THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Land-use competition and agricultural greenhouse gas emissions in a climate change mitigation perspective

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Abstract

Productive land for food production, bioenergy, or preservation of nature is a limited resource. Climate change mitigation puts additional pressure on land via higher demand for bioenergy to replace fossil fuels and via restrictions on deforestation—two processes that limit the availability of land for food production, and may thus also raise food prices. Methane and nitrous oxide emissions from agriculture may also need to be reduced to efficiently mitigate climate change. This thesis deals with this in three ways.

In papers I–II, we estimate greenhouse gas emissions from food production for current diets and expected future developments, together with alternative dietary developments and potential technical improvements in the agricultural sector. Costs and possibilities for reaching climate goals are analyzed for the different diets. The results indicate that a phase out of ruminant products would cut mitigation cost in half, for staying below a 2°C limit, and it may be necessary if the climate sensitivity is high.

In papers III–IV, a conceptual and transparent partial equilibrium model of global land-use competition is developed, analyzed and applied. The model is to a large degree analytically explored and price differentials between crops are derived. The model is subjected to a detailed characterization of its mechanisms and parameters that are critical to the results. We conclude that the total amount of productive agricultural area and bioenergy yields are of crucial importance to the price impacts from large-scale introduction of bioenergy. We also show how limiting bioenergy production to marginal land could be difficult to implement in practice.

In paper V, we use two established indicators for poverty and sensitivity to food-price changes to capture peoples' vulnerability to rising food-prices in four Sub-Sahara African countries/regions. In contrast to previous studies, we include all food products instead of just one or a few main staples. We found that the vast majority of people are net consumers of food and that the inclusion of more than main staples increases their net position as consumers and thus vulnerability to high food prices.

Keywords: Land use competition, GHG emissions, Diets, Food consumption, Bioenergy, Partial equilibrium model, Climate change, Integrated assessment model, Mitigation, Livestock

List of publications

I. David Bryngelsson, Stefan Wirsenius, Fredrik Hedenus and Ulf Sonesson, "How small can the climate impacts of food be made through changes in diets and technology?", *Food Policy* **In Review**, (2014).
FH had the idea, DB and SW collected the data and performed the modeling, DB, SW and FH analysed the results, DB and SW wrote the paper with contributions from FH and US.

II. David Bryngelsson, Fredrik Hedenus, Daniel Johansson, Christian Azar and Stefan Wirsenius, "How much does meat and dairy consumption influence the cost of stabilizing the climate?", *Environmental Research Letters* **In Review**, (2014).
CA had the idea, DB performed the modeling with contributions by FH; DB, FH, DJ, CA and SW analysed the results, DB wrote the paper with contributions from FH, DJ, CA and SW.

III. David Bryngelsson and Kristian Lindgren, "A conceptual partial equilibrium model of global agricultural land use", *Working Paper* (2013).
DB and KL had the idea, performed the analysis, and wrote the paper.

IV. David Bryngelsson and Kristian Lindgren, "Why large-scale bioenergy production on marginal land is unfeasible: A conceptual partial equilibrium analysis", *Energy Policy* **55**, 0301-4215 (2013).
DB and KL had the idea and performed the analysis, DB wrote the paper with contributions from KL.

V. David Bryngelsson, Anders Åhlén, Christian Azar and U. Martin Persson, "The effect of food-price movements on African households", *International Journal of Agricultural Resources, Governance and Ecology* **9**, 1741–5004 (2012).
MP posed the question, DB and AÅ designed the research, AÅ performed the literature review with contributions from DB, DB and AÅ performed the analysis, DB and AÅ wrote the paper with contributions from CA and UMP.

Relevant publications not in this thesis

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 and Control* **In Press**, (2015).

U. Martin Persson, Daniel J.A. Johansson, Christel Cederberg, Fredrik Hedenus and David Bryngelsson, "Climate metrics and the carbon footprint of livestock products: where's the beef?", *Environmental Research Letters* **In Review**, (2015).

