THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

# Agents, auctions and interactions: Modelling markets for ecosystem services and renewable energy

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CHALMERS UNIVERSITY OF TECHNOLOGY
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**Abstract**

If we are to mitigate climate change and tackle other pressing environmental issues such as biodiversity loss, environmental policies will be crucial. The papers in this thesis all focus on how individual behaviour and lack of information affects the outcome of environmental policy, using agent-based models where individual actors and their behaviour are explicitly modelled.

In paper I-III the focus is to compare an agent-based modelling approach with a partial equilibrium model in a framework of land-use competition between bioenergy and food crops. The agent-based model, where landowners are uncertain about price levels at the time of harvest, exhibits unstable dynamics that provides insights beyond the partial equilibrium model. This type of dynamics is typical of cobweb models, and paper I-III extends the cobweb literature by introducing markets that are interlinked through land use competition, showing how instabilities can be transferred from one market to another. The system can be stabilised, for example, by allowing a share of the actors to have perfect information of the upcoming prices.

Paper IV focus on payment for ecosystem services programs, where landowners are given monetary compensation to let their land provide an ecosystem service. The paper uses an agent-based model to explore the performance of different program designs, such as fixed payments, a uniform auction and a discriminatory auction, in differing circumstances. The main finding of the paper is that the context in which the program is implemented has a determining impact on what the best policy design is.

Paper V is centered around the allocation of subsidies for onshore wind power through auctions in Germany 2017. In these auctions a special design was used where some winners were awarded their submitted bid, while others were awarded the highest winning bid. In the paper, the specific choice of design and how it may incentivise aggressive bidding is discussed along with an analysis of the outcomes of the German auctions.

**Keywords:** Agent-based modelling, Environmental Policy, Land-use competition, Cobweb model, Market interactions, Bioenergy, Payment for Ecosystem Services, Auctions, Auctions for renewable energy, Renewable Energy

# List of publications

I. Liv Lundberg, Emma Jonson, Kristian Lindgren, David Bryngelsson and Vilhelm Verendel, “A cobweb model of land-use competition between food and bioenergy crops”, *Journal of Economic Dynamics & Control, 53:1–14*, (2015).

   KL had the idea, LL, EJ and KL performed the modeling with contributions from DB and VV. KL, LL and EJ analyzed the results with contributions from DB and VV. LL and EJ wrote the paper with contributions from KL.

II. Emma Jonson, Liv Lundberg and Kristian Lindgren, “Impacts on stability of interdependencies between markets in a cobweb model”, *Advances in Artificial Economics, 1:195–205*, (2015).

   EJ, LL and KL had the idea, EJ suggested modelling approach while LL implemented the model. EJ and LL analyzed the results and wrote the paper, both with contributions from KL.

III. Kristian Lindgren, Emma Jonson and Liv Lundberg, “Projection of a heterogeneous agent-based production economy model to a closed dynamics of aggregate variables”, *Advances in Complex Systems, 18.05n06*, (2015).

   KL had the idea and developed the model. KL, EJ and LL implemented the model and analyzed the results. KL wrote the paper with contributions from EJ and LL

IV. Liv Lundberg, Martin Persson, Francisco Alpizar, Kristian Lindgren “Context Matters: Exploring the Cost-effectiveness of Fixed Payments and Procurement Auctions for PES", *Ecological Economics, 146, 347-358*, (2018).

   LL, MP and FA had the idea. LL developed and analyzed the model, with comments from KL and MP. LL and MP wrote the paper with comments from KL and FA

V. Liv Lundberg “Auctions for all? Reviewing the German wind power auctions in 2017", Under review, *Energy Policy*, (2018).

## Relevant publications not in this thesis

Emma Jonson, Christian Azar, Kristian Lindgren, Liv Lundberg "Exploring the competition between variable renewable electricity and base load capacity", *Energy Systems, 1-24*, (2018).

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Göteborg, November 2018
Liv Lundberg

# Contents

# Chapter 1

# Introduction

*Our planet is a lonely speck in the great enveloping cosmic dark. In our obscurity, in all this vastness, there is no hint that help will come from elsewhere to save us from ourselves. The Earth is the only world known so far to harbor life. There is nowhere else, at least in the near future, to which our species could migrate. Visit, yes. Settle, not yet. Like it or not, for the moment the Earth is where we make our stand.*
Carl Sagan, Pale Blue Dot: A Vision of the Human Future in Space

In the last century human population has grown from under two, to over seven billion people. Primary energy use has increased tenfold from 50 EJ/year to over 500 EJ/year (Roser and Ritchie, 2018a; Smil, 2016) and agricultural land-use has risen from below 3 billion hectares to close to 5 billion hectares (Roser and Ritchie, 2018b; Goldewijk et al., 2017). There have been technological, scientific and medical advances that have raised hundreds of millions of people out of poverty and saved other millions from previously fatal diseases.

At the same time, the progress has been coupled with environmental degradation that threatens the foundations for our subsistence. Ever since the industrial revolution, coal, oil and gas have been the fuels propelling development and economic growth. Today, over 85% of the primary energy consumption in the world comes from coal, oil and gas (Roser and Ritchie, 2018a) and this dependency on fossil fuels is the main driving force of climate change.

While climate change gets the most attention from media, it is not the only environmental problem with huge impacts for life on earth. Today human activity and interference with ecosystems are causing an unprecedented rate of species extinction and loss of biodiversity (Assessment, 2005; Steffen et al., 2015) . The oceans are struggling with acidification, pollution and warming (Stocker et al., 2013; Haward, 2018; Visbeck, 2018). In many countries, and especially in fast growing economies like India and China, air-pollution causes health effects that impacts millions of people every year (Cohen et al., 2017).

While these problems may paint the picture of a very dark future, there are also positive trends. In just the past ten years, the global installed capacity of solar photovoltaic (PV) has grown with a factor of almost forty. The cost of wind power has gone down to levels where it is competitive with fossil fuel power plants (Sawin et al., 2017). There are also environmental problems, such as ozon depletion, that to a large extent have been solved. These trends have not appeared out of thin air. They have been made possible by environmental policies.

Environmental concerns started to enter the current fields of economics and policy making in the 1960's – a time that is often also referred to as the birth-time of the modern environmentalist movement, sparked by Rachel Carson bestselling book "Silent Spring" from 1962 (Pearce, 2002). Today there is a multitude of environmental policy designs but regardless of whether it is through marked based instruments, such as taxes and subsidies or through other types of policies, such as information campaigns or direct regulation, the aim of environmental policies is to steer the behaviour of actors in society. In market-based instruments, that are increasingly popular, this is done through economic incentives. In economic theory it is often, implicitly, assumed that individuals are rational and have access to perfect information. However, in reality, people may not always be rational and crucial pieces of information might be missing at the time when decisions has to be made.

## 1.1 Thesis outline

Lack of perfect information and how it can impact the outcomes of environmental policies, is a central part of this thesis. It is an important component in all five papers, but in slightly different ways.

Paper I-III are framed around the question of land-use competition between crops for bioenergy and food production, but their focus and main contribution lies in exploring the interactions between different markets when actors lack information about future prices and how this causes price fluctuations.

The lack of information that is important in paper IV is on the end of program officials who want to incentivise landowners to provide an ecosystem service by offering economic compensation. As the landowners are more likely to know the cost of letting their land provide the service, there is an information asymmetry between the program officials and the participants, which can make it hard to set an appropriate payment level. Paper IV is focused on how this asymmetry can be reduced, and efficiency improved, by the introduction of auctions. In an auction the participants submit bids for how much they want to be paid to provide the service - and thereby disclose their private information about the cost.

In paper V the focus is on the allocation of subsidy payments to producers of electricity from wind power through auctions. The paper revisits the auction framework from paper IV, but here a second layer of information deficiency emerges. In paper IV it is assumed that the landowners have perfect information about their costs (whether this always is the case in the real world may however be discussed). In auctions for renewable energy, participants bid for projects that may not be finished until years later, and since costs of solar and wind power are decreasing rapidly it is hard to know what the actual cost of the project will be at the time of the bidding. This lack of information, in combination with the auction environment with competitive bidding, may drive participants to submit bids that are so low that they end up being unprofitable.

The main method, that is used in all five papers, is agent-based modelling where individual actors and their behaviour can be explicitly modelled. The first three papers are centered around developing and exploring an agent-based model and comparing it to a partial equilibrium model (where rationality and access to perfect information is implicitly assumed). In paper IV an agent-based model is used together with a literature review of payment for ecosystem services programs that uses auctions. In the last paper the focus is mainly on analysing auctions that took place in Germany 2017 and to provide a theoretical discussion on the specific auction design that was used, but the paper also uses an agent-based model to illustrate the hypothesis put forward in the theoretical discussion.

## 1.2 Aim and scope

As the papers in this thesis touch up on quite different topics and range from a conceptual and methodological focus in paper I-III, to a more applied perspective in paper IV and V, it is hard to summaries their aim all at once. To facilitate reading, the papers have been grouped in to two sections: the "cobweb papers" (paper I-III) and the "auction papers" (paper IV-V).

Paper I-III use a combination of models with different structure, that describes the same system, to explore questions such as:

- Under what circumstances do agent-based models yield the same results as a partial equilibrium model? What are critical assumptions?

- How sensitive is the modelled system to perturbations?
- Which mechanisms may stabilizes and destabilises the system?

Paper IV-V are more applied and focused on evaluating the use of procurement auctions as part of environmental policy and they center around questions such as:

- When are auctions useful and appropriate to use? When are they not?
- What happens in auctions that deviate from the standard assumptions of actor homogeneity and rational behaviour?
- What have been the outcome of real life auctions for payment for ecosystem services (paper IV) and renewable energy (paper V)?

Despite their broad scope, the papers in this thesis are still connected by the methodology of agent-based modelling, and by the focus on how individual behaviour and lack of information affects the outcome of environmental policy.

Chapter 2

# Environmental policy

*'I've grown impatient with the kind of debate we used to have about whether optimists or the pessimists are right. Neither are right. There is too much bad news to justify complacency. There is too much good news to justify despair.'*
Donella Meadows, The state of the planet is grim. Should we give up hope?

*'You may be able to fool the voters, but not the atmosphere.'*
Donella Meadows, No Point In Waiting Around For Leadership

Environmental policy plays a role in all five papers of this thesis. The first three papers may not have a direct focus on policy, but their framing of competition for land between bioenergy and food production assumes that demand for bioenergy is significantly higher than today and it is likely that such an development would be driven by policies to promote renewable energy. Paper IV and V addresses environmental policies directly as they focus on auctions in payment for ecosystem services programs and for allocating subsidies for producers of renewable electricity.

There are numerous types of environmental policy instruments that can be classified in many different ways. Two categories that are often used are the separation of policies into "command and control" and "market based" instruments. An alternative classification, where more types of policy instruments fit in, is used in Sterner and Coria (2013) (based on (World and Bank, 1997)). In this classification system instruments are divided into categories based on whether they are "using markets", "creating markets", "environmental regulation" or "engaging the public". Policy instruments that are "engaging the public" are focused on providing information and engaging the public in environmental conservation. "Environmental regulation" is focused on bans (like the ban of DDT in the 1970's), standards (like the emissions standards that are currently used for vehicles in the European Union), or quotas. The focus on this thesis is mainly on instruments that are "using markets" (such as subsidies for renewable electricity production) and that are "creating markets" (such as payment for ecosystem services programs).

## 2.1 Policies for renewable energy

Today, about two-thirds of the world's greenhouse-gas (GHG) emissions come from electricity and heat production, industry and the transport sector (Birol, 2015). Therefore, when it comes to mitigating climate change, switching towards carbon-neutral energy sources is crucial.

At the end of 2016, 176 countries had targets for renewable energy (REN21, 2017) and in reaching these targets, policies for renewable energy has played, and most likely will continue to play, a crucial role.

### Taxes and Cap and Trade schemes

In economics, environmental issues are often framed as market failures, resulting from negative externalities. Externalities can briefly be described as unintended consequences of an economic activity that affects a third party who wasn't involved in the economic activity.

