends together and 100% means that all the friends are friends together. A low clustering coefficient increases the chance of receiving new signals from the network,

[6] We tested each model for possible non-linearity with respect to concern for global warming with nested models, but none resulted in a significantly better fit according to F-tests.

[7] This can be calculated by multiplying the regression coefficient for concern with the distance between ends of the scale: $3 \times 17.232 \approx 52$.

and it can be achieved by making friends in many unconnected groups.[8]

We found an average local clustering coefficient of 9.2% (median 7.2%, standard deviation 7.8%). Models 3 and 4 in Table 3.2 display regression results for the local clustering coefficient. For Model 4 we controlled for background variables and added the number of friends as a covariate to account for the correlation between clustering and number of friends ($\rho = -0.29$, $t = -21.76$, degrees of freedom 4991, p-value < 0.001). We found no statistically significant association between clustering and concern for global warming. This suggests that the concerned and unconcerned have similar densities in their friendship circles, and, in this respect are equally likely to receive new signals. But overall, the concerned are expected to receive more signals due to their higher friend count.

3.3.3 Probability of friendship

Finally, by using logistic regression, we investigated how concern for global warming relates to the probability of friendship (Table 3.3). That is, we try to assess the probability of finding a channel of communication between concerned and unconcerned respondents. We looked at all possible pairs of respondents and estimated a model to predict a friendship given the similarities and differences between the two. We measured the difference in concern by the pair's distance on the 4-point scale and used dummy variables for each level of separation as explanatory variables in the logistic regression models. In addition, we controlled for same sex[9], age difference, and the square of age difference (to capture the non-linearity). In Model 1, we found that a difference in the level of concern for global warming decreases the likelihood of friendship considerably. When two people deviated by just one point on the four point scale, the predicted probability of friendship was 35% smaller relative to two like-minded people.[10]

It important to emphasize that the regression coefficient should not be interpreted as a causal relationship in the sense that adjusting the level of concern would make friendships more or less likely. However, the estimated coefficient, as we are interested in the transfer capacity of the network, does help us predict where to find such capacity.

In the following we go further and try to better understand why more channels exist between the similarly concerned. We do this by adding control

[8] Note that the local clustering coefficient needs to be estimated, as we observed a tie between the respondent's two friends only if at least one of them had participated (see Appendix).

[9] We added a separate dummy variable for both being men or both being women.

[10] The marginal effects were calculated for two people of the same age and opposite sex.

	Dependent variable:			
	Number of friends		Clustering coefficient	
	(1)	(2)	(3)	(4)
Concern for global warming	17.781*** (3.374)	17.232*** (4.212)	−0.137 (0.153)	0.092 (0.185)
Number of friends				−0.014*** (0.001)
Age	−4.071*** (0.228)	−3.362*** (0.333)	0.032** (0.010)	0.039** (0.015)
Woman	−34.974*** (5.252)	−31.269*** (6.089)	−1.277*** (0.237)	−1.610*** (0.265)
Constant	376.824*** (11.381)	361.764*** (21.981)	9.244*** (0.520)	11.620*** (1.000)
Background variables	no	yes	no	yes
Observations	4996	3668	4790	3532
R^2	0.074	0.148	0.008	0.129
Adjusted R^2	0.073	0.140	0.008	0.121
Note:				*p<0.05; **p<0.01; ***p<0.001

Table 3.2: Linear regression on the number of friends and local clustering coefficient. Each column reports the ordinary least square estimates of the regression coefficients of a linear regression model. Standard errors are reported in parentheses. The clustering coefficients were measured in percentage points. Background variables include relationship type, size of residential area, education level, social class, and position on left–right and liberal–conservative axes. The full regression table is reported in the Appendix.

variables to account for possible confounding factors that might explain why similar concerns predict friendships.

One reason why two people might be more likely to be friends is that they are more social. As shown in the previous section, concern for global warming is related to sociality (measured by number of friends). To account for this variation, Model 2 included the sum of the pair's number of friends as a covariate. However, we found no clear change in the association between concern and friendships as compared to Model 1. It seems that the relationship between like-mindedness and likelihood of friendship cannot be explained by variation in sociality alone.

	Dependent variable:			
	Likelihood of friendship			
	(1)	(2)	(3)	(4)
Difference in concern for global warming:				
1 point	-0.437^{***}	-0.385^{***}	-0.318^{***}	-0.311^{***}
	(0.019)	(0.019)	(0.019)	(0.019)
2 points	-0.838^{***}	-0.791^{***}	-0.599^{***}	-0.563^{***}
	(0.037)	(0.037)	(0.038)	(0.039)
3 points	-0.957^{***}	-0.980^{***}	-0.719^{***}	-0.599^{***}
	(0.086)	(0.086)	(0.086)	(0.092)
Sociality		0.002^{***}	0.002^{***}	0.002^{***}
		(0.00003)	(0.00003)	(0.00003)
Constant	-4.737^{***}	-6.463^{***}	-6.641^{***}	-6.553^{***}
	(0.019)	(0.030)	(0.040)	(0.042)
Age and sex control variables	yes	yes	yes	yes
Background variables	no	no	yes	yes
Other environmental concerns	no	no	no	yes
Marginal effect of deviating in concern:				
1 point	−35.18%	−31.90%	−27.19%	−26.71%
2 points	−56.54%	−54.62%	−45.05%	−43.00%
3 points	−61.38%	−62.43%	−51.22%	−45.02%
Observations	6608430	6608430	6608430	6608430
Akaike Inf. Crit.	169523.6	162544.2	159243.9	159102.0
Note:				*p<0.05; **p<0.01; ***p<0.001

Table 3.3: Logistic regression on the probability of friendship. Each column reports the maximum likelihood estimates of the regression coefficients of a logit-model. Standard errors are reported in parentheses. All models include indicators for both women and both men, and difference in age and its square. Background variables include same education, same relationship type, same questionnaire language, same size of residential area, same social class, and position on left–right and liberal–conservative axes. Other environmental variables include differences in concern for air quality, water pollution, and biodiversity loss. Sociality was measured by the sum of the pair's number of friends. The full regression table is reported in the Appendix.

Another potential explanation why friendships may be related to similar concerns for global warming is that similar concern is a proxy for other similarities. Like-mindedness in political issues and values or the same education and social environment could affect the probability of friendship. In Model 3 we controlled for such background variables. We included controls for same education level, relationship type, questionnaire language, social class, and residential area size, and differences on the left–right and liberal–conservative axes. If the relationship between concern and the probability of friendship were to dissipate after controlling for these variables, it would seem plausible that our initial observation was just an artefact of other mechanisms driving both concerns and friendship formation. However, compared to Model 2, the association between difference in concern and likelihood of friendship was only slightly weaker. This implies that, indeed, similarity of concern does reflect other similarities that are associated with the probability of friendship. But still, the role of concern for global warming remained strong, as the marginal effect on the probability of friendship of deviating by one point in concern was -27.19%. This suggests that the relationship between friendship and concern for global warming is not merely a reflection of respondents' social or political backgrounds but also has an independent role in social interactions. However, it is possible that the relationship is a result of social affinities we have been unable to measure.

But one might still argue that concern for global warming reflects a more general awareness of environmental problems and that this is what drives the relationship. To assess this idea, in Model 4 we added controls for the other environmental concerns that were measured in the questionnaire, namely air quality, loss of biodiversity, and water pollution. Compared to Model 3, the association remained strong, although we observed a small, non-significant decrease in the coefficients. This shows that, independent of similarities in other environmental questions, a similar concern for global warming predicts a higher probability of friendship. Furthermore, compared to other environmental problems, global warming had a substantially stronger association with friendships.[11]

Moreover, it seems the association between similar concern and friendship cannot be explained by the large proportion of weak links in Facebook networks, as we found no association between strength of link and like-mindedness. When measuring the strength of a link by the share of common friends (Granovetter, 1973), we observed only a non-significant correlation of 0.0067 between the difference in concern and link strength. ($t = 1.3734$, degrees of freedom 41662, p-value 0.1696). This means we would expect to find the same association in social networks that contain only strong ties.

[11]Full regression tables are included in the Appendix.

Variation in the probability of friendship can significantly affect how information is diffused in the network. Information, attitudes, and opinions about climate change can be transmitted from friend to friend, but the observed network seems to be structured so as to restrict the flow from the concerned to the unconcerned. To emphasize this point, Model 1 in Table 3.3 indicated that a friendship was nearly three times more likely to exist between two like-minded people compared to people at opposite ends of our scale. The effect is supported by previous research showing that the diffusion of information is weaker between dissimilar people (Centola, 2011).

3.4 Conclusions

The results show that the structure of the social network is related to concern for global warming, and we have argued that this is relevant for the functioning of the network. Friendship circles, which consist of like-minded friends, can act as echo chambers that reinforce existing opinions. The unconcerned occupy equally integrated groups, but they have fewer friends, which puts them in a disadvantaged position to send or receive signals through the network. Friendships are much less likely to occur between people who disagree on the seriousness of global warming, even if they have similar political and social backgrounds and agree on other environmental issues.

Social networks offer novel perspectives to understand how the public forms opinions about climate change.

First, on the basis on our empirical results we are able apply network theory to help understand how the social network might support or hinder climate change communication. Social network analysis has long been used to study how information, opinions, and influence spread between individuals and recently it has been applied also to understand science communication (e.g. Contractor and DeChurch, 2014). In many respects the message of climate scientists is not unlike that of other information spreading through social networks and we can expect it to be subject to the same dynamics that govern other information. This allows us to capitalize on previous research on social networks to shed new light on the communication of climate change.

Second, the network perspective can be viewed in relation to the deficit model of science communication (see Irwin and Wynne, 1996; Kahan, 2010), which emphasizes that the gap between public and expert opinions on climate change could be bridged by providing more and better information. Our observation that the level of concern varies between different parts of the network could be a result of heterogeneous exposure to information sources and poor diffusion of that information. This is in line with the contemporary view that social factors play an important role in the formation of risk perceptions. It is possible that climate science has been able to reach some social groups better than others, to the effect that the science is understood better in some parts of the network. Furthermore, ideological biases in news coverage of climate change maybe reflected in the social structure (Carvalho, 2007; Dunlap and McCright, 2008).

Moreover, our empirical analysis suggests that social ties are related to risk perceptions even within social groups. We have shown that individual concerns predict network properties when socio-economic background variables are controlled for. This implies that people are less likely to be connected if they disagree on the level of threat that global warming poses even if they are members of the same social group.

Third, online social media, which distribute user-generated content over the social network, can be viewed as a parallel or complementary channel of communication comparable to traditional news media. Unlike news media based on mass communication, social networking sites operate as platforms where individuals can create and exchange information with their peers. The digital revolution has changed the way people consume news content and the way news coverage affects the public. The more competitive market environment has hindered the traditional news media's ability to produce high quality science reporting and inform the public of climate change (Boykoff and Yulsman, 2013). This has further strengthened the role of new forms of information production and distribution through social networking sites and other social media. Scientist should take advantage of these new channels and learn how to increase the likelihood of their research being shared on social media (Milkman and Berger, 2014). But on the other hand, traditional news media still provide an essential source of information for most people, despite the rise of social media, and their influence can even be amplified by the social media. In fact, one of the most popular forms of interaction on social networks sites is to share links to news articles. And it is plausible that the informational biases found in news media (Boykoff and Boykoff, 2004, 2007) will be perpetuated in the social media. Future research should investigate the interplay between social media and traditional news media and its effects on public perceptions of climate change.

Finally, it must be said that the social network perspective does give a rather dismal view of the challenges of science communication. Our finding that the network structure adds to the tenaciousness of opinions does not directly give us simple or definitive tools that could be used to improve communication. But for those who do practical work with science communication and aim to improve the communication, the network perspective does provide some ideas that merit consideration when thinking of ways to convince the public. Our findings indicate that the social network serves to filter information and preserve old opinions, and it is difficult to convince an individual if the social surrounding remains unconvinced. This suggests that science communication might be improved by targeting social groups as a whole (see Hine et al., 2014). Moreover, if the message relates to values that are shared by both the concerned and unconcerned (see Bain et al., 2012; Hoffman, 2011), so as to emphasize similarities instead of differences between individuals, the social network would operate more efficiently in transmitting the message. Therefore, broadening the debate to shared political objectives might help to communicate experts' concerns and generate more support for science-based climate policies.

Appendices

3.A Local clustering coefficient

We did not observe the local clustering coefficient directly, but we could estimate it for those who have friends in the sample. Consider the full undirected Facebook network (N, G), where N is the set of nodes and $G \subset \{(i,j) : i,j \in N,\ i \neq j\}$ is the set of friendships.

Let $N_i = \{j \in N : (i,j) \in G\}$ be node i's set of friends and d_i the number of friends. The number of pairs of friends is $p_i = d_i(d_i - 1)/2$. Let $c_i = |\{(j,k) \in G : j,k \in N_i\}|/2$ be the number of friendships between the members of N_i. Now the true local clustering coefficient is

$$t_i = \frac{c_i}{p_i}.$$

Let $\tilde{N} \subset N$ be the set of nodes we sampled. Let $\tilde{G} = \{(i,j) \in G : i \in \tilde{N} \text{ or } j \in \tilde{N}\} \subset G$ be the set of friendships we sampled. Now, for each $i \in \tilde{N}$ we observed N_i.

Let $\tilde{d}_i = |N_i \cap \tilde{N}|$ be the number of i's friends in the sample. We observed all pairs except the ones where both nodes were outside of the sample. The number of pairs we observed was then the number of all pairs less the unobserved pairs, which we denote by $\tilde{p}_i = d_i(d_i-1)/2 - (d_i - \tilde{d}_i)(d_i - \tilde{d}_i - 1)/2 = d_i\tilde{d}_i - (\tilde{d}_i^2 + \tilde{d}_i)/2$.

Let $\tilde{c}_i = |\{(j,k) \in G : j,k \in N_i \text{ and } (j \in \tilde{N} \text{ or } k \in \tilde{N})\}|/2$ be the number of friendships between the members of N_i that we observed.

The estimated clustering coefficient is then

$$\tilde{t}_i = \frac{\tilde{c}_i}{\tilde{p}_i}.$$

This is what we could observe and use for our analysis.

3.B Full regression tables

Here we report in full the regression tables of the main text. Tables 3.4 and 3.5 present all coefficient estimates of Tables 3.2 and 3.3, respectively.