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Göteborg, March 2015
David Bryngelsson

Contents

Chapter 1

Introduction

Climate change is arguably one of the biggest challenges currently facing the global society and mitigation of its consequences will require international political cooperation and trust at unprecedented levels, in combination with engineering feats and coordinated societal planning. The actions needed to combat the problems of climate change depend mainly on significantly reduced emissions of greenhouse gases (GHGs) and aerosols, but also on poverty alleviation and other adaptation measures for the already inevitable climate changes.

There are several options for how to reduce emissions of GHGs, most of which focus on reduction of carbon dioxide (CO_2) emissions from the energy system. The main example of this is replacement of fossil fuels with nuclear power or renewable energy sources, such as wind power, solar power, or bioenergy, instead of coal or natural gas power for electricity generation; or biofuels, hydrogen, or electricity instead of petroleum fuels in the transport sectors, assuming the electricity or hydrogen come from carbon dioxide neutral primary energy sources. Each technological solution comes with its specific advantages, potentials, challenges and problems. Foreseeing all future problems that each potential solution may bring can be challenging on many levels, as externalities may change with scale and time, and there may be environmental, economic, or other limitations that we have not yet conceived of. As former US Secretary of Defense Donald Rumsfeld (2002) said regarding the US invasion of Irak *"there are known knowns [... and] there are known unknowns [...] But there are also unknown unknowns"*, and the latter tend to be the hardest. There are subsequently reasons to spend some time trying to shed light on both known and unknown externalities before blindly embarking on large-scale transformations of society, just as well as when invading another country. However, using these uncertainties as excuses for inaction is unlikely to be a good idea.

An example from the environmental field where one solution caused another problem—and of a different scale—is the introduction of automobiles with internal combustion engines. When cars, busses and lorries made an entrance into society they were regarded as environmentally beneficial since they did not produce any of the main pollutant of the time, horse manure (Ponting, 2007, p.330, 377). Horse manure clogged the streets of urban areas as it had rapidly increased from about 3 million tons per year on the streets of Britain in 1830 to no less than 10 million tons by 1900. In addition to manure there was the issue of disposing the approximately 1500 dead horses that were left on the streets of New York each year (Ponting, 2007, p. 352). Beneficial as the automobiles were then, few people envisaged the problems of congestion and local air pollution that cars were to bring to our cities today, not to mention the large-scale problems of climate change that they contribute to. The implications of the former two could maybe have been regarded as *known unknowns*, but the latter can most certainly be viewed as an *unknown unknown* for policy makers a century ago, even though Svante Arrhenius (1896) at this time published his ground braking paper on climate change, in which he estimated the temperature response of a two to threefold increase in the atmospheric concentration of carbon dioxide. However, he also estimated that at the contemporary rate of fossil fuel use it would take a millenium for this to happen. He did not envisage the rapid increase in fossil fuel use that were to follow.

Manure and dead horses on the streets are fortunately a problem of the past—at least in the developed world—but the problems of congestion, air pollution and climate change are pressing. The focus of this thesis is related to how the problem of climate change may be partially solved without creating too severe new problems, or at least to create an awareness for some of the problems and implications that proposed solutions may bring. More particularly, the focus is on mitigation of GHGs from the food sector, on market effects due to land-use competition as a result of increased bioenergy demand, and on poor peoples vulnerability to rising food prices in four Sub-Sahara African regions.

The climate change mitigation discourse has historically focused on reducing fossil fuel use in the energy sector and on curtailing deforestation. However, the agricultural sector is also an important contributor to greenhouse gas (GHG) emissions, with livestock alone standing for almost 15% of anthropogenic GHG emissions (Gerber et al., 2013), and expansion of land for pasture is one of the main drivers for tropical deforestation (Hargrave and Kis-Katos, 2012, Sparovek et. al., 2007). Deforestation, which mainly takes place in the tropics, stands for another 13% of anthropogenic CO_2 emissions (IPCC, 2014, p.7). Food sector GHG emissions are also expected to make up an increasing share of total emissions as the energy system gets decarbonized—assuming that climate change mitigation is taken seriously—while emissions from the agricultural sector are still expected to rise. This increase in food sector emissions is anticipated due to a rapidly growing global population that is getting richer and hence demanding richer diets, with larger quantities of meat and dairy (Alexandratos and Bruinsma, 2012).