An example of a negative externality is the emission of $CO_2$ from power plants. These emissions are not the purpose of the process, but they are a side effect that will affect third party actors by contributing to climate change. Since the externality affects a third party and not the polluter, there is no incentive for the polluter to reduce the emissions. Imposing a tax on emissions is a way to internalise the costs of the externality and bring it into the profit equations of the polluter. If the exact cost imposed on the third party by the externality can be quantified (this is also known as the marginal social damage of the emissions) and is set as the tax level, this is known as a Pigovian tax. Estimating the marginal cost of damages to society from pollution is however often very hard.

When a tax is put on $CO_2$ emissions, it will become more expensive to produce electricity with coal power, as the producer in addition to other costs has to pay the tax, while the cost for producing electricity from wind power will be unaffected. In an electricity market, the introduction of a $CO_2$ tax may therefore shift which power source that is cheapest/most expensive. This is why taxes are classified as a "market using" instrument.

An alternative policy measure to limit pollution is cap and trade systems, which is an instrument that falls under the "creating markets" category. In cap and trade systems the governing body sets a cap on the amount of emissions that are allowed during a period. Polluters then need to have permits for all of the emissions that they emit and there is a limited amount of permits that corresponds to the cap. This way, a market is created where permits can be traded between firms and, as with a tax, a price is put on pollutions. The difference between a tax and a cap and trade system is that with a tax the government controls the price of emissions, while in a cap and trade system they control the quantity of emissions.

### Subsidies

An alternative approach to taxes and cap and trade schemes is to give economic subsidies to actors that are not polluting. Just as taxes are classified as "using markets" so are subsidies, but they work in the opposite direction. Using the example of electricity production again, introducing a subsidy instead of a tax in that system would mean that actors producing electricity from renewable energy sources would get financial aid, that the actors that produces electricity from fossil-fuels would not get. Subsidies can come in different forms but common types for renewable energy are subsidies for paying part of the investment cost, or guarantees that the producer will be allowed to sell electricity at a fixed price that is higher than the normal electricity price.

Adding a price on carbon in an electricity system with fossil fuel producers is likely to increase the electricity price, while giving a subsidy to producers without carbon emissions is likely to decrease it. If demand is elastic, changes in the price will impact demand, and thus it is likely that a price on carbon will lead to decreased electricity consumption, while subsidies have the opposite effect.

When it comes to cost-effectively transforming the energy system, putting a price on carbon is generally seen as the superior option by economists (Tietenberg, 2013). The focus on incentivising polluters to reduce emissions by penalty charges, puts the costs of pollutions on the actors that are contributing to them, which is often referred to as the "polluter pay principle". This is easily perceived as fair and with a general price on carbon, the incentive is to reduce emissions where it is most cost-effective to do so. The charges can also be a source of income for the government, while in the case of subsidies the government (or someone else) has to finance the subsidy. Yet, in the real word, there is no global price on carbon. Some countries, like Sweden, has a tax on carbon, and the European

Union has the Emissions Trading Scheme (putting a price on carbon through cap and trade) but there are few cases when the price has been high enough to have a significant impact. However, while the fight for putting a price on carbon has been slow and difficult, subsidies for renewable energy have slipped through the political landscape with much more ease.

When it comes to mitigating climate change, fossil fuel interests are often represented by large cooperations with substantial funds and political power to resist policies that will directly interfere with their profits, such as taxes, while they may put in less efforts to resist subsidies. Subsidising renewable energy has however lead to the growth of a strong industry that has its own interests in ensuring that renewable energy is promoted over fossil fuels (Meckling et al., 2017).

Another reason to use subsidies is to support new technologies, that are expensive and still not mature but that have the potential to drop in cost. This reasoning is based on the concept of learning curves (or experience curves) - that basically states that when an industry gains experience with a technology, costs goes down. By subsidising new technologies that would be unprofitable without the support, a market for the technology can be created, allowing the emergence of an industry around the technology. As the industry gains experience with the technology, technological development and competition between companies can start to push down the cost until it is low enough for the technology to be profitable without subsidies (Sandén and Azar, 2005; Wene, 2000).

Up until the last few years, one of the main arguments against solar and wind power has been their high investment costs. However, due to technological progress and learning effects their costs have dropped drastically (for solar PV modules the cost has decreased with an average of 10% per year since 1980 (Farmer and Lafond, 2016)). Today, the costs are so low that they sometimes are on par with, or even lower than, conventional fossil fuels when it comes to the levelized cost of electricity.

### *Feed-in tariffs and other subsidy schemes*

To date, one of the most successful and widespread policies when it comes to promoting renewable energy (especially solar and wind power), has been feed-in tariffs (FITs).

Policies to give producers extra compensation for producing electricity from renewable energy was used already in the 1980's in the US, but the policy structure that has become known as "Feed-in tariffs" was introduced in the Renewable Energy Sources Act in Germany 2000.

Feed-in tariffs are centered around the principles of having long term contracts (often 15-25 years) where the producers are guaranteed grid access and a fixed payment per kWh of produced electricity that is sufficient to cover costs (Couture et al., 2010; Mendonça, 2009). If the tariff is sufficiently high, technologies that are entitled to feed-in tariffs become safe investment options (Mitchell et al., 2006), and this has for example led to a strong interest in investing in renewable energy from pension funds (Schaps, 2016; FinancialNews, 2018; Rundell, 2018).

While feed-in tariffs can be highly beneficial to the producers of renewable electricity, they have to be financed somehow. How this is organised varies between countries. Funding can come from the government and be included in the national budget, which has been the case in for example the Netherlands, or it can be paid for by adding surcharges on top of the normal electricity price, as has been done in Germany (Couture et al., 2010). The later alternative has however led to complaints and concerns about increasing electricity prices.

Feed-in tariffs creates a dynamic where the producers of renewable electricity are removed from the electricity market - or rather, they are still contributing to the supply (and thus impacting the electricity price), but they are not themselves subject to market signals in the form of prices. When solar and wind power are introduced at a large scale, which today mainly takes place through policies such as feed-in tariffs, they produce "cheap" electricity whenever the sun is shining or the wind is blowing (due to their low running costs), pressing down electricity prices (Hirth, 2013; Sensfuss et al., 2008). As producers of renewable electricity are guaranteed grid access and get paid a fixed sum per kWh, they have no incentive to decrease production even when there is an excess of demand and prices are plummeting. Thus, when abundance of renewable resources coincides with low electricity demand and limited transmission capacity (so far this has mainly taken place with wind power), electricity prices can even turn negative (Fanone et al., 2013; Schaps and Eckert, 2014). Falling electricity prices at times when there is abundant electricity supply from renewable energy sources may be good news for consumers, but they are not popular among large scale power companies.

The cost of funding as well as the potential impact on electricity prices has been used to criticise feed-in tariffs and fuel calls for alternative policies that are more "market based". In the "Guidelines on State aid for environmental protection and energy" from the European Union in 2014, it is declared that the use of feed-in tariffs in member states shall be exchanged to market-oriented mechanisms, such as feed-in premiums, tradable certificates, or competitive bidding (from the Commission and others', 2014; Justice and Environment, 2014).

In feed-in premium schemes the participants receive a premium on top of the electricity price. The premium can either be fixed, or sliding –meaning that it depends on the spot market electricity price (Couture et al., 2010). The premium provides an extra income, but as it is put on top of the electricity price, the participants are not completely removed from the electricity market as in the case of feed-in tariffs.

Tradable certificates, which are also known as "Green certificates" or "Portfolio standards", is a mechanism where producers of electricity from renewable energy sources are awarded certificates when they produce a given amount of electricity (for example one certificate per MWh). The end consumers (or their suppliers) of electricity are then obligate to buy a certain number of green certificates (related to how much electricity that they use). The producer still sells the renewable electricity on the normal electricity market, but the certificates provides an extra income (Ringel, 2006). Tradable certificates are used in several European countries, such as Sweden, Norway, and the UK, and also in some states in the US. Compared to feed-in tariffs the revenues from certificates are not as safe and predictable for the producers of renewable electricity, since the price of the certificates varies with supply and demand.

Finally, there is competitive bidding, which is also known as tendering or "auctions for renewable energy", and for the interested reader this policy mechanism is discussed in depth in section 5.5 as it is the central theme of paper V.

## 2.2 Payment for ecosystem services (PES)

While about two-thirds of the world's greenhouse-gas (GHG) emissions come from sectors such as electricity production, industry and transport, most of the remaining part stems from agriculture and land-use change.

In addition to contributing to climate change, deforestation and land-use change are also a main cause of biodiversity loss. The 2005 Millennium Ecosystem Assessment report states that a substantial loss in the diversity of life on earth has taken place due to the past 50 years of rapid change of ecosystems caused by human activity (Assessment, 2005) and out of the nine planetary boundaries presented in Rockström et al. (2009); Steffen et al. (2015) "Rate of biodiversity loss" is one of the boundaries that is already passed and have reached the red "high risk" zone.

There is a huge variety of policies concerning land-use, forestry and nature conservation, including the creation of protected areas and natural parks, certification of products and direct regulation of forest governance. There are also large international programs such as REDD+ (Reducing emissions from deforestation and forest degradation) that was negotiated as a part of the United Nations Framework Convention on Climate Change. The focus here is however on the specific policy tool of Payment for Ecosystem Services (PES).

Payment for Ecosystem Services (PES), is based on the notion of voluntary transactions where landowners let their land provide an ecosystem service that is desired by an outside party, and is economically compensated for doing so (Wunder et al., 2005). The ecosystem service could be anything from carbon sequestration through reforestation, to wildlife conservation, watershed management or soil erosion prevention.

Originally, when the term "ecosystem services" was introduced by researchers in the late 1970's, the purpose was to increase public interest in biodiversity conversation through highlighting the values that are brought to society by ecosystems and the potential devastating consequences of loosing them.

In 1997, Costanza et al. attempted to put an actual monetary estimate on the services brought to humanity by ecosystems globally (the estimate in the article is 16-54 trillion US$ per year). Around the same time the concept started to be used in policy arenas, through projects and reports such as the "Ecosystem Approach", the "Global Biodiversity Assessment" and the "Millennium Ecosystem Assessment" (Gómez-Baggethun et al., 2010).

Today there are Payments for Ecosystem Services programs all around the world. Some are small scale programs conducted by non-governmental organisations, while others are huge governmental programs (Ezzine-de Blas et al., 2016). One example is the Conservation Reserve Program in the US, that in 2016, protected 23.8 million acres of agricultural land. Another example is the PES program in Costa Rica, that has been a part of the country's highly successful effort to decrease deforestation.

Even though PES programs have become popular, they have also been criticised. One criticism is that the concept of ecosystem services has an anthropogenic focus and promotes a world view where nature only is valued for its services and where humans are alienated from nature (Robertson, 2012; McCauley, 2006). Another criticism is that by introducing payments that are based on one or a few narrow features of the ecosystem that can be quantified, there is a risk that other important aspects are overlooked. When it comes to PES program participants, there are also concerns that paying for ecosystem services may crowd out voluntarily actions and that there may be a power imbalance between buyers and sellers of the services (Kosoy and Corbera, 2010). A lot of this criticism has been met in articles such as Schröter et al. (2014) and Wunder (2015).

Another part of the critique relates to whether PES programs actually provides additional environmental benefits (Pattanayak et al., 2010). How environmental additionally is affected by the design of the PES program, is discussed further in section 5.3.

# Chapter 3

# Methods

*"The Answer to the Great Question... Of Life, the Universe and Everything... Is... Forty-two," said Deep Thought, with infinite majesty and calm.*
*"Forty-two!" yelled Loonquawl. "Is that all you've got to show for seven and a half million years' work?"*
*"I checked it very thoroughly," said the computer, "and that quite definitely is the answer"*
Douglas Adams, The Hitchhiker's Guide to the Galaxy

With the fast development of computers during the last century, computer models have emerged as a highly popular tool to study systems with a large number of variables. For such systems, computer models offer the possibility to organise and process otherwise unmanageable amounts of data. They also enable scenario building where different possible future trajectories can be explored. These abilities, to structure and evaluate complex relations and mechanisms, have made computer models important tools for policy analysis.