	Dependent variable:			
	Number of friends		Clustering coefficient	
	(1)	(2)	(3)	(4)
Concern for global warming	17.781*** (3.374)	17.232*** (4.212)	−0.137 (0.153)	0.092 (0.185)
Number of friends				−0.014*** (0.001)
Age	−4.071*** (0.228)	−3.362*** (0.333)	0.032*** (0.010)	0.039*** (0.015)
Woman	−34.974*** (5.252)	−31.269*** (6.089)	−1.277*** (0.237)	−1.610*** (0.265)
In a registered partnership or civil union		21.436 (27.100)		1.939 (1.182)
Living together as married		18.606* (8.617)		0.287 (0.375)
In a relationship but not living together		53.027*** (12.543)		−0.002 (0.542)
Divorced		28.940* (13.136)		−0.970* (0.575)
Separated		73.735** (27.545)		−1.326 (1.174)
Widowed		21.497 (41.104)		4.267* (1.855)
Single		24.128** (8.414)		0.480 (0.366)
The suburbs or outskirts of a big city		−36.298*** (7.838)		0.350 (0.341)
A town or a small city		−10.579 (8.083)		−0.117 (0.351)
A country village		3.579 (14.903)		−0.042 (0.654)
A farm or home in the countryside		−20.573 (17.143)		−1.368 (0.757)
No formal education		−65.013 (122.387)		−6.359 (5.206)
Incomplete primary school		−23.673 (86.702)		−1.794 (4.258)
Complete primary school		−63.329 (33.450)		3.430* (1.476)
Incomplete secondary school: technical/vocational type		−14.445 (31.648)		−1.731 (1.409)
Complete secondary school: technical/vocational type		−20.183 (16.078)		0.642 (0.702)
Incomplete secondary: university-preparatory type		−21.077 (22.688)		4.841*** (0.994)
Complete secondary:		−27.907*		1.612**

university-preparatory type		(13.640)		(0.600)
Some education in a university of applied sciences or polytechnic		5.407 (14.540)		0.515 (0.631)
Complete university of applied sciences or polytechnic degree		-28.535^{*} (11.468)		-0.361 (0.502)
Some university-level education, without degree		20.565^{*} (9.007)		2.316^{***} (0.389)
University-level education, with bachelor's degree		27.855^{**} (8.831)		1.480^{***} (0.384)
University-level education, with doctor's degree		-25.667^{*} (12.195)		-0.199 (0.528)
Upper class		-20.862 (28.229)		-0.267 (1.233)
Lower middle class		-40.070^{***} (6.620)		-0.535 (0.288)
Working class		-47.212^{***} (10.523)		-0.377 (0.458)
Lower class		-37.671^{*} (15.687)		-0.954 (0.687)
Swedish questionnaire		76.545^{***} (21.652)		1.222 (0.937)
English questionnaire		68.337^{***} (8.507)		0.306 (0.367)
Left–right axis		3.342^{*} (1.497)		0.016 (0.065)
Liberal–conservative axis		-5.287^{**} (1.696)		-0.038 (0.074)
Constant	376.824^{***} (11.381)	361.764^{***} (21.981)	9.244^{***} (0.520)	11.620^{***} (1.000)
Observations	4996	3668	4790	3532
R^2	0.074	0.148	0.008	0.129
Adjusted R^2	0.073	0.140	0.008	0.121
Note:				*p<0.05; **p<0.01; ***p<0.001

Table 3.4: Regression analysis of number of friends and local clustering coefficient. The table reports the ordinary least square estimates of regression coefficients. Standard errors are reported in parentheses. The clustering coefficients were measured in percentage points. To avoid the dummy variable trap, we chose the following benchmarking categories: "A big city" for residential area size, "Married" relationship type, "University-level education, with master's degree" for education level, "Upper middle class" for social class, and Finnish questionnaire language. Left–right and liberal–conservative axes were coded from 1 to 10.

	Dependent variable:			
	Likelihood of friendship			
	(1)	(2)	(3)	(4)
Difference in concern for global warming:				
1 point	-0.437^{***} (0.019)	-0.385^{***} (0.019)	-0.318^{***} (0.019)	-0.311^{***} (0.019)
2 points	-0.838^{***} (0.037)	-0.791^{***} (0.037)	-0.599^{***} (0.038)	-0.563^{***} (0.039)

3 points	-0.957^{***} (0.086)	-0.980^{***} (0.086)	-0.719^{***} (0.086)	-0.599^{***} (0.092)
Age difference	-0.232^{***} (0.003)	-0.222^{***} (0.003)	-0.204^{***} (0.003)	-0.204^{***} (0.003)
Age difference^2	0.004^{***} (0.0001)	0.004^{***} (0.0001)	0.004^{***} (0.0001)	0.004^{***} (0.0001)
Both women	-0.026 (0.020)	0.095^{***} (0.020)	0.050^{*} (0.020)	0.041^{*} (0.021)
Both men	0.577^{***} (0.024)	0.464^{***} (0.024)	0.491^{***} (0.024)	0.495^{***} (0.024)
Sociality		0.002^{***} (0.00003)	0.002^{***} (0.00003)	0.002^{***} (0.00003)
Difference on the left–right axis			-0.147^{***} (0.005)	-0.146^{***} (0.005)
Difference on the liberal–conservative axis			-0.087^{***} (0.006)	-0.086^{***} (0.006)
Same social class			0.241^{***} (0.018)	0.239^{***} (0.018)
Same language			0.073^{***} (0.020)	0.068^{***} (0.020)
Same size of residential area			0.353^{***} (0.018)	0.343^{***} (0.018)
Same education level			0.653^{***} (0.019)	0.651^{***} (0.019)
Same relationship type			0.211^{***} (0.019)	0.215^{***} (0.019)
Difference in concern for air pollution:				
1 point				-0.078^{***} (0.019)
2 points				-0.321^{***} (0.030)
3 points				-0.488^{***} (0.081)
Difference in concern for water pollution:				
1 point				-0.016 (0.019)
2 points				-0.073 (0.059)
3 points				-0.282 (0.182)
Difference in concern for biodiversity loss:				
1 point				0.013 (0.019)
2 points				-0.038 (0.037)
3 points				-0.093 (0.098)
Constant	-4.737^{***} (0.019)	-6.463^{***} (0.030)	-6.641^{***} (0.040)	-6.553^{***} (0.042)
Observations	6608430	6608430	6608430	6608430
Log likelihood	−84753.80	−81263.10	−79605.95	−79525.98
Akaike Inf. Crit.	169523.60	162544.20	159243.90	159102.00

Note: *p<0.05; **p<0.01; ***p<0.001

Table 3.5: Logistic regression on the probability of friendship. Each column reports the maximum likelihood estimates of the regression coefficients of a logit-model. Standard errors are reported in parentheses. Left–right and liberal–conservative axes were coded from 1 to 10. Sociality was measured by the sum of the pair's number of friends.

3.C Estimating conditional degree and transitivity of a sampled network with complete neighbourhoods

When studying networks empirically, the researcher rarely gets to observe the complete network with all its nodes and edges. Instead, one must base the analysis on a sample of the network. The literature on network-related sampling methods dates back to the 60s (Frank, 2011, 2005), when one of the key goals was to survey rare populations with feasible sample sizes. Modern research focuses on the network itself and typically aims to use sampled network data to estimate parameters related to behavioural models (Chandrasekhar and Lewis, 2011). Still, a large portion of the empirical literature on networks does not explicitly define the underlying source of variation (Robins and Morris, 2007), and treats the sampled network as it was the population itself.

Unlike sampling a population which is defined as a set, network sampling can take various forms depending on the network's type and how the relationships between the individuals are sampled. Here we consider a single-mode undirected network where we observe all dyads involved with a sampled node.

Our aim is to study (2) conditional degree (or A-degree), i.e. the number of neighbours that have a certain property (property A), and (2) transitivity, or local clustering coefficient, i.e. the ratio of edges to dyads between one's neighbours. Moreover, we want use these node level statistics as dependent variables in a regression model.

As we do not have information on whole population to calculate the exact value of A-degree and transitivity, we must estimate them from a sampled. This causes two problems. First, estimation leaves measurement error in variables that will be used as dependent varibles in the regression model. The measurement error is absorbed into the regression residuals which increases the standard errors, but assuming the possible bias of the measurement error does not linearly dependent on the independent variables, the ordinary least squares (OLS) estimates of the regression coefficients are unbiased. Moreover, when the intercept of the regression model is not of interest, the measurement error can be allowed to be biased, as long as the last mentioned assumption holds. Second, the measurement errors are correlated because when an individual node enters the sample, estimates of A-degree and transitivity are affected for several nodes. Correlated measurement error and hence correlated error terms means that the default OLS estimators for the variance-covariance matrix are biased. This can lead to incorrect statistical inference. This problem can be resolved by using multiway clustering robust estimators for the standard error (Cameron and Miller, 2010).

In the following we (1) describe the setting for the analysis, (2) specify the sampling design and give a simplistic example, (3) define the estimators, (4) analyse the properties of the estimators in a simplistic example and describe required assumptions for a more general case, (5) relate the sampling design and estimators to the regression analysis and give the appropriate variance-covariance matrix estimator.

3.C.1 Preliminaries

Consider a set of nodes N and a set of dyads $D = \{(i,j) : i,j \in N,\ i \neq j\}$. We study an undirected network (N,G), where $G \subset D$ is the set of edges. The network is undirected if $(i,j) = (j,i)$ for all $i,j \in N$. We assume (N,G) represents the complete network that describes the population. We denote by $N_i = \{j \in N : (i,j) \in G\}$ the set of neighbours, or neighbourhood, of node $i \in N$ and by d_i the number of neighbours, i.e. the degree of i.

Next we define two node attributes which are the object of our inference.

First, suppose we want to examine a subset A of nodes N that is defined by some property of the nodes. We define the number of neighbours with property A as the A-*degree* of node i and denote it by

$$d_i^A = |N_i \cap A|,$$

where the vertical bars denote the cardinality of the set.

Second, we want to assess clustering, i.e. the density of neighbourhoods. In an undirected network the number of dyads between neighbours is $p_i = d_i(d_i - 1)/2$. We denote the number of edges between the members of N_i, i.e. the number of transitive closures, by $c_i = |\{(j,k) \in G : j,k \in N_i\}|/2$. The transitivity of i is

$$t_i = \frac{c_i}{p_i}.$$

In the following, our goal is to make inference on A-degree and the transitivity based on a sample of network (N,G).

3.C.2 Sampling scheme

Next we specify the sampling scheme which we wish to study. Let $\tilde{N} \subset N$ be the set of nodes in the sample, let $\tilde{D} = \{(i,j) : i \in \tilde{N} \text{ or } j \in \tilde{N}, i \neq j\} \subset D$ be the set of sampled dyads, and let $\tilde{G} = \{(i,j) \in G : i \in \tilde{N} \text{ or } j \in \tilde{N}\} \subset G$ be the set of edges in the sample. The sampled network $(\tilde{N}, \tilde{G})$ contains a complete list of neighbours of all sampled nodes, i.e. for each $i \in \tilde{N}$ we observe N_i. Hence, the sample contains information on all dyads except the ones where both nodes are excluded from the sample.

To express this formally, let s_i be a sampling indicator for node $i \in N$, for which $s_i = 1$, if $i \in \tilde{N}$, and $s_i = 0$ otherwise. Similarly, let s_{ij} be a sampling indicator for dyad $(i,j) \in D$, for which $s_{ij} = 1$, if $(i,j) \in \tilde{D}$, and $s_{ij} = 0$ otherwise. The sampling scheme which we study satisfies the following: if $s_i = 1$, then $s_{ij} = 1$ for all $j \in N$. As the network is undirected, $s_{ij} = s_{ji}$ for all $i,j \in N$. To emphasize that the sampling indicator for dyads is related to node sampling, we can also express it as a function of node sampling indicators:

$$s_{ij} = s_{ij}(s_i, s_j) = s_i + s_j - s_i s_j,$$

where $i \neq j$.

Number of observed dyads

Let $\tilde{d}_i = |N_i \cap \tilde{N}|$ be the number of i's neighbours in the sample. The number of dyads we observe is denoted by $\tilde{p}_i$. Given our sampling scheme, $\tilde{p}_i$ equals the number of all dyads less the unobserved dyads. To be exact,

$$\begin{aligned} \tilde{p}_i &= d_i(d_i - 1)/2 - (d_i - \tilde{d}_i)(d_i - \tilde{d}_i - 1)/2 \\ &= d_i\tilde{d}_i - (\tilde{d}_i^2 + \tilde{d}_i)/2. \end{aligned} \tag{3.1}$$

We assume that we cannot determine beforehand the sample size for the nodes or dyads in our sampling scheme. However, we consider the ex post observed sample size $\tilde{p}_i$ is fixed, as is customary in the Neyman-Pearson theory of hypothesis testing.

Furthermore, it is necessary to note that dyads are sampled in sets when sampling occurs at the node level. That is, if the number of i's neighbours in the sample increases by one from $\tilde{d}_i$ to $\tilde{d}_i + 1$, then the number of dyads in the new sample, $\tilde{p}_i'$, can be derived using equation (3.1) to get

$$\begin{aligned} \tilde{p}_i' &= d_i(\tilde{d}_i + 1) - ((\tilde{d}_i + 1)^2 + \tilde{d}_i + 1)/2 \\ &= d_i + d_i\tilde{d} - (\tilde{d}_i^2 + 2\tilde{d}_i + 1 + \tilde{d}_i + 1)/2 \\ &= \tilde{p}_i + (d_i - \tilde{d}_i - 1), \end{aligned} \tag{3.2}$$

where $(d_i - \tilde{d}_i - 1)$ is the number of new dyads observed because a new node was sampled.

Example

To give an example and a first approximation, suppose the sample of nodes is generated by a simple Bernoulli sampling process, i.e. each node has an identical and independent probability of being selected into the sample. We can define the sample by a sequence $s = (s_i)_{i \in N}$ of sampling indicators and the sample's probability distribution by

$$\mathrm{P}(s) = \prod_{i \in N} \theta^{s_i} (1-\theta)^{1-s_i},$$

where $0 < \theta \leq 1$ is marginal probability of a node being sampled, i.e. $\mathrm{P}\left(s_i = 1\right) = \theta$ for all $i \in N$.