High costs for climate change mitigation have frequently been used as a reason for inaction. Any potential reduction of these costs could be promising, as it would make political engagement more likely, with easier economic trade-offs and smaller sacrifices. Not to mention that for economic efficiency, it is advantageous to include as many sources of emissions as possible in a climate change mitigation scheme, and the abatement of non-CO_2 emissions is crucial if strict climate targets are to be reached (Hedenus et al., 2014). Emissions of nitrous oxide (N_2O) and methane (CH_4) are already included in the Kyoto protocol where they have been compared with CO_2 through the use of 100-year global warming potentials (GWP) (Shine, 2009). However, both methane and nitrous oxide emissions are exempted from both the European Union emission trading system (European Commission, 2014) and the Swedish carbon emission tax (Skatteverket, 2014).

Another important aspect for the climate impact from food production is its land use, which is in competition with natural land for biodiversity and for carbon storage, or with bioenergy production systems that have the potential to replace fossil fuels and thus reduce emissions from the energy system. Land-use requirements vary by an order of magnitude between different food types, both in respect to area and type of land (Elferink and Nonhebel, 2007; Eshel et al., 2014; Gerbens-Leenes and Nonhebel, 2002; Kastner et al., 2012). Ruminants, e.g. cattle and sheep, require large areas of land for grazing and fodder production, while monogastric animals, e.g. poultry and pigs, require much smaller areas for fodder production, due to faster reproduction and higher feed-to-meat productivity. Production of vegetables for direct human consumption requires yet smaller areas, which in turn leaves more land available for alternative use.

The area requirement for an average Swede's diet is 0.4 hectare, which to almost four fifths is used for beef and dairy production, even though these categories only supply one fifth of the calorie intake; beef is less than 4% of the total. The aggregate vegetarian products (crops for human consumption), on the other hand supply two thirds of the food energy, produced on only one tenth of the total land used. A shift away from all ruminant products to monogastric meat and vegetarian dairy alternatives, as is suggested in Paper I, would reduce the total area requirement to less than a third of the current level, even if total meat consumption is maintained, see Fig. 1.1. A shift to a vegan diet would reduce the required area to just over a fifth of the current.

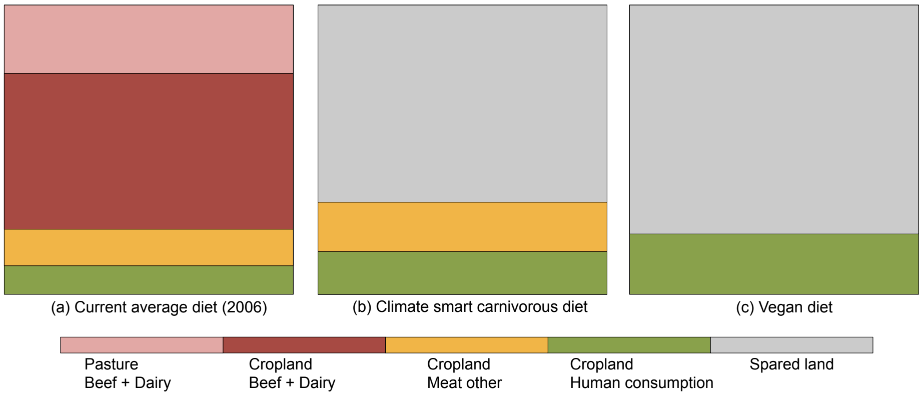

Figure 1.1: *Representation of relative area requirements for food production for three different diets. Panel* (a) *represent the current (2006) average for a Swedish individual, and panel* (b) *for a diet with equal amounts meat, but ruminant meat is replaced with poultry meat, and dairy products are replaced with legumes and vegetable oil. Panel* (c) *represents a vegan diet.*