Regardless of type, models are attempts at pinning down a messy and complex reality to a more comprehensible description, so that we can study it. The famous quote "Everything should be made as simple as possible, but no simpler" attributed to Albert Einstein, quite accurately describes the fine balancing act of model construction. Including too few or too general mechanisms will leave a model unable to make predictions about the reality it supposedly represents. Therefore, it may often be tempting to include as much as possible in a model in the hope of thereby making it an accurate mirror of reality. On the other hand, there is a risk that large complicated models become "black boxes" where no one can examine the assumptions that underlay the results. In the article, "A sceptic's guide to computer models", Sterman et al. (1991) recommends that computer models should be kept simple and used as pedagogical tools rather than as prediction instruments. This reasoning is echoed in Epstein (2008) where sixteen reasons to model, besides prediction, are presented. Köhler et al. (2015) takes it even further and suggests that there are times when a model should not be run at all, as sometimes, the important part of the process is not the output of the model, but the gaining and structuring of knowledge during the construction.

Computer models, that are based on micro-economic assumptions, are used in all of the papers in this thesis. The main focus is on agent-based modelling, which is explained and discussed in more detail in section 3.2. In the first three papers, the agent-based model is however compared to a partial equilibrium model of land-use.

## 3.1 Economic equilibrium models

Economists have for a long time been aware that behaviour of economic actors create patterns, that in turn influence the behaviour of the actors. So it might seem logical to study the patterns that economic agents create. But what if the agents are so many and diverse, and the feedback mechanisms so complex that this can not be done with the tools that we have? When economists started studying these questions, system science had not yet been properly introduced and there were no computers to facilitate the study of complex systems. So instead of trying to solve the unsolvable equations of a complex system, economists adopted a new approach. They started to ask, in what situation the system would be stable, and where no actors would have an incentive to change. By doing this it was possible to derive solvable equations, for which the solutions corresponded to the equilibrium of the system (Arthur, 2006). This is the basis for economic equilibrium models.

In partial equilibrium models, only a part of the economy is considered (often a single sector) and these models are often limited to a specific region of the world. All other factors are assumed to be exogenous, while the equilibrium between supply and demand for the specific good is calculated. Partial equilibrium models of land use, such as IMPACT (Rosegrant et al., 2005), allow for more detailed descriptions of land and its management. In contrast, general equilibrium models take the whole economy into consideration and finds prices and quantities that creates an equilibrium in the total economy.

Equilibrium models are often used in economics to evaluate policies. The nicely solvable equations do however come with a price, since they require great simplifications. In the models it is assumed that economic agents are homogeneous (or at most of two or three types) and that human behaviour can be described by mathematical expressions. In this context it has usually been assumed that economic actors are rational and have perfect information. Also, the world described by equilibrium economics is static and the theory does not explain how equilibria form. For some systems, these assumptions are sufficiently good, and then equilibrium economics can provide a valuable theoretical framework or a useful approximation. However, if the system contains dynamical aspects, or consists of not so rational actors, it might never reach an equilibrium (Arthur, 2006; Leijonhufvud, 1993).

## 3.2 Agent-based models

Many economic models are based on neoclassical economic theory, but there are also models that instead start from the actors in the system and simulate how their actions create macroscopic patterns. This kind of research has often been conducted in the field of complex systems and it has been used to study, for example, movement of bird flocks, traffic patterns and stock markets. Models simulating how autonomous actors behave and interact are generally classified as *agent-based models*. Agent-based models are used in all papers presented in this thesis.

Agent-based models have three basic components: agents, an environment and rules. The agents can represent persons, or larger entities such as companies or nations. The environment is the space in which the agents act, and it can be a geographical representation (such as a map) or something more abstract. The rules govern how the agents interact with each other and with the environment. Agents react to their environment and to other agents, and they can in turn affect the environment and other agents, just as described in Epstein and Axtell (1996): behaviour of economic actors creates patterns, which in turn influence the behaviour of the actors.

Agent-based modelling allows us to ask new kinds of questions. It makes it possible to study systems that are not in equilibrium as well as the formation of equilibria. The modelling of individual actors means that heterogeneity can be incorporated, but it also means that the notion of perfect rational behaviour, that is normally a prerequisite for neoclassical economics, can be dropped. Even though mainstream economics still adheres to many of these notions, the field has broaden towards complex systems, with the inclusion of research areas such as evolutionary game theory, experimental economics and behavioural economics (Fontana, 2010), where limitations to human "rationality" are emphasised in seminal publications such as Kahneman and Tversky (1979). This development, combined with the potential of agent-based modelling to incorporate features such as bounded rationality and heterogeneity, has made it an increasingly popular tool. In research of both land-use and energy systems, there is a vast literature based on agent-based models (Heckbert et al., 2010; Tesfatsion and Judd, 2006).

During the last decade, the use of agent-based modelling for studying land-use change has grown (Matthews et al., 2007; An, 2012). The agents in these models normally represent landowners, but they can also be larger institutions. The possibility to simulate relations and feed-backs between agent behaviour and the environment is a big advantage for agent-based modelling in land use studies. It is also possible to include explicit landscapes, using mapping technologies. Many studies focus on a specific area, and in these cases it is common that both the environment and the agent characteristics in the model are based on data gathered from field studies (d'Aquino et al., 2002).

### Agent-based models in paper I-V: Choices and limitations

In paper I-III an agent-based model of agricultural land-use is developed. The modelling approach is however different from common models in the field in the sense that there is no explicit geographical representation of land. The agents (representing landowners) do instead have heterogeneous qualities of land.

Paper IV also presents an agent-based model of land-use, but with the focus on nature conservation. In this model there is an explicit geographical representation of land and land-characteristics can be geographically correlated. The landscape is however computer-generated and not based on real land-data.

The agent-based model in paper V is of a renewable energy auction, so there is no landscape representation, but instead the agents have different expectations of the future costs and different economic conditions for building wind power plants.

In all of the models the behaviour of the agents is driven by economic reasoning. In paper I-III the agents chooses the production-type that maximises their estimated profit, and in paper IV and V the agents only take part of programs, or submit bids, that they calculate to be profitable. If you ask Adam Smith this might be a perfectly reasonable assumption, but if you ask a psychologist like Daniel Kahneman (one of the founders of the field of behavioural economics) he might have a very different opinion. What is reasonable may also depend on who the agents are representing. In some settings assuming that profit maximisation is a driving factor might be a perfectly reasonable approximation, while in others it might make the results completely irrelevant. The problem with replacing profit maximisation for the agents, is however what it should be replaced with. One could use decision heuristics from psychology or behavioural economics, or use a utility function that incorporates non-economic parameters - but in that case there is still the challenge of approximating what the value of those parameters should be.

An important thing to remember about agent-based models is that the foundations for the behaviour of the agents is decided by the modeller. Agents in the model will only behave as they have been coded to behave (possibly except in cases when evolutionary algorithms are used to adapt or evolve the behavioural rules) and so the model cannot be used to figure out human behaviour. It can however still be used to explore questions of the type: "if actors behave in this way - what will the outcome on an aggregate level be?".

Even though agent-based models provide new possibilities for studying complex environmental and societal systems, they are not without flaws and limitations. As all models, agent-based models can struggle with balancing what should be included or not, and with problems of finding reliable data. Another critique is that it can be difficult to follow and understand the processes of agent-based models, and that the models are hard to validate against empirical data (Tesfatsion and Judd, 2006). To facilitate for readers to compare and understand the processes in agent-based models, Grimm et al. (2006, 2010) suggested the use of the ODD-protocol to describe agent-based models. The protocol consists of three larger blocks: Overview, Design concepts, and Details (ODD), that are subdivided into seven elements: Purpose, State variables and scales, Process overview and scheduling, Design concepts, Initialization, Input, and Sub-models. Together this creates a coherent framework for how the model is structured, that should be possible for a reader to understand and follow. The ODD-protocol is not explicitly used or mentioned in the papers of this thesis, but the structure in which the agent-based models are presented is still similar to, and contains the elements of, the ODD-structure.

# Chapter 4

# Cobweb models

*Oft expectation fails, and most oft there where most it promises.*
William Shakespeare, All's Well That Ends Well

*Markets love volatility.*
Christine Lagarde, Managing Director of IMF

Agricultural systems are highly dynamic, and the prices of agricultural commodities can vary significantly, both over time and space.

Even though markets may love volatility (as quoted from Christine Lagarde, the current Managing Director of the International Monetary Fund, IMF), most people do not. In developed countries, changes in the price of staple foods, may go almost unnoticed. For poor people, in low-income countries, that spend a large share of their income on food, changes in staple food prices can be devastating. On a societal level, the strain of increasing food prices in developing countries, may contribute to starvation, increased poverty and social unrest, (Ivanic and Martin, 2008; Bellemare, 2015).

The basis for price variations are fluctuations in supply and demand, which can occur when production decreases rapidly (due to weather, political events etc.), or when demand increases without production catching up. But the mechanisms behind food price fluctuations are often complex. Since food prices spiked in 2007-2008, several extensive studies, that examined the driving factors behind food price fluctuations, have been published (Persson, 2014; Trostle, 2011; Roache, 2010). Unsurprisingly, they found multiple factors that influenced the global increase in food prices. Weather is an obvious factor that has a strong impact on the supply of food crops and, as an example, Australia, a major exporter of agricultural commodities, suffered severe draughts in this period. Another, more long term factor is that, economic growth, especially in previous low income economies, such as China, has increased the demand for meat. This has in turn increased the demand for feed products, putting more pressure on global agricultural markets. The trend of increasing demand, in combination with low supply and policy changes led to that grain stocks were unusually low around 2007-2008 and Piesse and Thirtle (2009) argues that this was the most important factor behind the price spike. Global food prices are also impacted by exchange rates (especially from the U.S. dollar), oil prices (increasing transport costs) and policy interventions, such as export bans and tariffs. Financial speculation in agricultural markets, with trading in futures, also has an impact on prices. Whether this impact is stabilising or actually increases price volatility is however disputed. Finally, as mentioned in the beginning, the increased demand for bioenergy in recent years influences the supply of agricultural commodities and may drive up global food prices (Trostle, 2011; Roache, 2010; Persson, 2014).

## 4.1 The cobweb model and the role of expectations

As noted above, there are multiple external factors that can influence food prices, both in the short and in the long run. However, there are also destabilizing factors that are endogenous to the agricultural system itself. Already in the 19th century, scholars noticed regularly recurring cycles in the production and prices of certain agricultural commodities (where one famous example is hog-cycles). To supporters of neoclassical economic theory this pattern was a nuisance, since theory at the time predicted that the systems should eventually reach an equilibrium. In the early 20th century a theory to explain the cycles started to emerge. The term "cob-web theorem" was first coined by Kaldor (1934) and further defined by Ezekiel (1938).

A common characteristic among agricultural markets is that there is a time lag between production decisions and realization (for example sowing and harvest), which causes short-run supply to be inelastic. Due to the time lag, suppliers have to base their production decisions on expected future market prices. There is however no guarantee that this expected price will be realized. Imagine that all actors on a market expect that the price of a certain commodity will be low the upcoming season (see $p_e$ in Fig. 4.1). There will then be less incentives to produce this commodity, so when it is time for harvest, there will be an under supply (see $q(t)$ in Fig. 4.1), pressing prices above the expected price (see $p(t)$

in Fig. 4.1). If the actors then expect that this higher price will be true also for the next season, this will result in an overproduction, pushing prices back down again, and so the cycle begins (see Fig. 4.1). The cobweb theorem states that the fluctuations will either converge, diverge, or fall in to a two-cyclic pattern, depending on the relation between the elasticity of demand and supply.