In our sampling scheme dyads are sampled by sampling nodes. More specifically, the probability distribution of dyad sampling can be derived from the probability distribution of node sampling. The marginal probability of dyad (i, j) being sampled, that is the probability of $s_{ij} = 1$, is denoted by

$$\begin{aligned}
\phi &= \mathrm{P}\left(s_{ij} = 1\right) = \mathrm{P}\left(s_i = 1 \text{ or } s_j = 1\right) \\
&= 1 - (1-\theta)^2 \\
&= 2\theta - \theta^2.
\end{aligned}$$

The covariance between dyad sampling indicators can be split into three cases. First, consider that two dyads have two common nodes, in other words the sampling indicators refer to the same dyad, and the covariance is the same as variance. The covariance between s_{ij} and s_{ji}, where $i, j \in N$, can be calculated simply by partitioning according to elementary events of the corresponding node sampling indicators s_i and s_j:

$$\begin{aligned}
\operatorname{cov}\left(s_{ij}, s_{ji}\right) = \operatorname{var}(s_{ij}) &= \mathrm{E}\Big[\left(s_{ij} - \phi\right)^2\Big] && (3.3) \\
&= \phi(1-\phi)^2 + (1-\phi)\phi^2 \\
&= \phi - \phi^2. && (3.4)
\end{aligned}$$

Second, suppose the dyads have one common node. The covariance between s_{ij} and s_{ik}, where $i \neq j \neq k$ can be calculated by partitioning according to elementary events of the corresponding node sampling indicators (s_i, s_j, s_k) to get

$$\begin{aligned}
\operatorname{cov}\left(s_{ij}, s_{ik}\right) &= \mathrm{E}[(s_{ij} - \phi)(s_{ik} - \phi)] && (3.5) \\
&= \phi^2(1-\theta)^3 + 2(\phi^2 - \phi)(1-\theta)^2\theta \\
&\quad + (1-\phi)^2((1-\theta)^2\theta + 3(1-\theta)\theta + \theta^3).
\end{aligned}$$

Third, if the dyads have no common node, they are independent, and

$$\begin{aligned}\operatorname{cov}(s_{ij}, s_{kl}) &= \mathrm{E}[(s_{ij}-\phi)(s_{kl}-\phi)] \\ &= \phi^2(1-\phi)^2 - 2\phi^2(1-\phi)^2 + (1-\phi)^2\phi^2 \\ &= 0,\end{aligned} \tag{3.6}$$

where $i \neq j \neq k \neq l$.

Furthermore, note that as the sampling probability of nodes, θ, approaches unity, also the sampling probability of dyads ϕ approaches unity and the covariances in equations (3.3) and (3.5) go to zero, in other words

$$\lim_{\theta \to 1} \operatorname{cov}(s_{ij}, s_{kl}) = 0$$

for all $i, j, k, l \in N$. This means that the linear dependence between dyad sampling decreases as the sample size increases.

3.C.3 Estimators

Let $\tilde{d}_i^A = |N_i \cap \tilde{N} \cap A|$ be the number of neighbours of i with the property A included in the sample. We define an estimator for the A-degree of i as

$$\hat{d}_i^A = \frac{\tilde{d}_i^A}{\tilde{d}_i} d_i. \tag{3.7}$$

Let $\tilde{c}_i = |\{(j,k) \in G : j, k \in N_i \text{ and } (j \in \tilde{N} \text{ or } k \in \tilde{N})\}|/2$ be the number of edges between the members of N_i which we observed. Now we can define an estimator for the transitivity of i as

$$\hat{t}_i = \frac{\tilde{c}_i}{\tilde{p}_i}.$$

Next, we study the properties of $\hat{d}_i^A$ and $\hat{t}_i$ as estimators for A-degree and transitivity.

3.C.4 Estimator properties

Random sampling

To continue the example from Subsection 3.C.2, assume again each node $i \in N$ has the same probability of being sampled. In this case the number of sampled neighbours with property A, $\tilde{d}_i^A$, is a random variable with a hypergeometric distribution, where d_i is the number of neighbours (population size), d_i^A is the number of neighbours with property A (successful states) in the population, and $\tilde{d}_i$ is the number of sampled dyads (draws). The expected value of a hypergeometric distribution is $\mathrm{E}\Big[\hat{d}_i^A\Big] = \tilde{d}_i d_i^A / d_i$.

We denote the estimation error of A-degree by $\eta_i = \hat{d}_i^A - d_i^A$. Now we can show that $\hat{d}_i^A$ is an unbiased estimator A-degree by applying the definitions and the expected value, to show the estimation error has a zero mean:

$$\mathrm{E}[\eta_i] = \mathrm{E}\Big[\hat{d}_i^A - d_i^A\Big] = \frac{E[\tilde{d}_i^A]}{\tilde{d}_i} d_i - d_i^A = \frac{\tilde{d}_i d_i^A / d_i}{\tilde{d}_i} d_i - d_i^A = 0.$$

Similarly, the variance of $\tilde{t}_i$ is given by the hypergeometric distribution:

$$\mathrm{var}(\tilde{d}_i^A) = \tilde{d}_i \frac{d_i^A}{d_i} \frac{d_i - d_i^A}{d_i} \frac{d_i - \tilde{d}_i}{d_i - 1}.$$

Moreover, variance goes to zero as the sample size increases, i.e.

$$\lim_{\tilde{d}_i \to d_i} \mathrm{var}(\tilde{d}_i^A) = 0,$$

which means estimator $\tilde{d}_i^A$ has an arbitrarily small variance around the corresponding true value, if the sample size is large enough.

Given how nodes are assumed to be sampled, also dyads are sampled from a distribution that gives a constant probability of being sampled, as shown in Subsection 3.C.2. Note that the number of draws of dyads is derived from the number of sampled nodes as shown in equation (3.2). Hence, the number of sampled edges $\tilde{c}_i$ is a random variable with a hypergeometric distribution, where p_i is the number of dyads (population size), c_i is the number of edges (successful states) in the population, and $\tilde{p}_i$ is the number of sampled dyads (draws). The expected value of the hypergeometric distribution is $\mathrm{E}[\tilde{c}_i] = \tilde{p}_i c_i / p_i$.

We denote the estimation error of transitivity by $\epsilon_i = \hat{t}_i - t_i$. Now we can show that $\tilde{t}_i$ is an unbiased estimator of transitivity:

$$\mathrm{E}[\epsilon_i] = \mathrm{E}\Big[\tilde{t}_i - t_i\Big] = \frac{\mathrm{E}[\tilde{c}_i]}{\tilde{p}_i} - \frac{c_i}{p_i} = \frac{\tilde{p}_i c_i / p_i}{\tilde{p}_i} - \frac{c_i}{p_i} = 0.$$

Similarly, the variance of $\tilde{t}_i$ is given by the hypergeometric distribution:

$$\mathrm{var}(\tilde{t}_i) = \tilde{p}_i \frac{c_i}{p_i} \frac{p_i - c_i}{p_i} \frac{p_i - \tilde{p}_i}{p_i - 1}.$$

Moreover, variance goes to zero as the sample size increases, i.e.

$$\lim_{\tilde{p}_i \to p_i} \mathrm{var}(\tilde{t}_i) = 0,$$

which means that variance of estimator $\tilde{t}_i$ can be made arbitrarily small by increasing the sample size.

General case

For our purposes, we only require that the conditional expectation of estimation error is a constant given the observed covariates x_i, that is $\mathrm{E}[\eta_i \mid x_i] = \gamma$ and $\mathrm{E}[\epsilon_i \mid x_i] = \gamma'$, where γ and γ' are arbitrary constants. Hence, we can allow for a more general sampling distribution. To characterize this in terms of the sampling distribution, first, the assumption for A-degree can be rephrased as

$$\mathrm{E}[\eta_i \mid x_i] = \mathrm{E}\Big[\hat{d}_i^A - d_i^A \mid x_i\Big] = \mathrm{E}\left[\frac{\tilde{d}_i^A}{\tilde{d}_i} \mid x_i\right] d_i - d_i^A = \gamma.$$

By noting that $\tilde{d}_i^A = \sum_{j \in N_i \cup A} s_j$ and $\tilde{d}_i = \sum_{j \in N_i} s_j$, we can rearrange the condition to get

$$\mathrm{E}\left[\frac{\sum_{j \in N_i \cap A} s_j}{\sum_{j \in N_i} s_j} \mid x_i\right] = \frac{d_i^A}{d_i} + \gamma'',$$

where $\gamma'' = \gamma'/d_i$ is chosen without loss of generality. This means that the conditional expectation of the proportion of sampled nodes with property A must be equal to the proportion property A in neighbourhood N_i, while allowing for a fixed bias.

Similarly for transitivity, we assume that

$$\mathrm{E}[\epsilon_i \mid x_i] = \mathrm{E}\Big[\tilde{t}_i - t_i \mid x_i\Big] = \mathrm{E}\left[\frac{\tilde{c}_i}{\tilde{p}_i} \mid x_i\right] - \frac{c_i}{p_i} = \gamma'. \tag{3.8}$$

To relate this to the sampling indicators, note that the number of sampled dyads between neighbours of i is $\tilde{p}_i = \sum_{(j,k) \in \tilde{D}_i} s_{jk}$, where $\tilde{D}_i = \tilde{D} \cap (N_i \times N_i)$ is the set of neighbouring dyads in the sample. Also, the number of edges in the sample between neighbours of i is $\tilde{c}_i = \sum_{(j,k) \in \tilde{G}_i} s_{jk}$, where $\tilde{G}_i = \tilde{G} \cap (N_i \times N_i) \subset \tilde{D}_i$ is the set of neighbouring edges in the sample. Now, equation (3.8) can be rephrased as

$$\mathrm{E}\left[\frac{\sum_{(j,k) \in \tilde{G}_i} s_{jk}}{\sum_{(j,k) \in \tilde{D}_i} s_{jk}} \mid x_i\right] = \frac{c_i}{p_i} + \gamma',$$

which means that the conditional expectation of the proportion of sampled edges to sampled dyads among neighbour of i must be equal to the population transitivity, while allowing for a fixed bias.

3.C.5 Regression analysis

The main goal in this analysis is to use both A-degree and transitivity as dependent variables in separate linear regression models. We assume there is linear dependence between A-degree and a vector of independent variables x_i of the form

$$d_i^A = \alpha + x_i\beta + u_i$$

and similarly for transitivity

$$t_i = \alpha' + x_i\beta' + u_i',$$

where α, β, α', and β' are unknown parameters and u_i and u_i are unobserved and independent error terms with zero mean, for each $i \in N$. The main interest is in estimating β and β'. Also as discussed earlier, given only a sample of the population, A-degree and transitivity cannot be calculated exactly, therefore we need to rely on estimates.

We can interpret the estimation errors of A-degree and transitivity as measurement errors of the true population values, and rearranging them: $d_i^A = \tilde{d}_i^A - \eta_i$ and $t_i = \hat{t}_i - \epsilon_i$, respectively. Now, we can use these errors to express the models in estimable forms:

$$\begin{aligned} \hat{d}_i^A &= \alpha + x_i\beta + v_i \\ \hat{t}_i &= \alpha' + x_i\beta' + v_i', \end{aligned}$$

where $v_i = u_i + \eta_i$ and $v_i' = u_i' + \epsilon_i$ are the error terms. The error terms v_i and v_i' are assumed to have constant means, which are not necessarily zero. This is to allows the measurement error part to have a constant bias. Furthermore, the error terms v_i and v_i' are not assumed to be completely independent. This is to allow for correlation between measurement errors, which results from the sampling process where an observed node affects the A-degree and transitivity estimates of all its neighbours. Instead, we assume that the error terms are independent between observed nodes that have no common neighbours.

To guarantee that the OLS estimators for β and β' are unbiased, we require a weaker assumption than those used in the simplistic example earlier. First, the measurement error can be allowed to be biased, as our interest is not in estimating α and α'. Second, the distribution of the measurement errors can be arbitrary, as long as their conditional expectations are constants, i.e. they are statistically independent of the explanatory variables. (Wooldridge, 2002).

Formally, for measurement error of A-degree we assume that

$$\mathrm{E}[\eta_i \mid x_i] = \mathrm{E}\left[\frac{\tilde{d}_i^A}{\tilde{d}_i} d_i \mid x_i\right] - d_i^A = \gamma,$$

where γ is some constant. Or equivalently, we require that $\mathrm{E}\left[\tilde{d_i^A}/\tilde{d}_i \mid x_i\right] - d_i^A/d_i = \gamma'$, which means that, given the explanatory variables, the expected difference between the sampled proportion of nodes with property A and the population proportion is fixed, but possibly different.

Similarly, in order for the OLS estimator for β' in a model for transitivity to be unbiased, we assume that

$$\mathrm{E}[\epsilon_i \mid x_i] = \mathrm{E}\left[\frac{\tilde{c}_i}{\tilde{p}_i} \mid x_i\right] - \frac{c_i}{p_i} = \gamma'',$$

where γ'' is some constant. Again, this means that, given the explanatory variables, the expected difference between the sampled proportion of edges per dyads and the population proportion is fixed, but possibly different.

Note that when γ or γ'' are not zero, the OLS estimators for α or α' are not unbiased.

Covariance matrix

We assume that the measurement errors might be correlated, because sampled nodes affect several other nodes in their neighbourhood. Subsequently, regression errors are also correlated. This causes a problem for the estimation of the variance-covariance matrix and can lead to under-estimated standard errors.

As the correlations are limited to the neighbourhoods of sampled nodes, the setting is equivalent to *multiway nonnested clustering*. For each $i \in \tilde{N}_i$, the neighbourhood $\tilde{N}_i$ forms a dimension of clustering, where we allow the nodes within a neighbourhood to be correlated. Our assumption imply that $\mathrm{E}[v_i v_j \mid x_i, x_j] = 0$ if there is no $k \in \tilde{N}$ such that $i, j \in N_k$, i.e. when there are no common neighbours.

Cameron and Miller (2010) propose the following estimator for the variance-covariance matrix (see also Cameron et al., 2011). First, let us define X as the design matrix of the model, and define $\hat{v}_i = y_i - x_i'\hat{\beta}$ as the regression residual, where $\hat{\beta}$ is the OLS estimate. Now the estimated variance-covariance matrix is

$$\hat{\mathrm{var}}(\hat{\beta}) = (X'X)^{-1}\hat{B}(X'X)^{-1},$$

where

$$\hat{B} = \sum_{i \in N}\sum_{j \in N} x_i x_j' \hat{v}_i \hat{v}_j I(i,j),$$

and where indicator $I(i,j)$ equals 1, if there exists $k \in \tilde{N}$ such that $i, j \in N_k$, and zero otherwise. This provides a way to make reliable inference despite the correlation between the measurement errors. The estimator is a generalization of White's (1980) heteroscedasticity consistent estimator.

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Chapter 4

Emissions trading in a network of linked markets

4.1 Introduction

Climate change is a global externality that is best solved through international coordination. Unfortunately international efforts to sign a binding global agreement to reducing greenhouse gases and mitigate climate change have been unsuccessful so far. But many countries have been reluctant to wait and have moved forward with unilateral climate policies, with a hope to coordinate efforts in the future (Stavins, 2010; Newell et al., 2013).