1.1 Objective and scope

This thesis consists of five appended papers and an introduction to those. The work deals with land use, land-use competition between bioenergy and food production, as well as GHG emissions from the food sector and their implications for climate change mitigation. The general background for the work is the assumption that society tries to mitigate climate change, while demand for energy services and food products keep increasing. The papers can be grouped into three different parts:

I. In the first part we analyze how GHG emissions from the food sector affect costs and possibilities for reaching climate goals, at the domestic Swedish level (Paper I) and on the Global level (Paper II).

II. In the second part of the thesis we investigate how the introduction of a global large-scale bioenergy demand may affect land prices and hence also food prices. We also investigate under which conditions the competition for land between bioenergy and food production can be limited. The work is based on a stylistic and largely analytical partial equilibrium model of land use without any geographic explicitness. Paper III is dedicated to describing the model, while the model is applied in paper IV.

III. The third part of the thesis (paper V) consist of a statistical analysis of production and consumption of food, and other products, in four Sub-Saharan African countries/regions. The analysis is intended to elucidate how poor people in food deficit countries may be affected by changes in food prices.

1.2 Discussion on Methodological Approach

This thesis follows a tradition at the division of *Physical Resource Theory* of interdisciplinarity and systems analysis, where methods are chosen based on the problems at hand. A problem based focus is a common characteristic of interdisciplinary approaches (Rhoten and Pfirman, 2007), and the problems relating to mitigation of climate change—which is the background to this thesis—transcends disciplines. The problems analyzed in this thesis have thus required disparate methods from the natural sciences as well as from economics, used in different proportions in the five papers. The specific methods used for each study are described in the summaries for each paper below and, of course, in the appended papers. This section is focused on a wider discussion of the methodological choices made, with a main focus on models.

1.2.1 Models as research tools

In common for the different approaches and methods in the thesis is a heavy reliance on models, from a simple stylistic model to a larger integrated assessment model (IAM). In this section I will try to put models as research tools into perspective and describe what models are and what they can be used for.

A model can be described as a *"deliberate simplification of a much more complicated situation"* (Solow, 1997), and it is important to choose one's simplifications carefully, if much is to be learnt—about the more complicated real world—from as few causal arrows as possible in the model. One should not confuse the mechanisms and dynamics of the models with reality, since the models are nothing more than crude approximations of parts of the latter—regardless of their levels of detail (de Vries, 2012, p. 219). However, as Box (1979) so beautifully put it *"all models are wrong, but some are useful"*, i.e., used in the right way they can be great tools for learning and for communication.

A model can be a great framework for organizing knowledge about a system under study (Köhler et al., 2015), and the process of constructing a model may help researchers elucidate gaps in their knowledge by making inconsistencies in their reasoning or hypotheses explicit. This latter effect may help the modeler pose the "right" questions, by focusing on the most important mechanisms for each behavior. Or at least mechanisms that can cause the observed behavior; however, there may be other and possibly unknown mechanisms at play. A model may mimic a behavior correctly, but through the wrong mechanism. Even though the construction of a model can be a tool to enhance learning, Köhler et al. (2015) argue that there are instances when the models should not be run, since it would not enhance any further learning. It can be compared to children building a treehouse, once the treehouse is finished, the game is over.

During the process of building a model there tends to be an allurement in adding evermore details and mechanisms to the model, as one learns more about the real system that the model is trying to mimic, or one figures out how an already known mechanism could be implemented in the model. There is, however, always a tradeoff between adding yet another level of detail or another mechanism to a model, improving its fit to the data, and loosing some transparency regarding its behavior. As the model turns more opaque, it may loose some of its explanatory power, at the same time as it may mimic historic reality better, boldly assuming that the added mechanism is relevant and implemented in a correct manner. Speaking about economic models Solow (1997) argues that there is little—if any—correlation between the mathematical depth of a model and its scientific value.