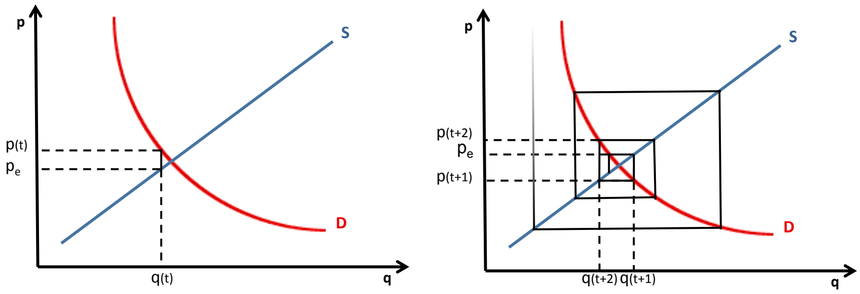



**Figure 4.1:** *Illustration of the cobweb theory. Important prerequisits of the theory is that there is a time lag between production decision and realization and that producers assume that the price at realization will be the same as the current price. In the first step of the illustration, producers expect that the price will be $p_e$ (which is slightly lower than the equilibrium price). This means that they will produce the quantity, $q(t)$ that corresponds to that price, on the supply curve. With quantity $q(t)$ on the market the realized price will be $p(t)$ (which is slightly higher than the equilibirum price). In the next period, producers assume that the price will still be $p(t)$, and therefore produce quantity $q(t+1)$, leading to price $p(t+1)$. So the cycle continues and in this illustration it diverges, causing larger and larger price fluctuations.*

If cycles could diverge, it would mean that price fluctuations would grow larger and larger. Taking this to its extremes, we would end up with explosive fluctuations requiring infinite production and infinitely high prices. This is, thankfully, not something that we observe in real markets, and the cobweb theory was already at an early stage criticized for this trait.

As a response to the critique, attempts have been made to modify and expand the scope of the model. The driving force behind the fluctuations in the original cobweb theory is that actors naively expect that prices will be the same as they were in the previous period. One of the earlier approaches to depart from the naive expectations was to introduce adaptive expectations among producers (Nerlove, 1958). Muth (1961) advanced the theory with the hypothesis that the actors' expectations of future prices will be consistent with the predictions of relevant economic theory, without any systematic forecasting errors. More recent studies, based on controlled laboratory experiments with human subjects, do however call this type of theories into question, since the human subjects only used different simple rules to guess future prices (Hommes, 2011; Hommes et al., 2007).

When the cobweb theorem was first presented it was built on equations, illustrated by graphs on paper. It explains endogenous fluctuations within markets in an elegant manner, but in its original form it only treats one commodity in a very specific setting.

## 4.2 An agent-based model of interacting cobweb markets: Paper I-III

Paper I-III in this thesis are centered around agent-based models with cobweb characteristics. The cobweb dynamics in the model stems from the delay between production decisions and profit realisations. The model is mainly centred around agricultural land-use and the question of land-use competition between bioenergy and food production, even though the model is generalised in Paper III to be valid for any system where actors have heterogeneous production capabilities and can choose between different production options. Commonly cobweb models only considers one market, but in these papers we extend the research on interacting cobweb markets, that was initiated by Dieci and Westerhoff (2010), by considering alternative goods that can be produced by the agents.

The papers is based on a micro-economic framework which is developed into both an economic equilibrium model and an agent-based model that has a bottom-up structure. The focus of the papers is to explore how different mechanisms (such as access to information) stabilise or destabilise coupled markets. The overarching research questions are:

- Under what circumstances do agent-based models yield the same results as the equilibrium model? When does it not?
- How sensitive is the system to perturbations?
- How can the system be stabilised?
- How do modelling assumptions and structure affect the results?

The papers focuses on slightly different aspects of the system and their impact on price stability.

**Paper I** focuses on price expectations, costs of switching crop and inertia in the crop switching rate.

**Paper II** focuses on the effects of introducing more crop types that are interlinked also on the demand side.

**Paper III** has two main contributions: generalising the model to non-agricultural settings and introducing regions with trade.

### *The model*

The following section provides an outline of the basic version of the model (as presented in Paper I). The extensions to the model are presented, in brief, in the paper sections. The model is of a land-use system where land quality is graded on a continuous scale. Each farmer has a given quality of land, $y_k$ and can choose between producing one out of three generic crop types, or to leave the land idle. The crop types are: intensively produced edible-type and forage crops (IP), extensively produced permanent pasture and forage crops (EP) and bioenergy crops (BE). The landowners in the model are assumed to be profit-maximising and in each time step they calculate the expected profit for the three crops and choose the crop with the highest expected profitability, or if all profits are negative, leave the land idle. The profit for crop $i$ for agent $k$, that has land quality $y_k$ is described by equation 4.1:

$$\pi_i(y_k, p_i) = (p_i - \beta_i)\eta_i y_k - \alpha_i \tag{4.1}$$

where $\alpha_i$ is the area-dependent cost (for things such as tillage and capital equipment etc.), $\beta_i$ are harvest-dependent costs (such as pesticides, fertilisers, etc), $\eta_i y_k$ is the expected yield for growing crop $i$ on land with quality $y_k$, and $p_i$ is the expected price of crop $i$ at harvest. For the structure of the model, the most important parameter in this equation is the expected price, $p_i$. All the other parameters are assumed to be static and known, but $p_{i,t}$ is a function of the quantity of crop $i$ at the time of harvest, and thus unknown to the farmer at the time when the production decision is made. This lack of knowledge is what drives the cobweb dynamics. In the *naive* version of the model, all land-owners assume that the price will be the same as in the previous year, and due to the cobweb dynamics explained above, this causes the model to be highly volatile.

As stated above, one of the research questions is how the system can be stabilised and in the model there are two main mechanisms that reduces volatility.

One of them is the crop switching rate, $\gamma$, that represents the fraction of the agents that are allowed to switch production each time step. The crop switching rate is a representation of inertia in real agricultural system and reluctance to switch production type. The other mechanism is improved information about the future price, by the introduction of *'rational'* agents, that have perfect information about the price at the time of harvest. The share of rational agents in the population is denoted $\rho$.

## 4.3 A cobweb model of land-use competition between food and bioenergy crops: Paper I

*Paper I introduces the model and explores the system on three different levels: the steady state where the sum of consumer surplus and producer surplus are maximised, which was presented already in Bryngelsson and Lindgren (2013), an aggregate dynamics model, where quantities can be described as a function of the quantities in the previous time-step, and finally the agent-based model, where the choices of individual land-owners are modeled.*

The steady state model shows what the price and quantities produced would be in equilibrium. The aggregated dynamics model introduce time into the model and allows for a deeper analysis of the stability characteristics of the system. In its simplest form, the agent-based model can be aggregated into the closed quantity dynamics, but when agents are allowed to dynamically choose between prediction methods or when a cost for switching production type is introduced, this can only be captured by explicitly modelling the agents.

The agent-based model, and the aggregated quantity dynamics model, are highly unstable and exhibits strong price fluctuations. The instabilities are transferred between the crop markets, since they are interlinked on the supply side by land-use competition. Through this, bioenergy demand affects food price volatility. Figure 4.2 shows the profitability for each crop type on the different land qualities. In the top left picture prices are 15% under equilibrium prices and the only crop that is profitable at all is the extensively produced permanent pasture and forage crops (EP). In the top right picture prices are in equilibrium and all three crop types are produced. In the bottom picture prices are 15% above equilibrium prices and bioenergy is the most profitable crop on a large portion of the land. These pictures gives an illustration of the volatility in the system and how relatively small changes in the price drastically changes what is most profitable to produce. They can also be used to understand the cobweb dynamics. If all agents would produce what was most profitable for them, in the top left picture only EP crops would be produced. This would lead to a huge shortage of IP and BE crops that would drive up their prices and an over-supply of EP crops that would press down this price. The next time step a lot of producers would choose to produce IP or BE instead of EP crops, which would lead to that the price of IP and BE crops would decrease and the price of EP would increase. And so the cycle goes on.

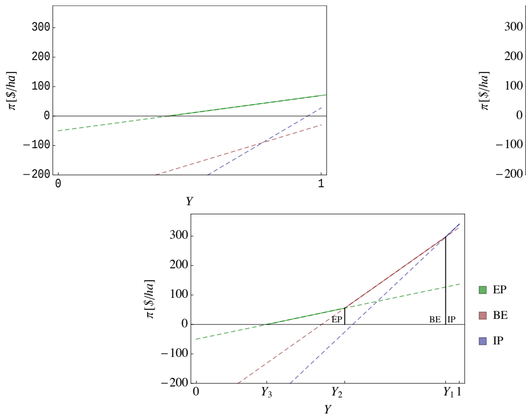



**Figure 4.2:** *Profitability for each crop type, on different land qualities, given that prices are* 15% *under equilibrium prices (top left), at equilibrium prices (top right) and* 15% *above equilibrium prices (bottom)*

Introducing "rational" agents with perfect information about the prices at harvest, can stabilise the system. The share of the actors that have to be rational for the system to be characterised by a stable state can be expressed by the inequality:

$$\rho > \frac{1}{2} - \frac{2-\gamma}{2\gamma(-\lambda_1)}\ . \tag{4.2}$$

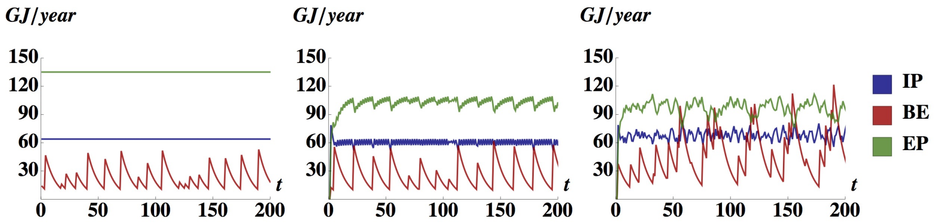
where $\gamma$ is the share of agents allowed to switch crop each time step, $\rho$ is the share of rational agents and $\lambda_1 > 0$ is a parameter that depends on the other system parameters, expressing the instability of the original system. The inequality shows that when more than 50% of the agents have perfect information the system is always stable.

If the rational agents are homogeneously spread on the different qualities of land in the model, and as long as there is no transaction cost for switching crop, the agent-based model can be aggregated to a price and quantity dynamics. This means that there is a closed description with only quantities (and prices) as variables that determines the dynamics, with no dependence on the agent-based micro state. If agents are allowed to dynamically choose between using the naive prediction method or paying for using the rational predictor, the agents that were previously most affected by price fluctuations chooses to pay for the rational predictor. This enables the model to stabilise with a lower total share of rational agents.

## 4.4 Impacts on stability of interdependencies between markets in a cobweb model: Paper II

*Paper II focuses on the effects of introducing more crop types that are interlinked on the demand side.* The interlinkage on the demand side is based on consumer willingness to substitute goods, and it is characterised by a cross-elasticity of demand. This means that the demand and price of one good is dependent not only on its own supply, but also on the availability of other commodities. The generic crops in Paper I is changed to generic crop *categories*, that can contain more than one generic crop. This means that the agents chose among a larger number of crops in their decision of what to sow. The expansion of the number of crops and the inclusion of demand side linkages is done in order to asses how a larger number of crops affect the dynamics and stability of the model. The aim of the paper is to study potential destabilising effect of increasing the number of crops, and if this is counteracted by demand side substitutability.

Increasing the number of crops within each category, without any demand side linkage, has a destabilising effect on the system. This is illustrated in Fig. 4.3, where time series for the total quantities produced of the three different crop categories are shown. The increasing instability, with an increasing number of crops, is caused by the supply side linkage, and the fact that with more crop types within each category, the equilibrium quantity of each crop type is smaller, which is a destabilising factor (this is further explained in paper I). If the new subdivisions of crop types are interlinked on the demand side (through substitutability between goods), this has a stabilising effect. The stabilising effect of substitutability comes from the fact that the crops can act as "buffers" for each other.




(a) 1 crop per category (b) 2 crops per category (c) 4 crops per category

**Figure 4.3:** *Time series of the quantities produced, for different numbers of crop types within each generic crop category (intensively produced edible-type and forage crops (IP), extensively produced permanent pasture and forage crops (EP) and bioenergy crops (BE)), without any demand side linkage. In the first graph, (a), there is just one crop type in each of the three categories, in the middle graph, (b), each category contains two crop types, in the last graph, (c), there are four different crop types in each category. As is illustrated in the figures, increasing the number of crops within each category, without any demand side linkage, has a destabilizing effect on the system*

## 4.5 Projection of a heterogeneous agent-based production economy model to a closed dynamics of aggregate variables: Paper III

*Paper III focuses on the effects of introducing regional markets and trade. The paper also discusses the model features that makes it possible (or impossible) to project the agent-based model to a closed aggregated quantity dynamics.*

Even if agents are heterogeneous, both in production capacity and with respect to their strategy for predicting future prices, the model can be aggregated to the quantity dynamic level, where quantities can be described as a function of the quantities in the previous time-step. The aggregation is not possible if agents include previous choices in their production decision instead of relying solely on market prices.