Emissions trading, despite its controversies, has been one of the main policy tools used to reduce emissions (Grubb, 2012). Many countries and regions have implemented local emissions trading systems with the ability to link them to other systems. Linking means that the regulator of one emissions trading systems allows its participants to use permits of another system. Open trade tends to result in a common price level for permits and equalize marginal abatement costs for emitters, which is commonly considered a requirement for efficiency (Montgomery, 1972). Thus, in principle, it is possible to achieve a globally efficient solution by first creating local emissions trading systems and later linking them together.

However, a common concern related to linking is that links make domestic permit market outcomes dependent on policy decisions of foreign regulators. When two permit markets are linked, one regulator might unilaterally create new permits and sell them to the linked market. These new permits would generate a profit for the one issuing them, but it would also dilute the effectiveness of climate policies by increasing emissions.[1] Preventing this, and

[1] Furthermore, Rehdanz and Tol (2005) and Itkonen (2009) show that linking gives an

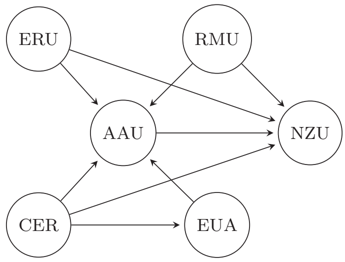


Figure 4.1: The graph depicts links between emissions trading systems at the end of the Kyoto period. The systems are identified by their emissions unit: Emission Reduction Unit (ERU), Removal Unit (RMU), Assigned Amount Unit (AAU), New Zealand Unit (NZU), Certified Emission Reductions (CER), EU emission allowance (EUA). Loops have been omitted from the figure.

other similar exploits, requires agreement and trust between the regulators.

It is well known that dependencies also arise indirectly when two unlinked systems trade with a common third system (Kranton and Minehart, 2000; Anger, 2008; Flachsland et al., 2009a; Newell et al., 2013). This means the problem exists even if there is no direct link between the systems. In the general case, considering a network of several emissions trading systems, linked together in an arbitrary manner, dependencies can be conveyed through several links. To our knowledge, no previous study has been devoted to the general case, which is understandable, as one could easily imagine that it is simply sufficient and necessary to have a path of links between two systems to make them dependent. Somewhat surprisingly, we find this is not the case.

Our main research questions is as follows: Given a network of arbitrarily linked emissions trading systems, which systems will be affected by a change in some other system? Knowing this is crucial for the policymaker, as the domestic policy outcomes could be undermined not only through its own links, but also through the links of its partners and their partners. In more technical terms, we ask how will marginal changes in exogenous variables of one system (e.g. the endowment of permits) change endogenous variables of other systems (e.g. price of permits). The emphasis is on the question of which systems will be affected and which will not.

Alongside the literature on emissions trading in general (Goulder, 2013), the idea of linking emissions trading system became a topical issue when

additional incentive to print more permits.

the Kyoto protocol established multiple emissions trading mechanisms with the possibility of using permits from different mechanisms to meet the emissions targets set by the agreement (see Figure 4.1). Since then, linking has been studied extensively in policy papers and technical reports, which cover diverse issues relevant for the implementation of linking policies, such as cost-effectiveness, distributional effects, and the compatibility of different design features (Haites, 2001; Ellis and Tirpak, 2006; Jaffe and Stavins, 2007; Itkonen, 2009; Mehling and Haites, 2009; Flachsland et al., 2009b; Tuerk et al., 2009; Hare et al., 2010; Newell et al., 2013). Some studies have focused on legal issues (Jaffe et al., 2009) or sectoral perspectives (Aasrud et al., 2009; Anger, 2010; Marschinski et al., 2012), while others have considered linking as a part of an international policy architecture (Flachsland et al., 2009a; Hare et al., 2010; Olmstead and Stavins, 2012). Cason and Gangadharan (2011) even performed a laboratory experiment where they tested the efficiency of different linking structures.

In academically oriented literature, the idea of viewing legal rights as factors of production originates from Coase (1960), while Dales (1968) and Crocker (1966) refined the idea into permits markets. Montgomery (1972) gave a proof for efficiency in a partial equilibrium model. In more recent literature, Copeland and Taylor (2005) frame linking as an application of trade theory and emphasise the general equilibrium effects, which show that benefits can be ambiguous (see also Chichilnisky, 1994; Marschinski et al., 2012). Some studies use numerical simulations to analyse the costs and benefits of linking in general equilibrium (Böhringer et al., 2005; Klepper and Peterson, 2006) or partial equilibrium (Anger, 2008) models. Rehdanz and Tol (2005) analyse linking with a particular focus on how it affects the incentives of regulators to uphold emissions targets that were set prior to linking.

In this paper, we follow the tradition of partial equilibrium analysis and set up a model with greenhouse gas emitting firms that participate in an emissions trading system which has a set of links to other systems. We restrict the analysis to the partial equilibrium in order to focus on permit markets and the links between them. We give an incentive to trade by allowing for heterogeneous firms and endowments. We set up the model to allow for both cap-and-trade and baseline-and-credit types of emissions trading schemes, that is, firms either need permits for their emissions or they receive credits from their emissions reductions.

To address the policymaker's concern for indirect influence, we use graph theoretic tools to derive a dependency structure from the equilibrium conditions. We show that in equilibrium the network is partitioned into segments, which we call supply and demand components. The members of these components face the same equilibrium price and they are connected by a specific sequence of links, which we call an alternating path of supply and demand. Each supply component has a matching demand component and vice versa. All members of a supply component effectively face the same demand generated by the matching demand component, even if there is no direct link between members. Similarly, all members of demand component effectively share the same supply generated by the matching supply component. By identifying the supply and demand components, we can answer our main research question: who influences who. The answer is characterized in the main theorem of the paper.

Furthermore, we get a subset of equilibrium conditions that allows us to study the comparative statics of the equilibrium and to show how changing endowments or production technology of one system affects the other systems. We show that a change in supply or demand will affect the price for all members of a supply component and the emissions of the matching demand component.

For a policymaker, who wishes to avoid unexpected interference to domestic policy outcomes by a foreign regulator, the theory provides an easy tool: If there is an alternating supply or demand path between two systems, they belong to the same component. Foreign regulators that are members of the same component or its matching counterpart are able to interfere with the domestic market, and the policymaker should take precautionary measures.

Even though we apply the theoretic framework solely for the analysis of permit markets, the model shows potential for more general use. Considering trade theory, the framework generalizes the comparison between free trade (all markets are linked) and autarky (no markets are linked) by allowing bilateral trade between some markets while disallowing it between others. From this point of view, one could ask, for example, what is the sufficient set of links needed to achieve an efficient outcome? Or which links need to be removed to achieve an effective embargo? [2] Our theory predicts, that only after removing all the alternating paths between the embargoed country and the rest of the world, would the global market tear apart into separate supply and demand components, forcing the embargoed country to lose its gains from trade.

To our knowledge, this is the first study devoted to the structure of dependencies in an equilibrium with an exogenous network of substitution possibilities and restrictions between competitive markets.

Our model is closely related to spatial price equilibrium models, where goods are sold between network nodes under perfect competition while each

[2] The appendix provides a simplistic example for Cuban cigars.

link entails a specific transport cost (Enke, 1951; Samuelson, 1952; Takayama and Judge, 1964). Mathematically our setting can be viewed as a special case, where the transport cost is either zero or infinite. However, within the spatial price equilibrium literature, to our knowledge, no study has attempted to provide a characterization of the equilibrium's dependency structure and answer our research question. Also, mathematically the our setting resembles network flow problems which are studied in operations research (see for instance Boyd and Vandenberghe, 2004), however the exact structure of these problem is very different to ours and relate to different questions.

More recent work on trading in networks has mostly focused on interaction between strategic agents and link formation, whereas our focus is on interaction between exogenously linked markets which consist of agent without bargaining power. In an early study, Jackson and Wolinsky (1996) investigate link formation with strategic individual while focusing on stability and efficiency of networks. In a related study, Kranton and Minehart (2000, 2001) consider exchange networks where individual buyers and sellers require a link between them in order to trade. In their model, buyers cannot resell their assets to other buyers. This feature is not suited for emissions permits as there is nothing preventing firms both buying and selling, only the use of foreign permits is limited. An assumption of bargaining power would be implausible in our case as permits are assets that are traded easily and typically have well-functioning secondary markets. Corominas-Bosch (2004) and Manea (2011) assume an exogenously given network, as do we, but again the focus is on strategic interaction. Ostrovsky (2008), Hatfield and Kominers (2012), and Hatfield et al. (2013) study the existence of equilibria in a trade network with a matching model in which agents have predetermined roles and goods are indivisible. With divisible goods and with a convex optimization problem, as in our case, existence of an equilibrium is immediate, and we can focus on the structure of dependencies. Also Hatfield and Kominers (2014) study divisible goods, but focus on complements, where as tradable permits are perfect substitutes. Miettinen and Poutvaara (2014) study link formation in a setting where strategic interaction is ruled out by assuming a uniform market price for links.

Even though the model setup we use is very conventional (e.g. compare with Samuelson (1952) and Baumol and Oates (1975)), the network of constraints between competitive markets open up a host of new questions and a need for graph theory, which enables us to contribute rather fundamental results. Our main theoretical contribution to the literature on networked markets is to give a detailed characterization of the equilibrium's dependency structure under perfect competition and with an exogenous network (Theorem 3).

In the next section we define necessary graph theoretic tools, set up the economic model, and discuss key assumptions. In Section 4.3, we solve the equilibrium and show some basic properties of the equilibrium. In Section 4.4, we derive a network to describe the equilibrium's dependency structure and construct necessary tools to analyse it. In Section 4.5, we analyse comparative statics. In the final section we conclude. In the appendix we give proofs, examples and an illustrative map outlining the theory.

4.2 Preliminaries

Next, we define the necessary graph theoretic concepts and set up the economic model. Graph theory not only helps to visualize the dependencies between markets, but it also provides a tool for rigorous deduction, and turns out to be extremely useful as we prove key propositions in the following sections.[3]

4.2.1 Graphs and connectivity

A graph (S, A) consists of a set of vertices S and a set of edges $A \subset \{\{s, r\} \mid s, r \in S\}$. A directed graph (S, A) consists of a set of vertices S and set of arcs $A \subset \{(s, r) \mid s, r \in S\}$. A (directed) graph (S', A') is a subgraph of (directed) graph (S, A) if $S' \subset S$ and $A' \subset A$. If (S', A') is a subgraph of (S, A) then (S, A) is said to be a supergraph of (S', A').

Vertices s_0 and s_k are connected by a path in graph (S, A) if there is a sequence of vertices $s_1, \ldots, s_{k-1} \in S$, $k \in \mathbb{N}$ such that $(s_{i-1}, s_i) \in A$ for all $i = 1, \ldots, k$.[4] Subgraph (S', A') of graph (S, A) is a connected component if (1) any vertices $s, r \in S'$ are connected by a path in (S', A') when $s \neq r$, (2) there are no $s \in S'$ and $r \in S \setminus S'$ which are connected by a path in (S, A), and (3) if $s, r \in S'$ and $(s, r) \in A$ then $(s, r) \in A'$.

4.2.2 The model

We construct a partial equilibrium model that focuses on dependencies between permit markets. We give a very simple description of the production side, in order to make the analysis tractable.

[3]For a similar approach, see De Benedictis and Tajoli (2011) who apply tools of network analysis to study international trade.

[4]Note that in some texts this would be referred to as a walk, with the distinction that a path has no repeated vertices or edges, but in our case this contrast makes no difference.

Consider a set of emissions trading systems S. Each system $s \in S$ has an endowment of permits $\omega_s > 0$ and regulates a set of firms which we call participants.[5] As our focus is on the relationships between the systems and not on what happens inside the the systems, we assume that each emissions trading system $s \in S$ can be described by a representative firm whose choices are equivalent to the sum of choices of the individual firms which participate in the system and trade permits under perfect competition. The representative firm produces output $y_s \geq 0$ using emissions $c_s \geq 0$ as a factor.[6] The production technology of the representative firm s is described by a strictly concave, twice continuously differentiable production function $f_s \colon \mathbb{R}_+ \to \mathbb{R}$ for which $y_s = f_s(c_s)$.[7]

Firms are obligated to buy permits if they wish to produce emissions. The rules of emissions trading dictate that each participant can emit an amount less or equal to the amount of permits it has acquired. That is, each firm must have enough permits to cover its emissions.

When several emissions trading systems coexist, some systems might allow their participants to use the permits of other systems, as if they were issued by themselves. This is called linking. Unless it is allowed explicitly, regulators will not accept foreign permits. In other words, the rules of each emissions trading system determine which permits its participants can use to comply with their obligations.

We call the set of emissions trading systems and the description of which permits they allow, a trading network:

Definition. A *trading network* is a directed graph (S, A), where the set of vertices $S = \{1, \ldots, n\}$ refers to a set of n emission trading systems and the set of arcs $A \subset S \times S$ specifies which permits are allowed in each system: $(s, r) \in A$ indicates that system r allows its participants to use permits of system s. We use binary variable $a_r^s \in \{0, 1\}$ to indicate that $(s, r) \in A$ and vector $a_s = (a_s^1, \ldots, a_s^n)$ to summarise which permits are allowed by system $s \in S$.

It is important to note that firms can buy and sell permits of any kind with whomever they wish. But for regulatory compliance they can only use

[5] Each firm is a participant of exactly one emissions trading system. See Goulder and Stavins (2011) for an account of the problems that arise from overlapping policy measures. For the same reason we omit emissions taxes from the analysis.

[6] As is common in the literature, we view emissions as a factor of production and not as an output with a negative price, which would lead to an equivalent theory.

[7] Alternatively, one could begin by deriving the choices of the representative firm by explicitly defining a set of participating firms P_s which have such production functions f_i, $i \in P_s$, that $y_s = \sum_{i \in P_s} f_i(c_i)$ and the sum has the properties assumed for the representative firm, and also $c_s = \sum_{i \in P_s} c_i$.

permits that are accepted by the system they participate in. The *emissions permit vector* of representative firm s describes how many permits of each system is held by the firm, and it is denoted by $e_s = (e_s^1, \ldots, e_s^n)$, where $e_s^r \geq 0$ is the amount of emissions permits of system r held by firm s. The *obligations constraint* requires that firms emit an amount less or equal to the amount of acquired permits which are accepted by their system.

The *resource constraint* requires that the sum of permits used cannot exceed the amount of permits issued. In practice, the initial endowment ω_s is usually either auctioned or allocated to participants freely. As permits are fungible assets, they typically have well-developed secondary markets.