Models can, just like processes in the real world, behave in different ways. An important difference between models is whether they are mechanistic or phenomenological. The former refers to models based on underlying causal mechanisms and the latter refers to models that mimic observed behaviors. The mechanisms do not need to be understod correctly for the model to be mechanistic, but the likelihood of the model performing well is, of course, higher if they are. All models are phenomenological at some level, unless they are based on the most fundamental physical representations of atomic structure, which of course is totally unrealistic for modeling larger societal processes, not to mention unnecessary. But for practical reasons a model can be said to be mechanistic if the analyzed level is higher than—and based on—the mechanisms that are mathematically explicit. An agent based model of traffic flow is mechanistic from the perspective of traffic behavior, if it for example is based on a population of agents that have places to visit during a day and transportation modes to choose between. Each individual agent in such a model can, however, be said to be phenomenological since they are modeled as simple agents that want to go to places and have some objective functions to maximize, but they are not described on a deeper level. This does not make the model phenomenological, since the individual agents are not the focus for analysis. This is in stark contrast with economic equilibrium models, for which the mathematical representation is at the same level as the observed behaviors, and the models are analyzed at the same level as they are mathematically represented; they are thus phenomenological. They are not based on a bottom-up representation of known behaviors of agents, but of observed aggregate market phenomena.

Then there are intermediate variants, such as bottom-up analyses based on equilibrium economics; GET is such a model. In this type of model the equilibrium (maximization) assumption is clearly phenomenological, but the aggregate model consists of several sectors and specific technologies, for which the modelers presumably have a mechanistic understanding. The results from all sectors are analyzed in conglomeration, thus producing a hybrid model.

1.2.2 Equilibrium economics

Most people would probably argue that they have a free will, are not completely predictable and that they are not driven only by profit maximization. However, the most common approach for modeling an economic system that inevitably depends on people's behavior, is economic equilibrium models that optimize a system to maximize a combined producer and consumer surplus. The main idea with equilibrium economics is that people maximize profits and in sufficiently large numbers actually demonstrate rather predictable behavior that can be modeled with simple equations.

Equilibrium economics evolved since economists wanted to find analytical solutions and thus had to simplify the questions asked, to what types of agent behaviors that lead to aggregate states in which there are no incentives to change behavior (Arthur, 2006). To argue for the limitations of these assumptions Bouchaud (2008) makes a comparison to physics where models can explain how small perturbations can cause large changes to the system and where optimal states—even when they exist—often are unstable enough to be basically irrelevant for the system behavior. Real markets are not efficient and are too complicated to be fully predicted (Bouchaud et al., 2008, p. 11), and Milton Friedman noted that if markets were efficient, the fundamental traders would not make any more profit than anyone else and would have no incentive to remain in the markets, as cited in Bouchaud et al. (2008, p. 12).

The answer to these shortcomings of equilibrium economics could be to study agent based models (ABM), which represent economics done in a more general way (Arthur, 2006). ABMs for economics would thus be a mechanistic bottom-up approach, based on the behaviors of for example individuals, firms or sectors. With this type of approach the questions asked can be more realistic, like “What do agents want to do, given the circumstances?”. This approach is not necessarily in conflict with the former, but rather a generalization, since the equilibrium represents a special case in an ABM.

ABMs, however promising from a mechanistic perspective, have yet to prove themselves useful for large-scale policy relevant questions. Equilibrium economics, with all of its well-known flaws, can be expected to reign the policy-relevant research scene until ABMs overcome many of their most important hurdles. Even though the assumptions of equilibrium economics never apply in reality, there are tendencies towards equilibrium situations, which gives the models strong explanatory power and much can be learnt from this. They may indicate in which directions market forces can be expected to pull, and maybe they can indicate where prices will be on average in some future, even though they are not capable of capturing any of the dynamic behaviors of markets that are responsible for much of the volatility (Bouchaud, 2008).

Equilibrium models can thus be argued to be phenomenological, but known to only partly mimic real phenomena, and they are used due to their mathematical elegance and the lack of better alternatives.