In the regional market model, the world is divided into eight separate regions that are neighbouring to each other as illustrated in Fig. 4.4. All regions have the same demand for each of the crops, but they have different production capabilities, which is represented in Fig. 4.4, where the darker colours represent better production capability. The two middle regions (R4 and R5) have the highest production capability and the two outermost regions (R1 and R8) have the lowest. Two neighbouring regions can trade with each other to a cost of $C_T$. Trade takes place if the price difference between the regions otherwise would be higher than $C_T$.

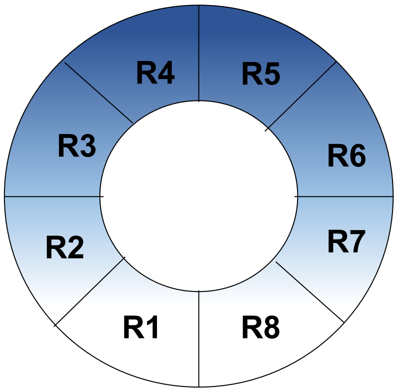



**Figure 4.4:** *Region 1 to 8. Two neighbouring regions can trade with each other to a cost of $C_T$. The colour of the region represent its production capability, and the darker the colour, the higher the capacity.*

When the transportation cost is low, the model works as in the basic setting. Production takes place where it is most profitable, which means that the bulk of the production takes places in the high capacity regions (R4 and R5) and that the quantities are then equally distributed among the regions, as can be seen in the two left frames in Fig. 4.5, that shows regional production, (top picture), and consumption, (bottom picture). If the cost of trade is high each region becomes more self-sufficient and the local commodity prices increases. Increasing the transportation cost also leads to larger price instabilities which, in the model, is driven by two factors. The first factor is that when trading is limited the regional markets can not act as buffers for each other in the case that a supply/demand shock hits one region. The second factor is that land quality within each region in the model is fairly homogenous, which means that the land-owners in that region have similar profit calculations. This means for example that if one land-owner judge bioenergy to be the most profitable crop this year, it is likely that the other land-owners in the region has the same idea and this homogeneity enhances the cobweb dynamics.

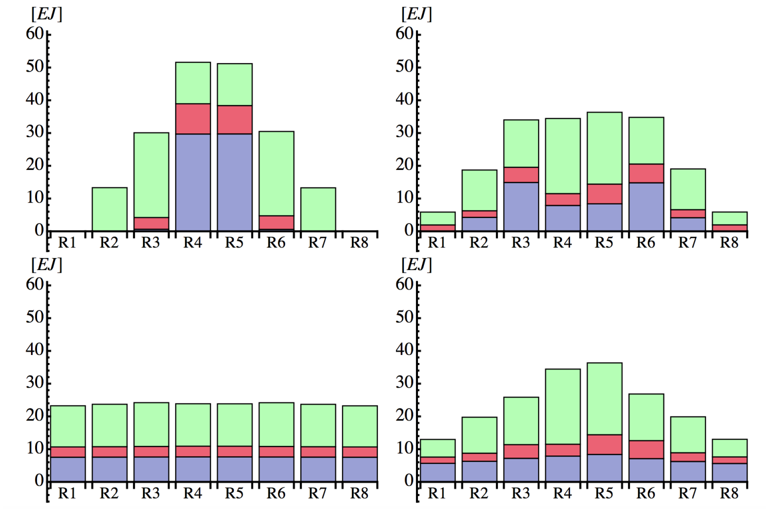



**Figure 4.5:** *A momentary picture of the harvested quantities in each of the eight regions (the top two pictures), and the quantities put on the markets (the bottom two pictures), when the transportation cost is very low (the left column) or high (the right column)*

## 4.6 Summary

The framework of land-use competition between food crops and crops for bioenergy described in Paper I-III, was originally introduced in Bryngelsson and Lindgren (2013). The work in this thesis started with the task of creating an agent-based model of the equilibrium model that was used in Bryngelsson and Lindgren (2013). What became apparent when the equilibrium model was transforming into an agent-based model, was that even minimal outer perturbations were enough to destabilise the system and cause violent fluctuations. This is one of the important lessons that can be drawn from paper I-III. Equilibrium models, that are broadly used to analyse many systems today, only tell that an equilibrium exist and what it is. They do not provide any information on the stability of the system. This does not mean that all equilibrium models are hiding highly unstable systems, but it means that we do not know anything about the stability by looking at the equilibrium.

It is worth mentioning that the agent-based model in paper I-III is a simplification of the real system and if more features were added, it may be less unstable. Applied equilibrium models, used for bioenergy assessments, generally have an extensive set of crops (see, e.g, Havlik et al. (2011)). Our original model only has three generic crops but in paper II the number of crops are expanded and demand side linkages is introduced, in order to asses how a larger number of crops affect the dynamics and stability of the model. A main conclusion that can be drawn from paper I and II is that interlinkage between markets, both on the demand and the supply side, is a crucial factor for system stability, and thus important to consider when constructing a dynamic model. Paper III considers trade between region, and even though the cost of trade in the model is called a transport cost, it may in reality be more realistic to view this factor as some sort of trade barrier. In the model lack of trade barriers leads to a more efficient allocation of production and consumption. There is also an environmental perspective to this since if less land is used for crop production it will decrease pressure to expand agricultural land into other areas, such as forests. Another advantage is that prices are more stable when crops can be traded on a global market, since the markets can act as bufferts for each other. It may however also be worth noting that in the global trade version of the model (when trade is free), almost no food is produced in the low capacity regions so they are highly dependent on import. This is not discussed in paper III, but it is of course a very vulnerable position to be in and one that many countries would try to avoid.

# Chapter 5

# Auctions

*"In 193 a.d., having killed the Emperor Pertinax, in a bold move the Praetorian Guard proceeded to sell off the entire Roman Empire by means of an auction. The winning bid was a promise of 25,000 sesterces per man to the Guard. The winner, Didius Julianus, was duly declared emperor but lasted for only two months before suffering from what is perhaps the earliest and most extreme instance of the winner's curse –he was beheaded."*
Vijay Krishna, Auction Theory

As can be noted from the auctioning of the Roman empire, auctions have been around for a long time. Today, emperor titles are not usually up for sale and the first thought that comes to mind when 'auctions' are mentioned might be obscure art objects, the bang of a gavel and 'sold to the lady in the back'. Auctions, though not always under that name, are nethertheless used for a large variety of purposes in modern society. For private citizens, the most obvious examples may be real estates deals and trading sites like e-Bay, but auctions are also used by businesses in for example procurement deals and commodity trade. Another important use of auctions are by government agencies, that have used auctions for purposes of allocating natural resources, such as mineral or oil rights, selling rights to electromagnetic bandwidth, selling long term securities or selling previously state owned companies to the private sector (Klemperer, 1999).

In the last decades, auctions have also entered the field of environmental economics and environmental policy instruments. One example of this is the use of auctions to allocate emission permits in the European Union Emissions Trading System (EU ETS), which was introduced in the second phase of the ETS (2008-

2012). In this phase only 10% of the permits where allocated through auctioning (the remaning permits were distributed through "Grand-fathering") (Hepburn et al., 2006), but in phase three (2013-2020) the anticipation is that the share will rise to about 50% (EuropeanCommission, 2018).

In the ETS, auctions are used to allocate permits to pollute, but auctions can also be used reversely, to allocate subsidies to investments that are deemed desirable for environmental protection. These types of auctions are known as procurement auctions, or multi-unit reverse auctions, and two examples are auctions in payment for ecosystem services programs and auctions for renewable energy.

In procurement auctions the participants submit bids for the amount of money that they want to be payed in order to take part in the program. There is normally a predetermined budget or quota (which could, in payment for ecosystem services auctions, be that a certain amount of hectares of land should be protected, or in renewable energy auctions that a given capacity of renewable energy should be installed) that decides how many of the participants that will be offered contracts. Then the participants with the lowest bids are offered contracts until the budget is exhausted or the quota is filled.

The purpose of this chapter is to give a background to, and overview of, procurement auctions for payment for ecosystem services and renewable energy. The chapter starts with a section that provides a brief, but general, overview of auction theory. It is followed by a section on auctions for payment for ecosystem services (Paper IV) and a section about auctions for renewable energy subsidies (Paper V). The last section provides some general points about procurement auctions and their pros and cons.

## 5.1 Auction types

Even though auctions has been used for a long time, the birth of modern auction theory is often attributed to the seminal paper published by William Vickrey in 1961. Depending on their purpose, auctions can be separated into different categories. The initial distinctions are whether the auction is for a single good (single-unit auction) or for multiple goods (multi-unit auctions), and whether the auctioneer is selling the good (normal auctions) or buying the good (reverse auctions). Examples of how auctions in environmental economics falls into these categories are provided in Figure 5.1. In the paper by Vickrey (1961) both normal single and normal multiunit auctions are treated.

Auctions can be designed in different ways, but for single unit normal auctions there are four major designs, that are presented in Vickrey (1961):

| | **SINGLE UNIT** There is only one winner in the auction. | **MULTIPLE UNITS** There are more than one winner in the auction. |
|---|---|---|
| **NORMAL AUCTION** **THE AUCTIONEER IS SELLING SOMETHING** Highest bid(s) wins | Auction selling the drilling rights to an oil field. | Allocation of emission permits through auctioning in the EU-ETS. |
| **REVERSE AUCTION** **THE AUCTIONEER IS BUYING SOMETHING** Lowest bid(s) wins | Auction for the right to build off-shore wind power plants at a specific location and receive a tariff for the produced electricity. | Auctions in payments for ecosystem services programs.<br><br>Auctions for determining and allocating subsidy payments to producers of renewable electricity |

**Figure 5.1:** *Examples of different types of auctions used in environmental economics sorted by category.*

- **English auction (also known as ascending auction)**: The typical art auction. The auctioneer starts at a low price, and then bidders cry out their bids and overbid each other until only one person is left with the highest bid, that they then pay for the object.

- **Dutch auction (also known as descending auction)**: Introduced in dutch flower markets. The auctioneer starts with a very high price which is then gradually decreased, until someone cries out, stopping the descent, and buys the item for that price.

- **Sealed bid first price auction**. All participants submit their bids at the same time in sealed envelopes so no-one knows what the other participants bids are. The one with the highest bid wins the item and has to pay their submitted bid.

- **Sealed bid second price auction (also known as Vickrey auction)**. All participants submit their bids at the same time in sealed envelopes so no-one knows what the other participants bids are. The one with the highest bid wins the item but only has to pay the price of the second highest bid.

For the general public, the english auction format is probably the most well known. However, in auctions for renewable energy and for payment for ecosystem services, sealed bidding, where participants are unaware of the other participants bids when they submit their own, is the norm and this is what the rest of this section will focus on.

## 5.2 First versus second price auctions

Looking at the academic literature on multiunit-auctions, a questions that researchers seems to come back to again and again is: "Should the auction be first or second price?"

So what does this mean? To answer that we have to, once again, go back to Vickrey (1961). In this paper Vickrey introduces the second price auction (which has later also become known as the "Vickrey-auction"), where the winner, instead of paying the submitted bid, only has to pay the second highest bid for the item. This might seem like an excellent idea for the winner, since he/she has to pay less, but why would any auctioneer of a sound mind use this rule? This is where auction theory meets game theory.

Assuming that participants would behave the same way in the two types of auctions, the auctioneer would get paid less in the second price auction. The rules of the auction does however affect the incentives of the bidders, which may cause them to act differently in the two auction types.