Given a trading network, prices are denoted by a non-negative vector $p = (p_1, \ldots, p_n)$. The price of output is 1. We assume prices are taken as given by the firms.

The *profit maximization problem* of a firm that represents system $s \in S$ of network (S, A) is to choose emissions $c_s \in \mathbb{R}_+$ and emissions permit vector $e_s \in \mathbb{R}_+^n$ to maximize its profits

$$f_s(c_s) + p_s\omega_s - pe_s,$$

subject to the obligations constraint

$$c_s \leq a_s e_s,$$

while prices $p \in \mathbb{R}_+^n$ are taken as given. Note that the value of the endowment $p_s\omega_s$ is also taken as given by the firms.

As the optimization problem is convex, we can use the Karush-Kuhn-Tucker theorem to derive the sufficient and necessary conditions for the firms solution. Using these conditions, we can show some useful descriptive properties of representative firms' behaviour.

Lemma 1. *In equilibrium, a representative firm*

1. *uses only the cheapest permits among the allowed,*
2. *never emits beyond its saturation point, and*
3. *may possess unallowed permits only if their price is zero.*

The existence of a solution is guaranteed by the extreme value theorem.

4.2.3 Discussion of model assumptions

The model assumes a fixed production function f_s for each $s \in S$. Later in our analysis we will consider the effect of improving production technology.

We will model this by introducing an additional factor of production which is used to replace emissions and which we denote by $\beta_s \in \mathbb{R}$. This can be interpreted as a backstop technology (Nordhaus, 1973). The firm's production function takes the form $y_s = f_s(c_s + \beta_s)$, and the firm takes $\beta_s \in \mathbb{R}$ as given. An exogenous increase in β_s allows the firm to produce output y_s with fewer emissions c_s. We will later use β_s to illustrate the effect of technological change on the market equilibrium. But for now, we omit technological change from the analysis by choosing $\beta_s = 0$.

Our assumption that representative firms take prices as given rests on the idea, that individual emissions trading systems establish perfectly competitive markets. Regulators aim to design emissions trading systems so that they generate competitive markets and reduce emissions cost-effectively. Already early theoretical literature (e.g. Hahn, 1984) identified the potential problems caused by market power. More recent studies have focused on particular design features such as initial allocation (Hahn and Stavins, 2011) and permit banking (Liski and Montero, 2011). Although it is plausible that poorly designed systems leave some market power to participants, our assumption is a reasonable starting point when focusing on the dependencies between systems in trading network. Furthermore, linking increases the market size so it can be expected to decrease bargaining power of participants (cf. Kranton and Minehart, 2001). The literature on bargaining in stationary networks (e.g. Corominas-Bosch, 2004; Manea, 2011) considers a departure from the assumption of perfect competition.

Also, assuming bargaining power would be less plausible in our case as the high tradability of permits effectively inhibits price discrimination between systems. One might consider an extreme case where a system with only one participant (monopoly) is located between two systems, and the firm sells to both markets. In such a case the monopoly could try to increase its profit by selling at different prices. However, nothing prevents the one paying lower price from reselling the permits to the one paying the higher price.

The production functions allow for a saturation point $\hat{c}_s$ above which there is no gain from further emissions, that is $f_s'(\hat{c}_s) = 0$, where f_s' is the derivative of f_s. In the emissions trading literature the saturation point is often called the *baseline* emissions level. In our application it would not be unreasonable to assume that all firms have a saturation point, i.e. all firms would emit a finite amount even without regulations, but we do not wish to waste generality.

Credit-and-baseline emissions trading systems can be seen as a special case where endowments equal baseline emissions. Actually, credit-and-baseline systems generate an amount of credits equal to the difference between the baseline and emissions, $\omega_s - c_s$, while emissions themselves require no permits. However using this type of formulation would lead to identical but less tractable results. That is, it makes no difference for the firm's behaviour whether it receives $\omega_s - c_s$ credits to sell, or it receives ω_s permits, uses c_s permits, and is left with $\omega_s - c_s$ to sell. Note that in order to have a positive price, this type of permits must have demand outside the system. One way to generate demand is with a link, i.e. by allowing a cap-and-trade systems to use them.

Our optimization problem can be formulated equivalently as a variational inequality problem (Nagurney, 1993), which has a multitude of numerical solving algorithms (Noor, 2004). However, we found it more convenient to formulate the economic model as a traditional optimization problem.

We assumes that links and permit endowments are exogenous, which rules out strategic behaviour on the part of the regulators, to focus on the competitive outcome in the trading network. Behaviour of the regulators is beyond the scope of this study. Nevertheless, we provide a necessary intermediate step towards that goal. In order to understand the incentives regulators have for forming links and issuing permits, we must first understand to what kind of an outcome a given choice would lead to.

4.3 Equilibrium

We assume a standard market clearing condition, which states that in equilibrium each resource constraint is binding if the price of permits is non-zero. That is, for all $s \in S$ the sum of permits used, $\sum_{r \in S} e_r^s$, equals the amount of issued permits, ω_s, if $p_s > 0$.[8]

An *equilibrium* of the model is a $(n^2 + 3n)$-tuple

$$(e_1^1, \ldots, e_n^1, \ldots, e_1^n, \ldots, e_n^n, c_1, \ldots, c_n, \lambda_1, \ldots, \lambda_n, p_1, \ldots, p_n)$$

which solves the profit maximization problems of the representative firms while satisfying the resource constraints and the market clearing condition. Shadow prices $\lambda_1, \ldots, \lambda_n$ are Lagrangian multipliers related to the obligation constraints, and can be interpreted as the marginal costs of regulation. Similarly, permit prices $p_1, \ldots, p_n$ can be interpreted as the competitive market equilibrium prices which are related to the resource constraints.

Lemma 2. *The decentralized perfect competition equilibrium outcome of the trading network is efficient.*

[8] Note that allows for the supply of permits to exceed the demand if price is zero.

The proof of Lemma 2, found in Appendix 4.A, states the Karush-Kuhn-Tucker conditions (KKT), i.e. equation and inequalities (4.9–4.13), which characterize the equilibrium.

First, we note that the KKT conditions include inequality constraints and not all equilibrium variables appear in each system's constraint due to the network structure. This suggest a possibility that a subset of equilibrium variables can be solved with a subset of the equilibrium conditions. In such cases, the value of the equilibrium variables will depend only on the exogenous variables that appear in the subset of equations. Our goal in the following chapters is to make an exact account of such subsets and show that they are essential in answering our main question: which systems will be interdependent in the equilibrium. Subsequently, this will allow us to study the comparative statics of changes made by foreign regulators.

If we were given a specific, fully parametrized model, we could follow a much simpler procedure to find out the dependencies: we could simply solve the model numerically, to find the total derivatives (or marginal effects of shocks), which determine whether an exogenous variable affects a given endogenous variable. However, this would not say anything about the general case and, moreover, would not produce a characterization of the dependencies, which is necessary when we want to understand how dependencies arise and what kind of network patters cause them.

Second, consider a firm which represents some system $s \in S$. We note that the profit maximization problem does not generally have a unique solution with respect to the emissions permit vectors e_s, even though the solution for emissions c_s is unique. This is because allowed permits are perfect substitutes, and when their prices are equal, firms are indifferent between them.

As the production function f_s is strictly concave, its derivative is also strictly decreasing and it has an inverse function $f_s'^{-1}$. We can use this (with the help of equation (4.8)) to express equilibrium emissions $c_s > 0$ in terms of the lowest price available:

$$c_s = f_s'^{-1}\left(p_s^*\right) = f_s'^{-1}\left(\min_{(r,s)\in A} p_r\right) \quad \forall s \in S, \tag{4.1}$$

where p_s^* denotes the lowest price available to system s. Equation (4.1) gives a unique amount of emissions for every price vector p.

We can use equation (4.1) to illustrate the complex network of dependencies that emerges from the equilibrium, and justify the need for new concepts and theory to sort out these dependencies. Looking at equation (4.1), the demand for emissions of system s depends only on the prices of permits, which are linked to s and have a minimal price. But what determines these prices?

Suppose r_1 is linked s. The supply of permits is fixed, so intuitively the price r_1 is determined by the firms that could also use these permits. These need not be linked to s. Suppose r_1 is linked to r_2. Would the demand of r_2 affect the price s pays? Again, equation (4.1) tells that the demand for emissions of r_2 depends on the prices of linked permits with a minimal price. Now we have to solve a similar problem for r_2 before we can solve the problem we started with. We see that the optimal choice does not depend only on the choices of immediate neighbours but potentially a much larger set of agents.

But not everything depends on everything. In principle, we could continue in this manner to find all agents which are relevant. If by doing so we arrive at a subset of relevant systems, we have found at a subset of the equilibrium constraints which allow us to determine the equilibrium outcome for a subset of equilibrium variables, whose value is independent of other equilibrium constraints. In the following subsections, our aim is to a give formal account of this idea.

4.4 Equilibrium network

Next, we apply graph theoretic concepts defined in Subsection 4.2.1 to analyse the dependencies between systems, with an aim to determine which equilibrium prices and emissions will be affected by changes in the endowment or technology of a given system.

Part 1 of Lemma 1 implies that permits whose price is higher than the lowest price will not be used by profit maximizing firms. Links from high price systems to low price systems will not be used. This suggest we can focus on a smaller set of connections than those included in the trading network. To study the equilibrium further, we define the subgraph that characterises the relevant dependencies between the equilibrium prices and quantities:

Definition. The *equilibrium network* of trading network (S, A) is the directed subgraph (S, M), where $M = \{(r, s) \in A \mid p_r = p^*_s\} \subset A$, and p_r and p^*_s are equilibrium prices.

It follows from part 1 of Lemma 1 that $e^s_r = 0$ if $(s, r) \notin M$ and $p_s > 0$. This means that all transactions will occur via the links of the equilibrium network. When a link exist in the trading network but not in the equilibrium network, it means that participants of one system are allowed use another system's permits but will not do so, because they have access to cheaper permits. It is also worth noting that, in equilibrium, the system's own permits might be too expensive for its participants to buy. More specifically, it is possible that $p_s > p^*_s$ and hence $(s, s) \notin M$, even if $(s, s) \in A$.

It important to note, that the equilibrium network is a function of the equilibrium, which in turn depends on the specification of the underlying economic model. This means that different trading networks, endowments, and production functions might result in a different equilibrium network. As our aim is to study which equilibrium variables are affected by changes in exogenous variables, and to depict this dependency structure with the concept of equilibrium network, we must consider the possibility that the equilibrium network is altered, in a discrete fashion, by these exogenous changes. The definition of equilibrium network immediately implies that its structure will change if the exogenous changes are large enough to change the ordering of equilibrium prices. This, however, occurs at a rather limited set of crossing points. In Section 4.5.1, we will introduce the property of nonzero equilibrium, which is sufficient to guarantee there exists an open set of exogenous variables in which the equilibrium network remains unchanged.

4.4.1 Adjacent sellers and buyers

Next, we connect positional properties of the equilibrium network to price equalization properties of the equilibrium. We begin by making such a connection between systems that have a mutual linking partner. Later, we extend it transitively to the whole network.

We define two adjacency relationships between systems in the equilibrium network, and in the following lemma, we show that these positional relationships imply an equivalence relation for prices.

Definition. Systems s and r are *adjacent sellers* in equilibrium network (S, M) if there is a system t such that $(s, t) \in M$ and $(r, t) \in M$.Similarly, s and r are *adjacent buyers* in equilibrium network (S, M) if there is a system t such that $(t, s) \in M$ and $(t, r) \in M$.

The concepts of adjacent seller and buyers define a network position between two systems, which depends on the existence of a third system with specific links to the first two systems. That is, systems s and r are adjacent sellers if there is a subgraph

$$s \longrightarrow t \longleftarrow r$$

and adjacent buyers if there is a subgraph

$$s \longleftarrow t \longrightarrow r$$

for some t.

When two firms sell to the same market or two firms buy from the same markets, under perfect competition, prices tend to be the same. The assumption of perfect competition rules out price discrimination, and in the following lemma, we relate this price equalization property to positions in the equilibrium network, namely adjacent sellers and buyers.

Lemma 3. *In an equilibrium network, the permits of adjacent sellers have an equal price, and adjacent buyers use permits with an equal price.*

It is important to note that Lemma 3 rules out situations where the equilibrium network contains a fourth system that sells or buys at a different price.

Lemma 3 is a price equalization result for pairs only. Next, we develop new concepts that allow us to apply Lemma 3 transitively to prove a similar price equalization result for wider sets. Due to the transitivity of the equivalence relation, prices are equated beyond adjacent pairs. We aim to find the largest set of system among which prices are equated.[9]

First, we note that the relationship of being adjacent sellers or buyers is symmetric, so all such relationships found in the equilibrium network can be summarized as an undirected graph.

Definition. The *adjacent seller graph* is the undirected graph (S, M_S), where $M_S = \{\{s, r\} \mid s, r \in S \text{ are adjacent sellers}\}$. The *adjacent buyer graph* is the undirected graph (S, M_D), where $M_D = \{\{s, r\} \mid s, r \in S \text{ are adjacent buyers}\}$.

4.4.2 Supply and demand components

The adjacent seller and buyer graphs can be used to partition the set of systems of the trading network into connected components that are essential for characterizing the dependencies between systems.

Definition. A *supply component* of equilibrium network (S, M) is a connected component in adjacent seller graph (S, M_S). Similarly, a *demand component* of (S, M) is a connected component in adjacent buyer graph (S, M_D).

Basic graph theory tells us that the connected components of a graph induce a unique partition for the set of vertices, and in a finite graph there is a finite number of components.

We can now show that both supply and demand components constitute a set of systems which have an equal prices.

[9] In technical terms, we aim to construct equivalence classes for the equal permit price relation.

Proposition 1. *In equilibrium,*

1. *permit prices of systems that belong to the same supply component are equal, and*

2. *prices paid by representative firms belonging to the same demand component are equal.*

Proposition 1 allows us to define a single price for all permit in a supply component. We denote the price of permits in supply component S_i by p_{S_i}. This is the price faced by all firms in a particular demand component.

To illustrate the idea behind Proposition 1, consider a supply component of equilibrium network (S, M). If systems s and r are members of the same supply component, then by definition, there must a particular type of path connecting them in (S, M). For example, consider a subgraph

$$s \longrightarrow t_1 \longleftarrow t_2 \longrightarrow t_3 \longleftarrow r ,$$

where s and t_2, as well as t_2 and r are adjacent sellers. Both pairs have a common system to which their permits are sold to, in this case t_1 and t_3, respectively. Similarly, in subgraph

$$s \longleftarrow t_1 \longrightarrow t_2 \longleftarrow t_3 \longrightarrow r ,$$

systems s and t_2, as well as t_2 and r are adjacent buyers, which buy permits from t_1 and t_3, respectively.