If this less than perfect fit between the model behaviors and the appearance of real economic and social systems is due to a poor scientific understanding of the mechanisms that drive peoples’ decision making, or if it is due to properties of peoples’ and groups’ behavior, is an interesting topic for study, but outside the scope of this thesis. Regardless, what can be said is that the mechanisms of peoples’ behavior are not well known and the economic equilibrium models are hence purely phenomenological in nature, with limited reliability regarding their results. Building large conglomerations of such sub-models may thus be difficult to use for furthering our knowledge. Either they behave as we expect and we do not learn much new, or they behave in different ways and we do not really know whether to trust them or not.

1.2.3 Detailed equilibrium models

There are, however, many modeling attempts made where high levels of detail and many sub-models are used in optimizing equilibrium models.

An illustrative example of the development towards high levels of detail is the search for the drivers for the food-price spike in 2007–2008, and then in particular with the focus on the rapidly rising resource competition from expanding bioenergy demand. A fair amount of work has been done to address this question. Persson (2014) identified and compared 121 studies that provide quantitative estimates for the food-price effect from increased bioenergy demand. Common for these studies is that most of them (over 90%) rely on large equilibrium models (partial, PE, or general, CGE) with high levels of detail. The reminder are statistical models. These modeling efforts generally try to examine the historic impact on food prices from the bioenergy demand increase in around 2007—2008 to improve their predictability of implications from future demand increases for bioenergy. Because of their high levels of detail, results from the models depend on many parameters (thousands to tens of thousands for geographically explicit models) and knowledge about their specific values at future times.

Persson (2014) concludes that there is low agreement between the 121 models that assign bioenergy's part as a driver for the food price spike between 11%–43%. The lack of an explicit representation of land markets is brought up as a major weakness, and different assumptions for demand elasticities as the main determinant for the disparate results. There is a shortage of good data for price elasticities and Berry (2011) argues that this is intrinsically difficult to measure; however, Roberts and Schlenker (2009) portray it as relatively straight forward. Also, even if accurate data for historic demand elasticity exists, this can be expected to change over time with economic and technological development, and it is uncertain how far out from the data points that extrapolation is reliable.

Both PE and CGE rely on the same basic principles of the existence of a unique optimal market equilibrium, based on perfectly rational and profit maximizing agents, with access to perfect knowledge, in all sectors.

One may ask whether the high levels of detail in these models improve their predictability or explanatory power, or whether it renders them less reliable. They are detailed from the perspective of being highly data intensive and that they are divided into several sectors et cetera, but they are actually simple from the theory perspective.

Another problem with large models and detailed scenarios, brought up by Morgan and Keith (2008), has to do with people's cognitive difficulty to estimate probabilities. The higher the detail in a scenario, the less likely that particular scenario is to come true, but readers assign higher probabilities to more detailed scenarios. As more detail and precise numbers are provided to a reader, his/her own ability to consider other plausible scenarios declines. These important psychological phenomena do not only apply to laymen, but also to experts, even if to a somewhat lesser degree (Morgan and Keith, 2008).

1.2.4 Our models

Looking at the example of Paper II, we use GET-Climate, with its climate module based on the comparatively complicated climate model in MiMiC, which itself is a "reduced complexity" climate model that for carbon cycles and other GHGs mimics the behavior of much more complicated models that are several times richer in detail, without actually including a mechanistic representation. It is a phenomenological model. These model parts are combined with a mechanistic representation of Earth's energy balance. Such an approach for modeling climate change may be appropriate for analyzing globally aggregated climate impacts of exogenous drivers for the climate, such as the energy system or the agricultural system, but it is unlikely to be appropriate for more detailed and disaggregated studies on climate impacts. Such a focus would rather require even higher levels of detail.