As a participant in a first price auction, your bid influences two things: the likelihood that you will win in the auction (the higher your bid are the higher the chans of winning), and how much you have to pay (the higher the bid the more you have to pay, and the lower the profit). A rational bidder who wants to optimise profit has to weigh these two factors and there is an incentive to submit a bid that is lower than the actual value, in order to increase profits. As shown in Vickrey (1961), under given circumstances (assuming that participants are risk neutral and that their value of the auctioned item can be described as drawn from a continious uniform distribution) the unique equilibrium bidding strategy $b_i$ for bidder $i$ is:

$$b_i = \frac{N-1}{N} v_i$$

where N is the number of bidders in the auction and $v_i$ is the bidders valuation of the item. This tendency to bid bellow the actual value of an item has come to be known as "bid-shading".

If you are instead bidding in a second price auction, your bid only directly influences the likelihood of you winning the auction. Bidding under your valuation of the item decreases the likelihood of you winning the item, without increasing your potential profit (since your bid does not impact how much you will have to pay for the item). Bidding above the value increases your likelihood of winning, but if you actually win and the second highest bid is above your value for the item you will have to overpay for the item. And, if the second highest bid is actually lower than your value, you would still have won even if you bid your true value. Hence, the equilibrium bidding strategy, in a second price auction is for participants to bid their true value of the item:

$$b_i = v_i$$

This is known as an incentive-compatible mechanism: the dominant strategy for all participants is to reveal their true value (preference) of the object. This is why second price auctions are popular among researchers.

What about auctioneers then? Won't they still get lower revenues in a second price auction? The theoretical answer, given the above stated circumstances, is *no*. In the simple form of second and first price auctions presented above, if participants bid according to the equilibrium bidding strategies, the expected revenues for the auctioneer will be the same for both auctions (the sellers loss from only getting paid the second highest bid in the second price auction is matched by the bid-shading causing over all lower bids in the first price auction), which was shown already in Vickrey (1961). This example is a special case of the "revenue equivalence theorem" that in its more extensive form was proved by Myerson (1981) and Riley and Samuelson (1981). The very essence of the theorem as quoted from Engelbrecht-Wiggans (1988), who extended the theorem to multi-unit auctions, is that: "the differences in how bidders bid in response to different pricing rules offsets the differences in the rules themselves".

In the 1961 paper Vickrey also discussed the auctioning of multiple goods by sealed bids and he outlines, though not by their currently most common names, the two main designs of multi-unit auctions, where multiple identical items are sold. The first auction design is today referred to as a discriminatory auction, pay-as-bid auction, or multi-unit first price sealed bid auction. The basic outline is that if $K$ items are sold, the $K$ highest bids win and they have to pay their submitted bid for the item. This is the multi-unit version of the first-price sealed bid auction. The other alternative is a uniform pricing auction (or just "uniform auction"), which is the multi-unit version of the second-price auction. In the uniform auction, the $K$ highest bids will still win, but they only have to pay the lowest winning bid, or the first-rejected-bid (depending on how the auction is designed). If winners only have to pay the first-rejected-bid the equilibrium bidding strategy will be the same as for the single unit second price auction: to bid truthfully. If the winners have to pay the lowest winning bid, their bid could still affect their revenues and thus the logic behind truthful bidding no longer holds (even though, their incentives to shade their bids are likely lower than in a first price auction).

The advantages of a uniform pricing auction is that if all participants are bidding truthfully, the goods are guaranteed to be allocated to the bidders who truly value them the most. And as pointed out by Vickrey, if the optimal strategy is to bid truthfully, regardless of what other bidders do, it can also save bidders from wasting time and money on doing market research to try to find out what others might bid.

So far this section has focused on "normal" auctions where the auctioneer is selling one or several items, but both auctions for renewable energy and payment for ecosystem services are multi-unit reverse auctions (also known as procurement auctions). The multi-unit auction types described above does however work just as well for reverse auctions, with the only difference that instead of submitting bids for how much they are willing to pay for the auctioned good, the participants submit bids of how much money they want to receive in order to comply with the program rules. The auction is used to find the actors who are willing to provide the service for the lowest cost and so the participants with the lowest bids are selected as winners. In a discriminatory auction this means that the K participants with the lowest bids are selected and then payed their asked bid. In a uniform auction the participants with the lowest bids will win as well, but all of the winners will be paid the first rejected bid (or the highest winning bid). If the participants are paid the first rejected bid the incentive is the same as in the normal uniform auction: to submit a truthful bid.

Coming back to the question that started this section "Should the auction be first or second price?", using the revenue equivalence theorem it may seem as though it wouldn't matter for the outcome of who wins in the auction or for the finances of the auctioneer. However, firstly the revenue equivalence theorem is only valid under certain circumstances and secondly it assumes that participants are behaving rationally and adjusts their bid to the auction environment that they are in, which in reality may not be the case.

## 5.3 Auctions in Payment for ecosystem service programs: Paper IV

Auctions in Payment for ecosystem services (PES) programs can be either discriminatory or uniform, but currently most PES programs are not using auctions at all, but fixed-payments. In a meta-study by Ezzine-de Blas et al. (2016) only seven out of the 55 studied PES schemes worldwide used auction mechanisms to allocate payments. The most noteworthy of those is the Conservation Reserve Program (CRP) program in the US that has been using auctions since the 1980's. Apart from the CRP, most of the programs that have used auctions have been trials or field experiments. In the late 1990s and early 2000s auctions were tried in Australia, Scotland and Germany by governmental programs, but these were not continued. In the late 2000s auctions has been used in small scale experimental field trials in developing countries such as Indonesia, Kenya and Malawi.

One of the reasons for why auctions have been suggested as a way to distribute payments in PES programs is to improve efficiency. In PES programs there is often an information asymmetry between landowners and program officials. The landowners are likely to better know the cost of providing the service, which can let them extract information rents by receiving higher payments than needed for participation. Information rents leads to fewer contracts being awarded and thus decreases the impact that the program can achieve for a given budget (Ferraro, 2008). A way to decrease information rents is to switch from fixed-payments programs, where all participants are paid the same amount, to auctions, where landowners themselves submit bids with the sum that they want to be paid in order to provide the requested ecosystem service. Contracts are then awarded to the participants with the lowest bids.

Even though auctions can increase efficiency by reducing information rents, there may also be problems of "adverse selection". Adverse selection means that landowners that would have provided the services also without payments self-select in to the program (Persson and Alpízar, 2013; Arnold et al., 2013) or that landowners whose land only provide low grade ecosystem services are selected. An important factor when it comes to the risk of adverse selection is the "baseline compliance" among landowners.

Baseline compliance is how likely the landowner is to let their land provide the desired service without being paid and it is something that is hard to target for or avoid. There might however be a correlation between the baseline compliance and the type of activity that is promoted/discouraged. Activities in PES programs can be divided into activity restricting and asset-building. Asset-building services are actions that has to be actively taken by the landowner –to change the status quo. Examples of this is reforestation or investments in new cleaning technologies for water. In these cases the landowner has to make an investment, that will cost money. Activity restricting actions on the other hand are services where the landowner is asked to refrain from doing a certain thing – to maintain the status quo. A clear example of this is programs targeting deforestation where landowners are paid to not cut down the forest on their land. Here the landowner does not need to pay anything, but is forgoing profits from not being able to sell the wood or using the land to grow crops that can be sold. Economically they may be similar, but looking at it from the point of a landowner (or through behavioural economics theory), asset building activities means that you have to put up money for an investment, which means that you will have less in your bank account, while when you just refrain from an activity, you miss out on a potential profit, but no money disappears from your account. This is an argument for why asset building services might be likely to have a lower baseline compliance (landowners are unlikely to do them unless incentivised to do so), while activity restricting activities may have a higher baseline compliance rate.

A way to avoid adverse selection, where landowners whose land only provide low grade ecosystem services are selected, is to use an environmental benefit index, where the index is a rating of how valuable the particular land plot is to conserve. As an example, imagine two land plots considered for wildlife conservation where one contains pristine rainforest, while the other is wasteland. Without any specific targeting any of the plots could be accepted into the program, but if an environmental benefit index was used the land-plot with the rain forest would get a higher score, and thus be prioritised into the program. Environmental benefit indexing can be used both in fixed-payment programs and in auctions. In auctions contracts are then awarded to the participants with the highest environmental benefit index score per asked payment.

### Paper IV: Context Matters: Exploring the Cost-effectiveness of Fixed Payments and Procurement Auctions for PES

*In Paper IV an agent-based model is used to compare the effectiveness of the following PES program designs: fixed payments, uniform auctions and discriminatory auctions, under differing circumstances.*

In Paper IV the effectiveness of fixed payments, uniform auctions and discriminatory auctions are compared, but under different circumstances, using an agent-based model. The agents in the model are landowners who are interested in taking part of a PES-program. The agents have three determining characteristics: their cost of providing the ecosystem service, the environmental benefit of their land, and their baseline compliance (which is a function of the cost). If the program is a fixed-payment scheme the agents will apply to the program if the payment level is equal to or higher than their cost of providing the ecosystem service. If the program is an auction, all agents will apply to it, and in the basic version of the model they will submit a bid equal to their cost of providing the ecosystem service.

One of the circumstances that is explored in the paper is the correlation between costs of provision and environmental benefit i.e. if land that has a high costs of provision (due to for example its good agricultural qualities, or proximity to a city) also provides high quality ecosystem services (by for example hosting a lot of wildlife) and vice versa (low quality land is inexpensive to protect), if there is no such connection, or if the connection is even the opposite (land that is cheap to protect also provides the best ecosystem services). A result from the paper is that if land with high ecosystem service values also is the most expensive to protect, it becomes much more important to include an environmental benefit index when applicants are evaluated (regardless if the payment levels are fixed or determined by an auction).

Another factor that is explored in the paper is the effect of the baseline compliance among program participants. Payment for ecosystem service programs are more effective if they are targeted towards services where baseline compliance is low, meaning that there is only a low chance that the landowner would provide the service without getting paid. We find that if programs have to be targeted to ecosystem services that are likely to be provided also without landowners getting paid, fixed payments where applicants are ranked and accepted based on an environmental benefit index score is preferable, even to auctions.

Even though an ecosystem value score can increase the ecosystem service provision of the program, it also comes with a trade-off if the program budget is limited and high ecosystem value scores are correlated with high provision costs, since prioritising participants with high ecosystem service provision will cost more and thus leave room for fewer participants. If the program aim is dual and focuses on both ecosystem service provision and poverty alleviation this may not be desired.

In the last part of the paper a table with a summary of the pros and cons of discriminatory auctions, uniform auctions, fixed payments, and using environmental benefit indexing is supplied, together with a simple decision scheme that can be used as a guide in the design of PES programs. The table and the decision scheme are based on a combination of knowledge from the literature, including both theoretical and case studies, and results from the agent-based model. To summarise it, the main conclusion of the paper is that context is highly important when choosing a program design for payment for ecosystem services: under some circumstances auctions may be most effective, while in others it might be fixed payments.

## 5.4 Independent private value auctions, common value auctions and the winners curse

Apart from the question of "first versus second price auctions" (or when the auction is multi-unit: discriminatory versus uniform auction), that is very present in paper IV, another research area that has kept auction theorist busy over the last decades are independent private value auctions and common value auctions. Unlike first and second price auction that are auction designs, chosen by the auctioneer, private and common values relates to the types of goods that are auctioned and it is not something that the auctioneer can impact (except by choosing what things to auction).

The early literature, such as Vickrey (1961), mainly studied independent private value auctions. In independent private value auctions the participants knows what their value of the auctioned object is and their value is independent of the other participants valuations. They do not know how other participants value the object. Auctions in PES programs have many characteristics of independent private value auctions, as the cost of providing the ecosystem service will differ from landowner to landowners and the owner is likely to best know this cost.

In a pure common value auction, the participants do not know the true value of the object but they have individual price signals representing their estimates of the value. However, the ex-post value is the same to all bidders once it is revealed. A real example of this is auctions for oil drilling rights. Before the auction none of the participating companies knows for sure how much oil there will be in the area, or even at what price it will be possible to sell the oil, thus the ex-post value is unknown. All companies taking part in the auction will try to make an estimate of the value, which they will then use to determine their bids. A more hypothetical, but very illustrative example, is of a professor auctioning a jar or coins to a class of students. The students are invited to try to guess the total value of the coins in the jar and submit bids for how much they are willing to pay for the jar. Ones again, the ex-post value is unknown at the time of the bidding, but the value will be the same to whoever wins the jar and actually collects the coins.