4.4.3 Alternating supply and demand paths

The illustration suggest another way of stating that two systems belong to the same supply or demand component: by defining an appropriate form of connectivity in the underlying equilibrium network.

Definition. Vertices s_0 and s_k are connected by an *alternating supply path* in equilibrium network (S, M) if there is a sequence of vertices $s_1, \ldots, s_{k-1}$, where $k \geq 2$ is an even number, such that $(s_{i-1}, s_i) \in M$ and $(s_{i+1}, s_i) \in M$ for all odd $i = 1, \ldots, k-1$. Similarly, vertices s_0 and s_k are connected by an *alternating demand path* in equilibrium network (S, M) if there is a sequence of vertices $s_1, \ldots, s_{k-1}$, where k is an even integer, such that $(s_i, s_{i-1}) \in M$ and $(s_i, s_{i+1}) \in M$ for all odd $i = 1, \ldots, k-1$.

In essence, alternating supply and demand paths constitute sequences of adjacent sellers and buyers, respectively. Based on the definitions, it is clear that two systems are connected by an alternating supply path or demand path if and only if they are members of the same supply component or demand component, respectively. As we will later show that supply and demand components are essential for specifying dependencies between equilibrium variables, alternating supply and demand paths will help determine whether two systems are dependent.

4.4.4 Matching supply and demand components

Next, we will show that each supply component is related to a particular demand component, and conversely each demand component is related to a particular supply component. We say that such components are *matching*.

Lemma 4. *Let (S, M) be an equilibrium network.*

1. *Let S_i be the set of systems in a supply component of (S, M) and $D_i = \{r \in S \mid \exists s \in S_i \colon (s, r) \in M\}$. Then D_i is the set of systems of a demand component of (S, M).*
2. *Let D_i be the set of systems in a demand component of (S, M) and $S_i = \{s \in S \mid \exists r \in D_i \colon (s, r) \in M\}$. Then S_i is the set of systems of a supply component of (S, M).*

Lemma 4 shows us that for each supply component there is a unique matching demand component, and vice versa. We denote the sets of systems of the supply component by S_i and D_i, where $i = 1, \dots, k$ is index for the k components.

Finally, we show that the set of arcs having an initial vertex in the supply component equals the set of arcs having a terminal vertex in the demand component. This result can be interpreted as a type of completeness property of matching supply and demand components and it will be pivotal in the next section where we analyse the comparative static results of the equilibrium.

Proposition 2. *If S_i and D_i are matching supply and demand components of equilibrium network (S, M), then*

$$\{(s, r) \in M \mid s \in S_i, r \in S\} = \{(s, r) \in M \mid s \in S, r \in D_i\}.$$

Proposition 2 means that all permits that are sold from the supply component are bought somewhere within the matching demand component. And the other way around, all permits bought by firms in the demand component are sold from the matching supply component.

4.5 Comparative statics

Next, we will study the comparative statics of the equilibrium. First, we define a concept, which we use to restrict to non-trivial equilibria. Second, we apply Propositions 1–2 to derive a (sub)system of equations, which characterizes the equilibrium locally and allows us to analyse the comparative statics. Finally, two comparative statics results are presented.

4.5.1 Nonzero equilibrium

Some constraints can be unbinding in the equilibrium if the endowment of permits is so large that there is no scarcity or the endowment is so small that firms stop emitting (i.e. exit the permit market). In such cases, marginal changes in the involved exogenous variables would have no effect on the equilibrium. Also, in the special case where constraints are binding in only one direction, analysing marginal effects would have to be restricted to semiderivatives. We will exclude these equilibria from the analysis and focus on the ones where constraints are binding within an open set. To be exact, we restrict to what we call nonzero equilibria[10]:

Definition. An equilibrium is *nonzero* for matching supply and demand components S_i and D_i if for all $s \in S_i$ and $r \in D_i$ applies $c_r > 0$, $\lambda_r > 0$, $p_{S_i} > 0$ and $e_r^s > 0$ when $(s, r) \in M$.

The nonzero assumption refers to the complementary slackness conditions of the optimization problem and implies that the resource and obligations constraints are binding. If there are permits with no value or non-emitting firms, then marginal changes in the exogenous variables will have either one-sided effects or no effect at all on the equilibrium variables. By restricting the analysis of comparative statics to matching components with a nonzero equilibrium, we are guaranteed that within an open neighbourhood of the exogenous variables the endogenous variables have an open neighbourhood in which the relevant equilibrium constraints are binding and fully characterize the equilibrium. This allows us to apply the implicit function theorem to analyse the marginal effects on the equilibrium prices and emissions of changes in the production functions and endowments.

[10]Note that, to avoid confusion, we do not use the term non-boundary as the equilibria are indeed on the boundary in the sense that the related constraints are binding.

4.5.2 Subset of equations

Finally, we will apply the theory and concepts we have developed so far to derive the theorem that gives a subset of equilibrium conditions that are necessary and sufficient to describe the equilibrium locally.

Theorem 3. *Consider an equilibrium which is nonzero for matching supply and demand components S_i and D_i. Variables c_r, $r \in D_i$, and $p_s, s \in S_i$ satisfy the equilibrium constraints if and only if*

$$\sum_{r \in D_i} c_r - \sum_{s \in S_i} \omega_s = 0 \tag{4.2}$$

and

$$f'_r \left(c_r + \beta_r\right) - p_{S_i} = 0 \quad \forall r \in D_i, \tag{4.3}$$

where $p_{S_i} = p_s = \lambda_r$ for all $s \in S_i$ and for all $r \in D_i$.

Theorem 3 says that equations (4.2) and (4.3) characterize the equilibrium, given it is nonzero, for matching supply and demand components S_i and D_i. It shows that the supply and demand components derived in the previous section were indeed the relevant subsets we needed to find in order to use comparative statics.

From Theorem 3 immediately follows that the equilibrium is unique with respect to c_r and p_s since f'_r is strictly decreasing.

Theorem 3 answers our main research question: Systems in the same supply or demand component and systems in their matching counterpart can affect each other.

At this point it is very important to understand the concept of matching supply and demand components. The members of a supply or demand component do not necessary have a link between them, nor are they necessarily connected by a path of links in the sense commonly defined (see Subsection 4.2.1).

Obviously systems do need to have some kind of a sequence of links between them to make the dependent: Systems are in the same supply or demand component if and only if they are connected by an alternating supply or demand path in the equilibrium network.

4.5.3 Marginal effects

With Theorem 3 we are able to use comparative statics to assess the economic outcomes resulting from a change in the endowment and the non-emitting factor that substitutes emissions.

Equations (4.2) and (4.3) define a unique, continuously differentiable implicit function which characterizes the nonzero equilibrium in some neighbourhood. The equations can be interpreted as an implicit equation: with the help of function $F\colon \mathbb{R}^{2n_D+n_s+1} \to \mathbb{R}^{n_D+1}$, where n_D and n_S indicate the number of elements in sets D_i and S_i, we can restate (4.2) and (4.3) as

$$F((c_r)_{r\in D_i}, p_{S_i}, (\beta_r)_{r\in D_i}, (\omega_s)_{s\in S_i}) = 0.$$

Now we can use the implicit function theorem to show that the implicit equation defines an implicit function between endogenous variables $(c_r)_{r\in D_i}$ and p_{S_i} and exogenous variables $(\beta_r)_{r\in D_i}$ and $(\omega_s)_{s\in S_i}$.

Recall that the second derivatives of the production functions f_r are continuous and strictly negative. It is easy to check that the Jacobian matrix of F with respect to the endogenous variables is invertible. Now according to the implicit function theorem, there is a neighbourhood of the endogenous variables and the exogenous variables for which there is a unique, continuously differentiable function, i.e. the implicit function, which maps exogenous variables $(\omega_s)_{s\in S_i}$ and $(\beta_r)_{r\in D_i}$ to endogenous variables $(c_r)_{r\in D_i}$ and p_{S_i} so that it satisfies equations (4.2) and (4.3). Comparative statics results can be analysed by studying the differential of the implicit function.

Corollary 1. *Consider an equilibrium which is nonzero for matching supply and demand components S_i and D_i.*

1. *An increase in endowment ω_s of system $s \in S_i$ will decrease price p_{S_i} and increase emissions c_r for all $r \in D_i$.*

2. *An increase in non-emitting factor β_r of system $r \in D_i$ will decrease price p_{S_i}, decrease emissions c_r and increase $c_{r'}$ for all $r' \in D_i \setminus \{r\}$.*

Part 1 of Corollary 1 means that increasing the endowment of any system of a supply component has an effect on the supply component's price level and the emissions of the matching demand component. Part 2 of Corollary 1 means that introducing clean technology to any firm in a demand component has a similar effect on the supply component's price level and causes a reallocation of the emissions of the matching demand component.[11]

The key observation made in Corollary 1 is that marginal exogenous effects are limited to the matching supply and demand components. Other systems in the network remain unaffected. As the members of a supply or a demand component are characterized by having an alternating supply or an

[11]The total amount of emissions is unaffected as it is fixed by the total number of permits.

alternating demand path between them, respectively, the dependencies described in Corollary 1 apply if and only if such paths can be found between systems in the equilibrium network.

4.6 Conclusions

We have set up a simple model to analyse trade given an underlying network of trade possibilities. We have shown that the market will be divided into areas of equal price due to the trade restrictions. Moreover, we have specified the link structure that characterize these areas: matching supply and demand components constitute market areas, which act as if they were unified sources of supply and demand, even if systems within the components are not directly connected. And firms remain unaffected by events that occur outside such market areas.

The theory produces a certain symmetry between supply-side and demand-side effect. If two systems belong to the same supply component, then a change in the supply of permits of one will affect the price of the other. The effect on the price change will be reflected on the emissions of matching demand component. Similarly, if two systems belong to the same demand component, then a change in the demand of permits of one will affect the emissions of the other. The effect on the emissions will be reflected on the price of the matching supply component.

The concepts of alternating supply and demand paths provide a convenient tool for finding out whether systems are interdependent. If we observe permits being sold from one system to another, we can conclude that they are connected in the equilibrium network. If these observed trade patterns form an alternating path between two markets, we can infer that systems belong to same component. In such a case, the policymaker should acknowledge that their policy outcome will depend on the actions of the foreign regulator, even if there is no direct link between the systems.

A more general policy implication of the theory is that links should made with caution—to avoid unanticipated dependencies between emission trading systems.

To avoid illicit printing of new permits, one of the biggest treats, the regulator could include a rule in each linking agreement that forbids making new links without the consent of all existing linking partners. This would prevent other systems from joining the same supply component and possibly making a profit at the expense of others. On the other hand, such a clause would not stop third parties from unilaterally allowing the use of foreign permits and thus connecting to the same demand component. This, however, can be considered less harmful: it would only make the domestic emission target more stringent but at the cost of the third party—equivalent of purchasing and retiring permits to reduce emissions, as some environmental groups already do.

To offer a rather abstract idea, alternating paths could be understood as pathways for price signals, which are necessary to equate prices and to achieve gains from trade. The theory shows that it is not necessary for agents to operate directly in the same market to equate prices. The essential requirement is to have a path of agents who share buyers and sellers. Without such paths the perfectly competitive markets are unable to generate the efficient outcome.

To maintain focus on the main research question, we have had to omit many topics that still merit some discussion. Our model can be interpreted as a generalization of a simple trade model. When all systems are linked, our model is reduced to a simple partial equilibrium model of production with open trade. When there are no links at all, our model corresponds to autarchy. In these extreme cases, the tools developed here are trivial. However, they allow us to study the intermediate cases. With intermediate linking structures, we can study how the equilibrium breaks up into separate markets, while losing benefits from trade. Or we can study which links are necessary to establish the open trade equilibrium, or which links need to be removed in order to cut the interdependence.

We have implicitly assumed that regulators have been willing to set up costly regulation by limiting the total amount of emissions. This of course can be motivated the political willingness to mitigate environmental degradation. To focus on the market dependencies, we have assumed emissions targets to be fixed. As such, links do not affect the total amount of emissions permits. However, as noted by Rehdanz and Tol (2005) and Itkonen (2009), links change the incentives for choosing emissions targets (see also Kranton and Minehart, 2001). Future research should examine how links impact the goals of mitigation policies in a complex networks, and what incentives regulators have for adding new links to an existing network.

Clearly, the theory constructed in this paper shows many possibilities for further investigation.

Appendices

4.A Proofs

Proof of Lemma 1

Proof. Let $s \in S$ and $p_r \geq 0, \omega_r > 0$ for all $r \in S$. As the optimization problem is convex and satisfies appropriate regularity conditions, such as the Slater's condition, the Karush-Kuhn-Tucker theorem gives the necessary and sufficient conditions for the solution. The conditions can be expressed with the help of a Lagrangian function

$$L_s(c_s, e_s^1, \dots, e_s^n, \lambda_s) = f_s\left(c_s\right) + p_s\omega_s - pe_s - \lambda_s(c_s - a_s e_s).$$

Karush-Kuhn-Tucker conditions are as follows:
for all $r \in S$ such that $a_s^r = 1$

$$\frac{\partial L}{\partial e_s^r} = \lambda_s - p_r \leq 0, \tag{4.4a}$$

$$e_s^r \frac{\partial L}{\partial e_s^r} = e_s^r\left(\lambda_s - p_r\right) = 0, \tag{4.4b}$$

$$e_s^r \geq 0, \tag{4.4c}$$

for all $r \in S$ such that $a_s^r = 0$

$$\frac{\partial L}{\partial e_s^r} = -p_r \leq 0, \tag{4.5a}$$

$$e_s^r \frac{\partial L}{\partial e_s^r} = e_s^r(-p_r) = 0, \tag{4.5b}$$

$$e_s^r \geq 0, \tag{4.5c}$$

and

$$\frac{\partial L}{\partial c_s} = f_s'(c_s) - \lambda_s \leq 0, \tag{4.6a}$$

$$c_s \frac{\partial L}{\partial c_s} = c_s\left(f_s'(c_s) - \lambda_s\right) = 0, \tag{4.6b}$$

$$c_s \geq 0, \tag{4.6c}$$

$$\frac{\partial L}{\partial \lambda_s} = c_s - a_s e_s \leq 0, \tag{4.7a}$$

$$\lambda_s \frac{\partial L}{\partial \lambda_s} = \lambda_s\left(c_s - a_s e_s\right) = 0, \tag{4.7b}$$

$$\lambda_s \geq 0. \tag{4.7c}$$

First, to state the first part of the proposition precisely, we aim to show, that if $c_s > 0$ then for all $r' \in S$ such that $(r', s) \in A$ and $p_{r'} > \min_{(r,s)\in A} p_r$ we have $e_s^{r'} = 0$.