The comparatively high complicatedness of the climate model is hence not a problem for the study in Paper II since its accuracy has been verified elsewhere,[1] and its opaqueness is likewise not a problem since detailed behaviors of the climate system is not focus for the study in question. Closer to the core of the analysis in the study is the energy system, which is analyzed in an optimizing partial equilibrium model. The optimization model GET used in Paper II is thus susceptible to the same critique as I raised regarding the equilibrium models mentioned above.

On top of the level of detail in an economic model, there are reasons to question the fundamental assumption of economic equilibrium on which all the models are based, including the stylized model in paper III and IV where we optimize global agricultural land use. This leads to the most fundamental question for the methods used in this thesis:

- What can optimization models actually tell us?

[1] Accuracy is here defined as its ability to reproduce aggregate climate response to increased levels of GHG compared to other larger climate models. We do not claim to predict the actual climate response, but to mimic other well renown climate models, see Johansson et al. (2006) and Johansson (2010).

1.2.5 What do the optimization models actually tell us?

To be blunt, the unattainable goal of all modeling efforts is to predict the future—the future under a range of *what if* scenarios regarding policies, technological developments, or some other relevant choice that the researchers investigate. However, prediction of the future is problematic due to the integrated complex systems that makes up both society and naturel systems (Köhler et al., 2015). There are still some outright attempts to forecast various societal developments, see Smil (2006) for an entertaining discussion on projections in the energy field where historic forecasts have been off by between an order of magnitude and infinity, for time-horizons of less than 30 years. The question is then what to do when prediction is impossible but the issues at stake are too important to be ignored.

This is where optimization models based on physical representations of technologies and limitations, such as GET-Climate can fill a function. Such a model can develop an internally consistent scenario that fulfills exogenous criteria—such as a 2°C temperature target—at the lowest possible energy system cost, under various constraints and estimates for climate sensitivity, cost developments for energy conversion technologies et cetera (Hedenus et al., 2013). The world will of course not follow a cost-optimized development, due to a plethora of other considerations and the lack of a cost minimizing world government, but such a scenario may still be interesting. It can shed light on what may or may not seem to be physically possible. It may provide a ballpark figure for aggregate costs, and it may provide an experimental setup for comparing different options, such as how much the energy system cost depends on other emissions.

There are other ways of representing the system, such as scenario analysis or stepwise modeling without perfect foresight, to mention a few. These other types of models have their distinct advantages and disadvantages, the comparison of which are outside the scope of this thesis.

1.2.6 Sensitivity analysis

Regardless of the level of detail and type of model, a thorough sensitivity analysis is key to understand how a model works and what results from the model are robust under changes in crucial parameter values. There is generally a dearth of thorough sensitivity analysis regarding main conclusions from model runs, i.e., how sensitive the main insights and conclusions are to parameter values (Persson, 2014). When there is a sensitivity analysis they may include some parameters that may, or may not, be important and then little discussion of real implications from this. The uncertainties tend to be treated as marginal issues, rather than as crucial for the main conclusions (Köhler et al., 2015). When ranges in results are large and uncertain it is still common to present some main results—based on parameter assumptions—in quantitative terms and as if they were certain.

The mathematical formulation required for formalized model building are not necessarily very good at capturing uncertainties, as important assumptions about model structure have to be made, so there is a danger that important uncertainties are obscured (Köhler et al., 2015).

For the studies on which this thesis is based, we have tried to be as transparent as possible concerning uncertain parameters and simplifying assumptions. We have also tried to conduct comprehensive sensitivity analyses where it has been possible and constructive to do so. However, we do not fool ourselves by holding any pretentions that we have covered this area in any completeness.

1.2.7 Final remarks

Throughout my PhD program my supervisors and I have had ongoing discussions about relevant choices of which mechanisms to include and which to exclude from the models we have worked with. The different research questions we have treated have resulted in a wide span of decisions regarding levels of detail and which mechanisms that were thought to be most fruitful for the questions at hand. At the lower end of the scale is the highly stylistic and to a large extent analytical model of global land use and land-use competition in Papers III–IV. At the other end of the scale is the integrated assessment model of the energy and climate systems GET-Climate (Azar et al., 2013) used in Paper II. This model has required years of development by several people, with the energy system model *Global Energy Transiton* (GET) first presented in Azar et al. (2003), and the climate module is adopted from the MiMiC model described in Johansson et al. (2006) and Johansson (2010).