While the distribution of bids in an independent private value auction will be based on the different values that the bidders has for the auctioned item, the bid distribution in a pure common value auction will be based on the estimates of the ex-post value. If the distribution of value estimates are centered around the real ex-post value, this means that some of them will underestimate it, while others will overestimate it. However, in a (normal) auction the one who submit the highest bid wins. This means that if you overestimate the ex-post value, you are likelier to win the item and the consequence of doing so is that you will have to pay more for the item then what it is actually worth. This is something that has become known as "The winners curse". It was mentioned already in the quote in the beginning of this chapter, where the unfortunate Didius Julianus bought Rome in an auction, but wasn't able to properly pay for it and ended up beheaded. Or as Thaler (1988), who provided the example with the professor making students bid to buy a jar of coin puts it: "Chances are very high that the following results will be obtained: (1) the average bid will be significantly less than the value of the coins (bidders are risk averse); (2) the winning bid will exceed the value of the jar. Therefore, you will have money for lunch, and your students will have learned first-hand about the "winner's curse."

## 5.5 Auctions for renewable energy: Paper V

The last decade there has been a trend to transition from feed-in policies towards auctions for renewable energy (also known as tenders or competitive bidding). Some early examples of countries adopting auctions for renewable energy are: China that used auctions for wind power already in 2003, Brazil that started using auctions for small scale hydropower and bioenergy in 2007, Portugal that has used auctions for wind power since 2006, and Ireland and the UK that started using auctions for renewables already in the 1990ths (del Río, 2017). Between 2005 and 2016 the number of countries that had employed auctions grew from 5 to 67 (IRENA, 2017) and in REN21 (2017) auctions are described as the most rapidly expanding policy tool to support renewable energy projects. A common argument for transitioning to auctions is that competitive bidding can help to further push down the cost of producing electricity from renewable energy.

Renewable energy auctions can be (and are) designed in many different ways, but a common characteristic in many of them is that actors who are interested in building renewable energy power plants submit bids to the auction where they specify the amount of money that they want to receive per kWh of electricity that their power plant produces (this can be compared to feed-in tariff programs where all participants are paid the same amount of money per kWh of electricity). If the only determining factor is the monetary bid, the ones with the lowest bids will be accepted until the capacity quota (in either W or Wh) is filled or the budget is exhausted. There can however also be other factors that are weighted into the decision process of which bids that are accepted, which is similar to the use of environmental benefit indexes in PES auctions. For renewable energy auctions examples of such other factors can be location of the project, preferences for small scale actors or technology type.

Another thing that can vary between auctions for renewable energy is whether the auction is for building a specific type of power plant at a pre-defined location, which is often the case for off-shore wind power, or if it is an auction where the participants are bidding for building a power plant at a location of their own choosing, which is more common for on-shore wind. In auctions without centrally pre-developed projects, participants will submit bids for differing locations, which means that they will have unique solar/wind conditions that affects the long term profitability of the project. The bidders will thus have values that are specific for them and independent of other bidders, which is consistent with the conditions of independent private value auctions. However, there are also other factors that impacts the value of the projects, such as the investment costs. Investment costs can be partially unique to bidders, but there are also common factors. Since there can be years between the bidding process and the actualisation of the power plant, and since the costs of solar and wind power have decreased rapidly in the past, the actual investment costs may not be known at the time of the bidding (IRENA, 2017). The price difference among the bids in renewable energy auctions are thus likely to be caused both by actual differences in project costs and by estimations of future investment costs. Participants that assume that future costs will decrease significantly will be more likely to submit lower bids, and therefore more likely to win. Here, there is a risk that bidders will win with bids that turn out to be unprofitable if investment costs decrease less than anticipated. As mentioned earlier, this is known as the winner's curse and it is discussed as a serious concern for renewable energy auctions in both IRENA (2017) and Haufe et al. (2017).

#### *Paper V: Auctions for all? Reviewing the German wind power auctions in 2017*

*Paper V gives an overview of the results from the onshore wind power auctions held in Germany 2017. The paper also discuses how the special auction design that was used, where small scale actors were given preferential treatment, may increase the risks of overly aggressive bidding.*

One of the countries that are now transitioning to a support system for renewable energy based on auctions is Germany. The first pilot auction for solar PV was held in April 2015 and in May 2017 the first auction for onshore wind power took place IRENA (2017).

Preparing a bid for an auction may require both resources, time and knowledge, and if the bid is not accepted the effort was made in vain. This may discourage small scale actors, that have limited resources and lack the possibility to spread risks through pursuing multiple projects at the same time, from participating in auctions. In Germany, approximately half of the installed capacity of renewable energy is locally owned and thus including small scale actors is an important issue. To improve the chances of small scale actors winning in the auction, a set of special rules where introduced in the first onshore wind power auctions in 2017. The special rules included longer implementation times and lower pre-qualification requirements for small scale actors, but they also stated that small-scale actors would be paid the highest winning bid (uniform auctioning), while large scale actors would be paid-as bid (discriminatory auctioning). The resulting auction design is a hybrid of a discriminatory auction and a uniform auction. Although both discriminatory and uniform auctions by themselves are common in the scientific literature, as well as in real world applications, combining them in this way is not.

The aim of paper V is to study this hybrid auction design, that in the paper is called a *mixed payments auction*.

The first part of paper V gives an overview of the rules and results of the German onshore wind auctions in 2017. In an unexpected turn of events, over 90% of the winning bids in 2017 were subject to the special rules, and the price level dropped from 5.78 €ct/kWh in May, to 3.82 €ct/kWh in November. There have been concerns over the authenticity of the small scale bidders, and these concerns is supported by the fact that the average project size of the winning bids from the "small scale actors" were twice the size of other winning bids.

The second part of the paper provides a theoretical discussion about the winners curse. Building on auction theory and previous literature, a theory is presented stating that the mixed payments auction design may increase the risks of overly aggressive bidding. The theory is based on the following reasoning. In a discriminatory auction where bidders are paid their submitted bid, there is a strong incentive for bidders to include a profit/safety margin on top of their estimated cost. In a uniform auction where the winners are paid the first loosing bid the equilibrium strategy is to bid ones actual cost. In a mixed-payments auction where some bidders are paid their bids and others are paid the highest winning bid, pay-as bid participants may have a hard time securing contracts if they include safety/profit margins. The mixed-payments auction may therefore cause pay-as-bid participants to bid more aggressively (by decreasing margins) in order to secure contracts, but it may also cause uniform pricing participants to be less careful in their estimations of costs, since their bid will most likely not determine their pay-off.

The third part of the paper focuses on an agent-based model that is used to test the conceptual framework presented in part two. The model illustrates how pay-as-bid participants have a hard time securing contracts in the mixed-payment auction when they include margins. It also shows how pay-as bid participants can increase their chans of winning by, over time, learning to decrease their margins, however with the potential risk of winning with bids that are unprofitable.

The outcomes of the Germany wind power auction are troubling if the low bids that was observed stem from speculation in falling investment costs, since this may cause winners to default on their contracts if their project does not turn out to be profitable. One main conclusion in the paper is that special rules for small-scale actors should be used with caution if they give significant competitive advantages and may affect realisation rates.

## 5.6 Summary

In both renewable energy support schemes and PES programs, the fundamental principle is to use monetary compensation to incentivise private actors to take actions or make investments that are not (necessary) profitable for the individual (in the short run) but that provides positive externalities for society. The "traditional" way of doing this has been through flat payments, where all who are accepted in to the program are offered the same payment that is set by the organisation that is running the program. If there is an oversubscription to the program it has been solved either through lottery, a "first-come-first-served"-basis or through some kind of ranking of applicants.

In both PES programs and renewable energy support schemes potential participants are likely to be heterogenous in terms of their costs for complying with the program standards. The participants are also likely to have an estimate of their costs of complying, while the program organisers may not know the distribution of costs, which is known as an information asymmetry. If costs are not well known it may be difficult to set an appropriate payment level. If costs are heterogenous and the payment level is flat, there is also going to be participants that are payed well above their costs of providing the service. If these participants were given a payment closer to their cost of complying the remaining sum could be used to enroll more participants in the program.

The main argument for auctions is that they can increase efficiency, in terms of either getting more of the targeted service for a fixed budget (for example enrolling more hectares of land in a PES program, or contracting more renewable energy capacity), or having to pay less for a given target (depending on whether the budget or the target is the fixed point). There are several mechanisms that contributes to the efficiency of auctions. Allocating contracts to the ones who can provide the service for the lowest cost, competitive bidding that incentivises participants to push down their bids, diversification of payments (in discriminatory auctions) that reduces overpayments to participants with low costs, and price discovery, since bidding incentivises the participants to disclose information about their costs of complying. All of these mechanisms are summarised in Figure 5.2.

In a setting where participants have heterogeneous costs that are known to them but unknown to the program agency, the participants offer the same service and are rational, auctions are undoubtedly more economically efficient than flat-payment schemes. This has been shown repeatedly in the literature (examples for PES programs: (Horowitz et al., 2009; Messer and Allen, 2010)) and is also seen in Paper IV.

These assumptions may however not hold in reality, and in that case the "efficiency" gains from giving contracts to the lowest bidders may be contraproductive or even jeopardise the purpose of the program.

A concern with selecting the lowest bidders, that is mainly valid for PES programs, is if participants provide services of different quality. If the participants who bids the lowest per hectare of land wins in the auction, and there is a negative correlation between the quality and cost of providing the service, an auction will select participant with low costs and low quality. It may also be that participants with low costs are more likely to provide the service in the absence of a program. So in a worst case scenario, an auction may prioritise enrolling participants who provide low quality services and that are likely to have provided them also without the program. Which probably is the exact opposite of the type of participants that you would like to enroll. If the quality can be quantified the problem of adverse selection, when it comes to quality, can be reduced by including a benefit index that measures the quality and score participants by their bid to benefit ratio.

Another risk, that is more relevant for renewable energy auctions, emerges when the exact cost of complying with the program rules is unknown to the bidders and/or bidders don't behave rational. As explored in paper V and discussed

| | Advantage | Risk | Risk mitigation |
|---|---|---|---|
| Allocation of contracts to the lowest bidders | Contracts are allocated to the participants who can provide the service for the lowest cost, increasing efficiency. | Adverse selection: if participants provide different quality, and there is a negative correlation between the quality and cost of providing the service, an auction will select participant with low quality. | If the quality can be quantified, include a benefit index and score participants by their bid to benefit ratio. |
| Competitive bidding | Competitive bidding can push actors to cut profit margins and thus increase efficiency. | Can increase the risk of over aggressive-bidding, the winner's curse and winners defaulting on contracts. Bidding can also make it harder for small scale actors to secure contracts. | Include pre-qualification measures and/or penalties for defaulting on the contract. Have special rules for small scale actors |
| Diversification of payments | In a discriminatory auction, payments are diversified, since all winning bidders are paid their submitted bid. This increases efficiency since information rents are avoided | Diversified payment may be seen as unfair and politically undesirable, especially if the program also targets poverty alleviation. Can lead to bid shading, particularly in repeated auctions. | Use a uniform auction |
| Price discovery | Auctions can be used to discover the optimal payment level, since they incentivise participants to divulge private information about their costs through their bid. | This requires that the participants know their costs for providing the service. | |

**Figure 5.2:** *Advantages, risks and risk mitigation strategies for procurement auctions for renewable energy and PES. In the table the world "efficiency" refers to how much land that can be protected, or how many kWh of electricity that can be produced for a fixed budget*

in the section "Independent private value auctions, common value auctions and the winners curse" this may cause bidders to win with bids that are too low to be profitable, which may cause them to default on their contracts. This can to a certain extent be mitigated by enforcing pre-qualification measures, ensuring that bids are thoroughly prepared, and by having penalties for defaulting on the contract if you win, but it is hard to avoid all together.