By rearranging inequalities (4.4a) and (4.6a), we see that the marginal product $f_s'(c_s)$ is a lower bound for all prices among the allowed permits, that is

$$f_s'(c_s) \leq \lambda_s \leq p_r$$

for all r such that $(r, s) \in A$.

Assumption $c_s > 0$ implies that inequality (4.6a) is binding, i.e. $f_s'(c_s) = \lambda_s$. Inequality (4.7a) implies $a_s e_s \geq c_s > 0$, so there is some r for which $e_s^r > 0$ and $a_s^r = 1$. Equation (4.4b) implies that also inequality (4.4a) must be binding for such r, i.e. $\lambda_s = p_r$, therefore $f_s'(c_s) = \lambda_s = p_r$. Because $f_s'(c_s)$ is a lower bound,

$$f_s'(c_s) = \min_{(r,s)\in A} p_r. \tag{4.8}$$

For all r' for which $p_{r'} > p_r = \lambda_s$, that is $\lambda_s - p_{r'} < 0$, equation (4.4b) implies $e_s^{r'} = 0$.

Second, let there be a saturation point $\hat{c}_s$. Suppose, contrary to our claim, that $c_s > \hat{c}_s > 0$. Strict convexity and the definition of a saturation point implies that $f_s'(c_s) < f_s'(\hat{c}_s) = 0$. Now equation (4.6b) and inequality (4.6a) imply that $\lambda_s = f_s'(c_s) < 0$ which is a contradiction with inequality (4.7c), and hence $c_s \leq \hat{c}_s$.

Third, let $e_s^r > 0$ for some $r \in S$ such that $(r, s) \notin A$. Then equation (4.5b) implies $p_r = 0$. □

Proof of Lemma 2

Proof. To show efficiency, first, we construct a social planner's problem, where the planner may choose the amount of permits and emissions used by each system (i.e. representative firm) in order to maximize the sum of outputs, while satisfying obligations and resource constraints and the trade constraints defined by the trading network. Second, we show that the solution of a social planner's problem of maximizing the sum of outputs is equivalent with the decentralized perfect competition equilibrium in a trading network.

The social planner's problem is to choose emissions c_s for each $s \in S$ and emissions permits e_s^r for each $s, r \in S$ to maximize the sum of outputs while satisfying the obligations and resource constraints, that is, to solve

$$\max_{\substack{c_1,\ldots,c_n,\\ e_1,\ldots,e_n}} \sum_{s\in S} f_s\left(c_s\right),$$

so that resource constraints

$$\sum_{r \in S} e_r^s \leq \omega_s$$

and obligations constraints

$$c_s \leq a_s e_s$$

are satisfied for all $s \in S$.[12]

Next, we solve the social planner's problem and show that its solution is equivalent with the competitive equilibrium conditions.

As the optimization problem is convex and satisfies appropriate regularity conditions, such as the Slater's condition, the Karush-Kuhn-Tucker theorem gives the necessary and sufficient conditions for the solution. The conditions can be expressed with the help of a Lagrangian function

$$\begin{aligned} &L(e_1, \ldots, e_n, c_1, \ldots, c_n, \lambda_1, \ldots, \lambda_n, p_1, \ldots, p_n) \\ &= \sum_{s \in S} \left(f_s\left(c_s\right) - \lambda_s (c_s - a_s e_s) - p_s \left(\sum_{r \in S} e_r^s - \omega_s \right) \right), \end{aligned}$$

where $\lambda_1, \ldots, \lambda_n, p_1, \ldots, p_n$ are the non-negative Lagrangian multipliers.

Karush-Kuhn-Tucker conditions are as follows:
for all $s, r \in S$ such that $a_s^r = 1$

$$\frac{\partial L}{\partial e_s^r} = \lambda_s - p_r \leq 0, \tag{4.9a}$$

$$e_s^r \frac{\partial L}{\partial e_s^r} = e_s^r \left(\lambda_s - p_r\right) = 0, \tag{4.9b}$$

$$e_s^r \geq 0, \tag{4.9c}$$

for all $s, r \in S$ such that $a_s^r = 0$

$$\frac{\partial L}{\partial e_s^r} = -p_r \leq 0, \tag{4.10a}$$

$$e_s^r \frac{\partial L}{\partial e_s^r} = e_s^r(-p_r) = 0, \tag{4.10b}$$

$$e_s^r \geq 0, \tag{4.10c}$$

[12] Note that social planner has no negative externalities from emissions as they are assumed to fixed by the binding emissions targets set by the emissions trading systems.

for all $s \in S$

$$\frac{\partial L}{\partial c_s} = f_s'(c_s) - \lambda_s \leq 0, \tag{4.11a}$$

$$c_s \frac{\partial L}{\partial c_s} = c_s \left(f_s'(c_s) - \lambda_s \right) = 0, \tag{4.11b}$$

$$c_s \geq 0, \tag{4.11c}$$

$$\frac{\partial L}{\partial \lambda_s} = c_s - a_s e_s \leq 0, \tag{4.12a}$$

$$\lambda_s \frac{\partial L}{\partial \lambda_s} = \lambda_s \left(c_s - a_s e_s \right) = 0, \tag{4.12b}$$

$$\lambda_s \geq 0, \tag{4.12c}$$

$$\frac{\partial L}{\partial p_s} = \sum_{r \in S} e_r^s - \omega_s \leq 0, \tag{4.13a}$$

$$p_s \frac{\partial L}{\partial p_s} = p_s \left(\sum_{r \in S} e_r^s - \omega_s \right) = 0, \tag{4.13b}$$

$$p_s \geq 0. \tag{4.13c}$$

First, note that conditions (4.13) are equivalent with the market clearing conditions assumed to apply in the equilibrium. Now we see that the Karush-Kuhn-Tucker conditions for the social planners problem (4.9–4.13) are equivalent with a set of conditions which combines the market clearing conditions (4.13) and the firms' conditions (4.4–4.7) for all $s \in S$, where the latter have been derived by first solving the firms' problems individually, while taking prices as given. Hence the conditions (4.9–4.13) also characterize an efficient equilibrium for the representative firms of the trading network under perfect competition, as the sum of output cannot be increased and no firm can individually increase its profits by deviating from the social planner's optimum. □

Proof of Lemma 3

Proof. First, let s and r be adjacent sellers. Now there is a system t such that $(s, t) \in M$ and $(r, t) \in M$, and by definition $p_s = p_t^*$ and $p_r = p_t^*$. Hence $p_s = p_r$.

Second, let s and r be adjacent buyers. Now there is a system t such that $(t, s) \in M$ and $(t, r) \in M$, and by definition $p_t = p^*_s$ and $p_t = p^*_r$. Since systems s and r have the same minimum price among the allowed permits, Lemma 1 implies that the permits they use have the same price. $\square$

Proof of Proposition 1

Proof. First, let s and r be members of a supply component. Now there is a path of adjacent sellers between s and r. According to Lemma 3, each consecutive pair in the path must sell at the same price. Due to the transitivity of the equivalence relation, s and r sell at the same price. The proof of the second part is similar. $\square$

Proof of Lemma 4

Proof. Let S_i be the set of systems in a supply component of (S, M) and $D_i = \{r \in S \mid \exists s \in S_i \colon (s, r) \in M\}$. Let $s, r \in D_i$. Now there are vertices $t_0 \in S_i$ and $t_l \in S_i$ such that $(t_0, s) \in M$ and $(t_l, r) \in M$. If $t_0 = t_l$, then s and r are adjacent buyers. Suppose $t_0 \neq t_l$. Since S_i is a supply component, t_0 and t_l are connected by a path of adjacent sellers, which we denote by sequence of vertices $(t_0, t_1, \ldots, t_{l-1}, t_l)$. For each $j = 1, \ldots, l$, subsequent system (t_{j-1}, t_j) are adjacent sellers, and hence there exists a $q_j \in D_i$ such that $(t_{j-1}, q_j) \in M$ and $(t_j, q_j) \in M$. Now vertices q_{j-1} and q_j are adjacent buyers for all $j = 2, \ldots, l$, as are (s, q_1) and (q_l, r), so s and r are connected by a path in the adjacent buyer graph.

Also note that vertices in D_i are not connected to other vertices of the supergraph outside of D_i: if $s \in D_i$ were connected to $r \in S \setminus D_i$, we could use the same strategy as above to show, that $r \in D_i$, which would be a contradiction.

The proof for part 2 is similar. $\square$

Proof of Proposition 2

Proof. Let S_i and D_i be matching supply and demand components of equilibrium network (S, M).

Suppose $(s, r) \in \{(s, r) \in M \mid s \in S_i, r \in S\}$. Now $s \in S_i$ and $r \in S$, and part 1 of lemma 4 implies $r \in D_i = \{r \in S \mid \exists s \in S_i \colon (s, r) \in M\}$, therefore $(s, r) \in \{(s, r) \in M \mid s \in S, r \in D_i\}$.

Suppose $(s, r) \in \{(s, r) \in M \mid s \in S, r \in D_i\}$. Now $s \in S$ and $r \in D_i$, and part 2 of lemma 4 implies $r \in S_i = \{s \in S \mid \exists r \in D_i \colon (s, r) \in M\}$, therefore $(s, r) \in \{(s, r) \in M \mid s \in S_i, r \in S\}$. $\square$

Proof of Theorem 3

Proof. Consider a nonzero equilibrium for matching supply and demand components S_i and D_i.

To show sufficiency, let variables c_r, $r \in D_i$, and $p_s, s \in S_i$ satisfy the equilibrium constraints. The nonzero property and Propositions 1 imply that $p_{S_i} = p_s > 0$ for each $s \in S_i$, so the related resource constraints (4.13) are binding and we can use part 1 of Lemma 1 to restate the constraints equivalently as

$$\sum_{(s,r)\in M} e_r^s = \omega_s \quad \forall s \in S_i. \tag{4.14}$$

Similarly, the nonzero property means that $\lambda_r > 0$ for each $r \in D_i$, so the related obligations constraints (4.12) are binding and we can use part 1 of Lemma 1 to restate the constraints equivalently as

$$\sum_{(s,r)\in M} e_r^s = c_r \quad \forall r \in D_i. \tag{4.15}$$

Using equations (4.14) and (4.15), together with Proposition 2, we can equate the sum of emissions demands of demand component D_i and the endowments of supply component S_i:

$$\sum_{r\in D_i} c_r = \sum_{r\in D_i} \sum_{(s,r)\in M} e_s^r = \sum_{s\in S_i} \sum_{(s,r)\in M} e_s^r = \sum_{s\in S_i} \omega_s.$$

This can be summarized as equation (4.2).

Also for all $s \in S_i$ and $r \in D_i$ such that $(s,r) \in M$ the nonzero property implies $e_r^s > 0$, which means constraint (4.9) is binding so that $\lambda_r = p_s$. Following Proposition 1, all prices of the supply component are bound to be equal. As $c_r \geq e_r^s > 0$ and constraints (4.11) are binding, equation $f_r'(c_r + \beta_r) = \lambda_r = p_s = p_{S_i}$ applies for all $s \in S_i$ and $r \in D_i$. This allow us to restate equation (4.8) as equation (4.3).

It is easy to show necessity by assuming equations (4.2) and (4.3) and checking that the relevant equilibrium conditions are satisfied. □

Proof of Corollary 1

Proof. Consider an equilibrium which is nonzero for matching supply and demand components S_i and D_i. First, let $s \in S_i$ be a system that increases its endowment ω_s, i.e. it issues more permits. We can use the implicit function derived from equations (4.2) and (4.3) to get the system of equations that specifies the implicit function's partial derivatives:

$$\sum_{r\in D_i} \frac{\partial c_r}{\partial \omega_s} - 1 = 0 \tag{4.16}$$

and

$$f_r''(c_r)\frac{\partial c_r}{\partial \omega_s} - \frac{\partial p_{S_i}}{\partial \omega_s} = 0 \quad \forall r \in D_i. \tag{4.17}$$

Equation (4.17) can be rearranged to get

$$\frac{\partial c_r}{\partial \omega_s} = f_r''(c_r)^{-1}\frac{\partial p_{S_i}}{\partial \omega_s} \quad \forall r \in D_i \tag{4.18}$$

and plugged into equation (4.16) to get

$$\frac{\partial p_{S_i}}{\partial \omega_s} = \left(\sum_{r\in D_i} f_r''(c_r)^{-1}\right)^{-1} < 0, \tag{4.19}$$

which is negative because the second derivative of a strictly concave function is negative. Plugging this into equation (4.18) gives

$$\frac{\partial c_r}{\partial \omega_s} = f_r''(c_r)^{-1}\left(\sum_{r'\in D_i} f_{r'}''(c_{r'})^{-1}\right)^{-1} > 0 \quad \forall r \in D_i. \tag{4.20}$$

Inequality (4.19) implies by that increasing the endowment, the price of all permits in the supply component will decrease, and inequality (4.20) implies that emissions will increase in all systems of the demand component.

Second, let $r \in D_i$ be a system that increases $\beta_r \in \mathbb{R}$, i.e. replaces emissions with the non-emitting factor. Now the implicit function defined by equations (4.2) and (4.3) has a derivative that is determined by equations

$$\sum_{r'\in D_i} \frac{\partial c_{r'}}{\partial \beta_r} = 0, \tag{4.21}$$

$$f_{r'}''(c_{r'})\frac{\partial c_{r'}}{\partial \beta_r} - \frac{\partial p_{S_i}}{\partial \beta_r} = 0 \quad \forall r' \in D_i \setminus \{r\}, \tag{4.22}$$

$$f_r''(c_r+\beta_r) + f_r''(c_r+\beta_r)\frac{\partial c_r}{\partial \beta_r} - \frac{\partial p_{S_i}}{\partial \beta_r} = 0, \quad r \in D_i. \tag{4.23}$$

We evaluate the derivative at $\beta_r = 0$, and rearrange equations (4.22) and (4.23) to get

$$\frac{\partial c_{r'}}{\partial \beta_r} = f_{r'}''(c_{r'})^{-1}\frac{\partial p_{S_i}}{\partial \beta_r} \quad \forall r' \in D_i \setminus \{r\} \tag{4.24}$$

and

$$\frac{\partial c_r}{\partial \beta_r} = f_r''(c_r)^{-1}\frac{\partial p_{S_i}}{\partial \beta_r} - 1, \quad r \in D_i.$$

Plugging these into equation (4.21) gives

$$\frac{\partial p_{S_i}}{\partial \beta_r} = \left(\sum_{r' \in D_i} f''_{r'}(c_{r'})^{-1} \right)^{-1} < 0, \tag{4.25}$$

which is negative as the second derivatives of a strictly concave function is negative. Plugging equation (4.25) into equation (4.24) gives

$$\frac{\partial c_{r'}}{\partial \beta_r} = f''_{r'}(c_{r'})^{-1} \left(\sum_{r' \in D_i} f''_{r'}(c_{r'})^{-1} \right)^{-1} > 0 \quad \forall r' \in D_i \setminus \{r\}, \tag{4.26}$$

while equation (4.21) is equivalent to

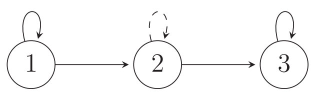
$$\frac{\partial c_r}{\partial \beta_r} = - \sum_{r' \in D_i \setminus \{r\}} \frac{\partial c_{r'}}{\partial \beta_r} < 0, \tag{4.27}$$

where the expressions are negative due to inequality (4.26).