#### ***Auctions in a context***

As presented above, auctions can improve program efficiency but there are also potential pitfalls. The following section is arranged around questions that might be worth considering before deploying an auction in a PES program or in a renewable energy support scheme.

*Is the surrounding organisation and regulatory framework in line with the auction objectives?*

If there are more contracts than bidders, there is no point in having an auction. One things that influences participation rates is trust in the institution that is running the program. If participants has to make an investment it is important that they feel confident that they will actually receive the payments promised in the program. It is also important that the rules are clear and transparent, and since taking part of an auctions requires preparation sudden rule changes may decrease confidence. Another issue is to ensure that the program is aligned with other policies. Auctions for renewable energy will not be successful if there, at the same time are other policies that obstructs renewable electricity producers from selling their electricity to the grid. An example of this is the Japanese auctions for solar PV in 2017 and 2018 that has been heavily undersubscribed. This has been explained as a result of lacking guarantees from the government with regards to access to land and grid connections (Beetz, 2018). Another, but opposite, example can be found in South Africa, where well-structured auctions, with proper regulation and support, successfully replaced a failing feed-in tariff program (Eberhard and Kåberger, 2016).

*What is the time-perspective of the program?*

Programs using procurement auctions can have different time frames, ranging from one-shot events, to auctions that are repeated year after year (such as the Conservation Reserve Program that has targeted soil erosion in the US, since

1985). If auctions are repeated over time there is a possibility that participants will learn to adapt their bids, to optimise profit. If a discriminatory auction is used in a PES programs, where the actual cost of land is stable, participants with low costs, that may initially submit low bids, can learn, from other participants, or from their own previous experience to increase their bids. This will in the long run decrease the efficiency of the auction and it is illustrated with the agent-based modelled in paper IV. There are also discussions about it happening in the Conservation Reserve Program (Claassen et al., 2008; Reichelderfer and Boggess, 1988).

If a program is targeting actors to make them abstain from doing something (such as cutting down rainforest in forest conservation programs), the effects will only last while the program is in place. Therefore these types of programs need a long-term horizon to be effective. They can also be vulnerable to changing crop prices if the alternative to conservation is crop production, as rising crop prices would increase the opportunity cost of providing the ecosystem service (Muradian et al., 2013). In contrast, when it comes to renewable energy the growth of solar and wind power has pushed down their costs so drastically, so that even if support programs are still (often) needed they will most likely be obsolete in the near future.

*What is the basis for payments?*

In subsidy programs the payments can be either performance based or based on participation. Renewable energy support schemes are typically performance based, since participants are payed per kWh of electricity that they produce. This means that there is no issue of payment being made to participants who does not comply with the program requirements. In auctions there is however an issue of winners defaulting on their contracts. In this case no payments are made, and there may be penalty charges for the participants, but since auction quotas often are based on targets for renewable energy expansion, it means that those target will not be met.

While it is easy to measure the electricity output from a wind power plant or solar PV installation (and it is likely that if things are done correctly the expected electricity output will be delivered) it may be harder to measure the output of ecosystem services. In a water management scheme, for example, there might be other factors than the landowners agricultural practises that impacts the downstream pollution levels. Or unexpected factors may come in and change the outcome, such as a storm destroying the forest enrolled in a PES program.

If PES programs are performance based, the landowners bear a large risk, since they may implement the practice but still not reach the intended outcome and thus not get payed. Because of this, PES-programs are usually not performance based payments, but rather based on participation. However, this also means that participants can enroll in the program, collect the payment and then not deliver the ecosystem service. To avoid this, the program agency can monitor the participants and impose sanctions in cases of non-compliance. The monitoring will however impose a cost on the program agency and may be hard to implement on a full scale in large programs (Wunder et al., 2008).

*Does the intended participants have the capacity to take part in the auction and to submit competitive bids?*

Auctions are likely to require higher administrative costs, both for the institution running the program and for participants. As discussed in Paper V preparing a bid for an auction requires resources, that are lost if the bid is not accepted. For actors with substantial resources, such as larger companies, this may not be an issue, since they can spread risks through pursuing multiple project simultaneously and may already have in-house resources required to prepare the bid. However, if bidders lack these kind of resources, it may dissuade them from applying for a program if enrolment is through an auction. Since auctions allocate contracts to the lowest bidders, it may also be that small-scale actors, even if they dare enter, will have a hard time submitting competitive bids and securing contracts. This has been a repeated concern in auctions for renewable energy. There are attempts to facilitate small-scale actors taking part in auctions, but as discussed in Paper V, it is not easily done.

Another factor is that the whole point of auctions is that bidders know their costs better than the auctioneer, so if bidders are unable to make accurate estimates of their costs, the auction approach will not work as intended.

*Are there other goals of the program, except cost-effectively maximising the primary target?*

Even though auctions are used to be economically efficient it is not uncommon that the program also have other objectives. Sometimes these complimentary objectives are clearly stated, while other times they might be hidden in the details. In PES programs, poverty alleviation is a common dual goal, which often also is coupled with promotion of small-scale actors. For renewable energy complimentary goals can for example be to protect small scale actors or national industries, or to promote/discourage capacity development in certain locations. There are ways to factor in other concerns in auctions and one way is to give the participants an index, based on if they provide the desired quality (for example points for having land that is valuable to protect, or living in a poor neighbourhood). This is however hard to combine with uniform auctions (which is discussed in paper IV). Since targeting may include prioritising participants with higher costs (that has a high benefit index score), it usually means that in total, fewer participants can be enrolled, which in it self might be undesirable if poverty alleviation is one of the goals. Using other types of targeting (such as the special rules deployed in the German wind power auction) may distort competition, and change the incentives in the bidding process. This is something that should only be done with caution, as it may have unexpected consequences (as discussed in paper V). When considering auction types, it is also worth thinking about whether diversified payments (which is used in discriminatory auctions), will be politically feasible due to fairness considerations.

#### Final remarks

One of the main arguments for auctions is that they can increase efficiency and this should not be forgotten. If funds for environmental policy programs are limited, they should be put to good use. However, it is also clear that auctions come with their own set of problems and some of them are linked to the mechanisms that pushes economic efficiency.

Competitive bidding may be great if it means that the profit of already wealthy actors decrease a little, so that low-income electricity consumers doesn't have to pay as much extra on their electricity bill. But it is destructive when competition become so fierce that the winning bidders can't afford to provide the service and instead default on their contract. By choosing the lowest bids more participants can be enrolled in the program, but if it means that the ones that enrols are actors with low quality services that they would have provided anyway, it is not such a great idea.

If the auction setting is close to the theoretical world, where the service provided by the actors is homogenous, and all actors are equally qualified to estimate the costs of providing the service, an auction may be a great way of improving efficiency. If these assumptions are not fulfilled, auctions can still be useful, especially if properly adapted, but they should be used with caution, and in some case, not at all.

# Chapter 6

# Discussion, Conclusions and Contributions

*'Never underestimate reality'*
Tomas Kåberger

All five papers in this thesis do, to some extent, revolve around how microeconomic behaviour and lack of perfect information affects the outcomes of environmental policies. The papers do, however, have different focuses and even though paper I-III are framed around the issue of competition between bioenergy and food production, their main content is theoretical and focused on model development.

The models in paper I-III are not intended to predict real world food prices. They are built on a highly simplified description of the land-use system where it for example is assumed that variables regarding costs of crop production are the same all around the world, that there is no storage and that there are no other agricultural policies at play - which is all far from reality. So what is the purpose of developing such simple models that do not account for all aspects of the system? One reason is to be able to study specific mechanisms in isolations, by not making the models so complex that the results become hard to disentangle and interpret.

The mechanisms that are studied in paper I-III are factors that stabilises or destabilises the system and mechanisms that differentiates an agent-based model from a partial equilibrium model. The main destabilising factor in the agent-based model is the cobweb dynamics where actors naively expects that the current price will hold until harvest and when landowners with "perfect information" are introduced the model can be stabilised. Since the crops are interlinked on the supply side through land-use competition, a crop that easily fluctuates in profitability (which the bioenergy crop in the model do) can cause price instabilities for the other crops. If crops are interlinked on the demand side, through substitution, this on the other hand increases stability, as crops can act as buffers for each other.

The instabilities can only be observed in the dynamic version of the model and this is worth noting if equilibrium models are used in the evaluation of new policies. A policy that moves an equilibrium point in an unstable system might perturb the system and cause unintended fluctuations that would not be predicted by an equilibrium model.

While paper I-III have a theoretical focus, paper IV and V have a more pronounced purpose of providing policy relevant contributions. Paper IV is however still based on a relatively simple and generic agent-based model. The distributions used in the model are not based on real data and the type of ecosystem services that is targeted is not specified. If the aim would have been to evaluate the design of a specific payment for ecosystem services program, it would be more appropriate to use real data from that setting. Using synthetic distributions that can be freely varied does however provide the possibility of using the model to do a sweep of how policies work in different types of settings and compare them. What was found by doing this was that the setting determines which policy design that is most efficient.

Paper V moves one step further from the general and conceptual, towards the applied and specific, as the paper examines the policy design that was used for onshore wind power auctions in Germany 2017. The most important take-away from the paper is that the auction design used in Germany, where certain bidders had special rules, may change the incentives of the participants. This in turn may distort the outcome. In the case of Germany, there is a risk that these rules led to overaggressive bidding, which could risk the expansion rates of wind power.

Table 6.1 provides a summary of the papers. In the left column it is described how each paper contributes to the scientific literature. In the right column some general insights that are found in, or illustrated by, the papers are provided. These general insights could be of interest to people outside the specific scientific fields, but may not be novel in the academic literature.

Since agent-based modelling is such an integral part in this dissertation, it might be relevant to ask if it is the optimal tool that should always be used to study land-use competition, payment for ecosystem services programs or auctions for renewable energy. But my answer to that would be: No. Definitively not. To understand these systems, and to provide the best possible support for policy decisions, I would advocate for a combination of studies from different, relevant fields, where agent-based modelling can be one part.

Environmental policy and regulations are usually targeting highly complex systems. In these systems there are numerous actors that interact with each other and that may, or may not, behave rationally. There are feed-back loops and learning effects combined with a quickly changing social and technological landscape. There may be political power struggles and strong lobbyist movements guarding their interests, as well as other political goals that may, or may not, align with environmental protection. This means that policies that seem good on paper, may turn out different in reality, and that systems that may seem stable can turn out to be highly volatile. The work in this thesis explores a few of these aspects, and a key insight is the importance of considering both the dynamics of the systems and the surrounding context when implementing environmental policies.

| Paper | Main scientific contributions | General insights |
|---|---|---|
| **I** | The paper extends the research on interacting cobweb markets.<br><br>The paper also introduces a new combination of heterogeneity that includes both production capabilities and price expectations to the cobweb model. | A system can have instabilities that are not noticeable in an equilibrium model.<br><br>Competition for land links bioenergy and food markets and price volatilities can therefore spread between the markets. |
| **II** | The paper extends the model in paper I by including more crop types and a demand side linkage between them through substitution. | If crops are substitutable on the demand side, this decreases price volatility since the crops can act as buffers for each other. |
| **III** | The paper introduces regional markets into the model from paper I and II and provides a discussion on the model features that make it possible to project an agent- based micro-dynamics to a closed form dynamics on the level of regionally aggregate quantities. | Trade barriers leads to a less efficient allocation of production, and may cause prices in the regional markets to be more volatile. |
| **IV** | The paper provides a comparison of PES-program designs through the use of an agent-based model, where actors are heterogenous with respect to both cost of provision, environmental benefit and baseline compliance. In previous papers these different actor heterogeneities have not been simultaneously studied. | The geographical, political, and economical context should be taken into serious account when PES-programs are designed. In some settings auctions are superior, while in others fixed payments may be better. |
| **V** | The "mixed-payment-auction" design that was used in Germany, but that has not previously been discussed in the academic literature, is described and analysed. | There is a risk that the "mixed-payment-auction" design used in Germany can incentivise overaggressively bidding, which in the long run may cause winners to not fullfill their contracts. This could lead to that wind power targets are not met. |

**Table 6.1:** *The main scientific contributions and some general insights from the papers*

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