Inequalities (4.26) and (4.27) tell us that cleaner technology in one firm decreases its own emissions while allowing others to emit more. Inequality (4.25) tells us that cleaner technology decreases the price of permits in the matching supply component. □

4.B Numerical example

Consider emissions a trading network (S, A) with systems $S = 1, 2, 3$ and arcs $A = \{(1,1), (1,2), (2,2), (2,3), (3,3)\}$. The corresponding graph is depicted below.



Let $f_s(c_s) = \theta_s c_s - c_s^2$ and $\omega_s = 1/4$ for $s = 1, 2, 3$, and $\theta_2 = \theta_2 = 2$ and $\theta_3 = 5$. We can derive the derivatives $f'_s(c_s) = \theta_s - 2c_s$ and the saturation points $\hat{c}_s = \theta_s/2$. Given the arcs, the resource constraints are $e_1^1 + e_2^1 \leq \omega_1$, $e_2^2 + e_3^2 \leq \omega_2$, and $e_3^3 \leq \omega_3$.

Consider the equilibrium of the specified model. First, note that part 2 of Lemma 1 implies that in equilibrium $f'_s(c_s) > 0$ when $c_s < \hat{c}_s$. Because $c_s \leq a_s e_s \leq \sum_{r \in S} \omega_r = 3/4 < \theta_s/2 = \hat{c}_s$ for all $s \in S$, it follows that $f_s(c_s) > 0$. Now inequality (4.11a) implies $\lambda_s > 0$, therefore equation (4.12b) implies that obligation constraint (4.12a) is binding, and inequality (4.9a) implies that $p_r > 0$ and resource constraint (4.13a) is binding for all $s, r \in S$.

Given that the obligation constraint (4.12a) are binding, inequalities (4.9a) (4.11a) implies that

$$2 - 2e_1^1 \leq p_1,$$
$$2 - 2\left(e_2^1 + e_2^2\right) \leq p_1 \quad \text{and} \quad 2 - 2\left(e_2^1 + e_2^2\right) \leq p_2,$$

and

$$5 - 2\left(e_3^2 + e_3^3\right) \leq p_2 \quad \text{and} \quad 5 - 2\left(e_3^2 + e_3^3\right) \leq p_3.$$

If $p_3 > p_2$, then $e_3^3 = 0$ and $e_3^3 \neq \omega_3$, which would contradict the binding resource constraint for system 3. If $p_3 < p_2$, then $e_3^2 = 0$. As $e_2^1 \geq 0$ and $c_2 \geq e_2^2 = \omega_2 = 1/4$, which means $p_2 = \lambda_2 = f_2(c_s)$, we get

$$3/2 \geq 2 - 2\left(e_2^1 + e_2^2\right) = p_2 > p_3 = 5 - 2\left(e_3^2 + e_3^3\right) = 9/2,$$

which is a contradiction. Therefore $p_3 = p_2$.

If $c_2 = 0$, then $c_1 = e_1^1 = 1/4 > 0$ and inequalities (4.9a) and (4.11a) imply that $3/2 = 2 - 2e_1^1 = p_1 \geq 2 - 2\left(e_2^1 + e_2^2\right) = 2$, which is a contradiction. If $c_1 = 0$, then $c_2 \geq e_2^1 = 1/4 > 0$ and inequalities (4.9a) and (4.11a) imply that $2 = 2 - 2e_1^1 \leq p_1 = 2 - 2\left(e_2^1 + e_2^2\right) \leq 3/2$, which is a contradiction. Therefore $c_1 > 0$ and $c_2 > 0$. Also $c_3 \geq e_3^3 = \omega_3 > 0$

Now equation (4.11b) implies that $f_s(c_s) = \lambda_s$ for $s = 1, 2, 3$.

Suppose $p_1 = p_2 = p_3$. Now $e_1^1 = c_1 > 0$, $e_3^3 > 0$, and either $e_2^1 > 0$ or $e_2^2 > 0$, which implies $\lambda_1 = \lambda_2 = \lambda_3 = p_1 = p_2 = p_3$. Hence the marginal products must be equal:

$$2 - 2e_1^1 = 2 - 2\left(e_2^1 + e_2^2\right) = 5 - 2\left(e_3^2 + e_3^3\right).$$

By plugging in the resource constraints, we get

$$2 - 2(\omega_1 - e_2^1) = 2 - 2\left(e_2^1 + e_2^2\right) = 5 - 2\left((\omega_2 - e_2^2) + \omega_3\right). \tag{4.28}$$

Both sides of the first equation in (4.28) can be reduced by 2 and divided by -2 to get $\omega_1 - e_2^1 = e_2^1 + e_2^2$ and solved to get $e_2^1 = \frac{1}{2}\omega_1 - \frac{1}{2}e_2^2$. The second equation in (4.28) can be rearranged to get, $e_2^1 = \omega_2 + \omega_3 - \frac{3}{2} - \frac{3}{2}e_2^2$. Equating these gives $\frac{1}{2}\omega_1 - \frac{1}{2}e_2^2 = \omega_2 + \omega_3 - \frac{3}{2} - \frac{3}{2}e_2^2$, which can be solved to get

$$e_2^2 = \omega_2 + \omega_3 - \frac{3}{2} - \frac{1}{2}\omega_1 = -\frac{9}{8} < 0,$$

which is a contradiction.

Suppose $p_1 > p_2 = p_3$. Now $e_2^1 = 0$, $e_1^1 = \omega_1$, and $p_1 = \lambda_1$, which implies $3/2 = 2 - 2e_1^1 = p_1 > p_2 = 5 - 2\left(e_3^2 + e_3^3\right) \geq 4$, which is a contradiction.

Therefore in equilibrium the prices must have order $p_1 < p_2 = p_3$. Now, because $p_2 > \lambda_2$, equation (4.9b) implies that $e_2^2 = 0$. As the marginal products of systems 1 and 2 are equal, $2 - 2e_1^1 = 2 - 2e_2^1$, we can solve their permit usage: $e_1^1 = e_2^1 = c_1 = c_2 = \omega_1/2 = 1/8$. The price of permit 1 is set to the marginal product, $p_1 = 2 - \frac{2}{8} = \frac{7}{4}$. Given the resource constraints $e_3^2 = e_3^3 = \omega_2 = \omega_3 = 1/4$ and emissions are $c_3 = 1/2$. Also the prices of permit 2 and 3 are set to the marginal product of system 3:

$$p_2 = p_3 = 5 - \frac{2}{2} = 4.$$

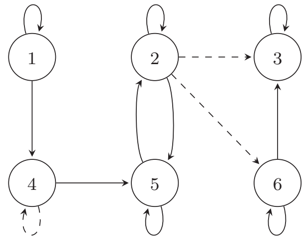
The equilibrium network is determined as (S, M), where $S = 1, 2, 3$ and $M = \{(1,1), (1,2), (2,3), (3,3)\}$. This depicted by the solid arcs in the previous graph. Note that arc $(2, 2)$ is missing which indicates that system 2 is not using its own permits in equilibrium.

The equilibrium network contains 2 pairs of demand and supply components: components with low price, $D_1 = \{1, 2\}$ and $S_1 = \{1\}$, and components with high price, $D_2 = \{3\}$ and $S_1 = \{2, 3\}$. We can denote the supply components' prices by $p_{S_1} = p_1$ and $p_{S_2} = p_2 = p_3$, respectively.

Note that this is a rather pathological situation for system 2 as it is not using its own permits. Furthermore, its supply and demand components are not matching. So supply component S_1 is matched with its demand component D_1, and demand components D_2 is matched with its supply component S_2. So according to Corollary 1, changes in the supply S_1 would affect its emissions while changes in demand in D_2 would affect the price of its permits.

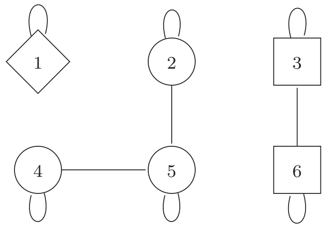
4.C Graphical example

Consider a trading network of six systems whose links can be depicted by the following directed graph:

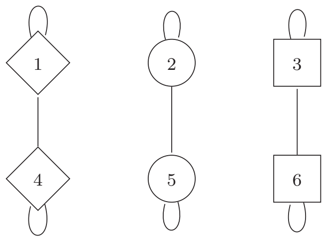


Suppose the dashed arcs are part of the trading network but not the equilibrium network. That is, the dashed links are removed because at the arc's terminal vertex the lowest available price is cheaper than the price at the initial vertex.

Now we can determine which vertices are adjacent sellers to construct the adjacent seller graph:

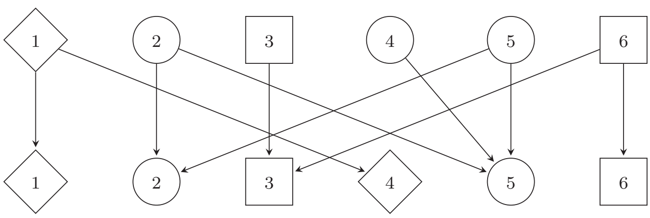


Here the different vertex shapes identify the three supply components that emerge. Similarly we can determine the adjacent buyers to construct the adjacent buyer graph:



We identify the matching demand component with the corresponding shapes. Sets $\{1\}$, $\{2,4,5\}$, and $\{3,6\}$ indicate supply components and sets $\{1,4\}$, $\{4,5\}$, and $\{3,6\}$ indicate their matching demand components, respectively.

Equivalently, the equilibrium network can be formulated as a bipartite graph where one set represents supply and the other demand, and where all nodes are included in both sets.



From this formulation we can identify matching supply and demand components. For example, the circle nodes $\{2,4,5\}$ on the upper row form a supply component. Its matching demand component can be found on the lower row, the circle nodes $\{2,5\}$. The reader might find it useful to confirm that Lemma 4 and Proposition 2 apply for this graph.

Finally, we can easily determine which systems will be affected by changes in exogenous variables. For example, a change in the endowment of system 4, which is a member of the ”circle component”, will affect the price of permits 2, 4, and 5 and emissions of systems 2 and 5. Similarly, replacing emissions by a non-emitting factor in system 4 will affect the price of permit 1, decrease emissions in system 4 and increase emissions in system 1.

4.D Cuban cigars example

Consider the United States embargo against Cuba that prohibits the US residents from purchasing Cuban cigars. Would a decrease in the supply of Cuban cigar (an adverse weather event for example) cause an increase in the price of cigars in USA?

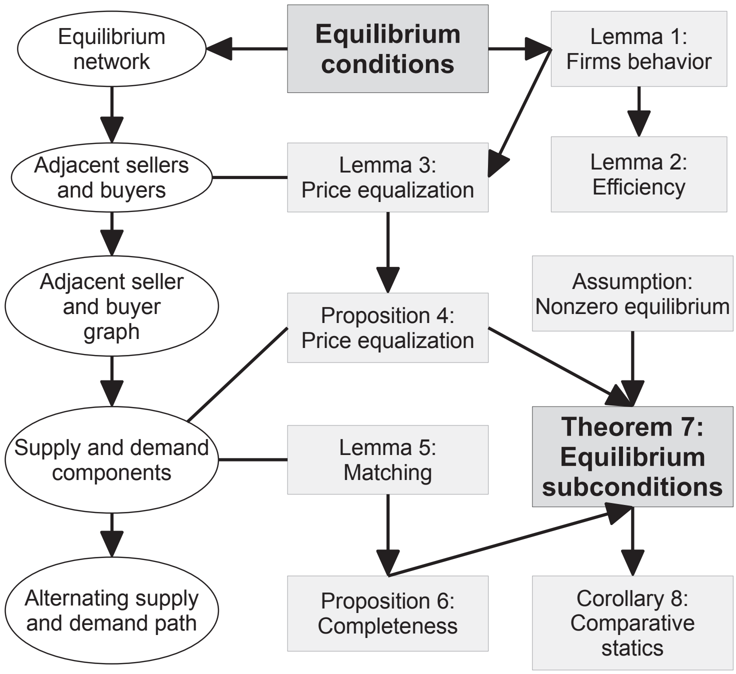
Consider a simplified setting where the market for cigars consists of two sellers, Cuba and Dominican Republic, and two buyers, USA and Canada. Assume for argument's sake that Cuban and Dominican cigars are substitutes. Suppose Canadians can buy both Cuban and Dominican cigars but US residents can buy only Dominican cigars. Now, Cuba and Dominican Republic are adjacent sellers as they both sell to Canada, hence they are members in the same supply component. Similarly USA and Canada are adjacent buyers as they both buy from Dominican Republic, hence they are members in the same demand component. The supply and demand components are matching. Theorem 3 states that USA, Canada, Cuba and Dominican Republic share, in practice, a common cigar market, where market price and quantity is jointly determined by demand from USA and Canada and supply from Cuba and Dominican Republic.

According to Corollary 1, the decrease in supply in one member of the supply component, Cuba, would increase price in all members of the matching demand component, including USA.

The rationale behind this effect is as follows. The decrease in Cuba's cigar supply would increase scarcity in the Canadian cigar market, allowing the Dominican suppliers to sell at a higher price. As US residents are competing for the same Dominican cigars as Canadians, they also would have to pay a higher price. Hence, a negative supply shock in Cuba has raised the price of cigars in USA.

4.E Outline of the theory

To help the reader, the following map outlines the structure of the theory and new concepts defined in this paper. The theory starts from the equilibrium conditions and leads to our main result in Theorem 3. The oval nodes depict the key concepts which we define and use to present the theory.



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