Finally, non of the models we have constructed can predict the future or describe exactly what would happen, should the analyzed policies be implemented, but in the legacy of Box (1979) I believe that they have been useful. I believe that the usage of models has been fundamental for getting many of the insights that we have reached from this work and that the models hopefully also have worked, and will work, as aids for communicating the insights about the real systems behind the models.

Chapter 2

GHG Emissions from Food Production

FAO projections (Alexandratos and Bruinsma, 2012) for future food consumption look very positive from a nutritional perspective, with ever increasing levels of calories per capita in general and consumption of livestock products in particular. However, increases in per capita consumption against the back-drop of an increasing population heading towards 10 billion by mid century (United Nations, Department of Economic and Social Affairs, Population Division, 2013) poses significant challenges regarding the possibilities for reducing GHG emissions enough to limit global warming to below 2°C, as adopted in the Cancun Agreements (UNFCCC, 2010).

Environmental problems have historically been met through supply side management and technical solutions to negative externalities in the production of whatever goods and services that were causing the problems. Examples of this range from end-of-pipe solutions in factories and power plants, such as sulfur filters in coal fired power plants, to mandatory catalyzers in personal automotive vehicles, to the Montreal protocol prohibiting the use of CFCs for refrigerators, and the replacement of chlorine for bleaching of printing paper. More recent examples are the current shift towards renewable sources of energy that do not depend on fossil fuels, and the initiated electrification of the personal vehicle fleet, both meant to primarily combat climate change. What is common for all these problems and solutions is that they do not require consumers to change behavior in any significant manner, nor have there been any real need for personal sacrifices, save for some minor increases in cost.

Reducing GHG emissions from the food sector is, however, fundamentally different to the examples stated above. Some of the GHG emissions from the food sector stem from fossil fuel use for mainly fertilizer production, agricultural machinery, and transport. Of course, these emissions can be reduced through technical measures e.g. fuel switches to non-fossil alternatives. The majority of GHG emissions from the food sector, however, are fundamentally different. These emissions consists of nitrous oxide (N_2O) and methane (CH_4), and they mainly come from chemical processis in soils, animal digestive systems or manure. They are diffuse and difficult to measure, they differ between production systems for the same products, they are inherently difficult to reduce, and most importantly they differ significantly between product categories, see Fig. 2.1. Supply side management—with technical abatement of emissions—is hence difficult, but there are large GHG reduction potentials from demand side management. Regulating what people eat is, however, less popular from a political perspective than is the regulation of production systems.

The idea of regulating food consumption for environmental reasons is not new. Lars Ingelstam and Göran Bäckstrand argued for rationed consumption of meat already in 1977 in the text *Hur mycket är lagom?* ("How much is enough?", my translation) (Wikipedia, 2009). Also at the division of Physical Resource Theory there is a long history of dealing with questions of consumption and its environmental consequences in general, and with food consumption (including production) and its externalities in particular. Björn Eriksson and Karl-Erik Eriksson (who founded the division) argued for decreased meat production in their visionary exercise for a sustainable future Swedish society already in 1980 (Eriksson and Eriksson, 1980) and Stefan Wirsenius wrote his PhD thesis on energy flows within the global food sector, Wirsenius (2000). In papers I and II we continue in this tradition by investigating how food related GHG emissions can be expected to develop in the future, how low they can become through technical measures and dietary changes, and how this development affects our possibilities and costs for reaching climate targets.

2.1 Paper I: How small can the climate impacts of food be made through changes in diets and technology?

In paper I we estimate how Swedish food related GHG emissions fit in the climate targets set in the EU for 2050 (European Commission, 2011), stating that aggregate GHG emissions should be reduced by 80–95% by 2050. The starting point of the study is the current food consumption, divided into representative

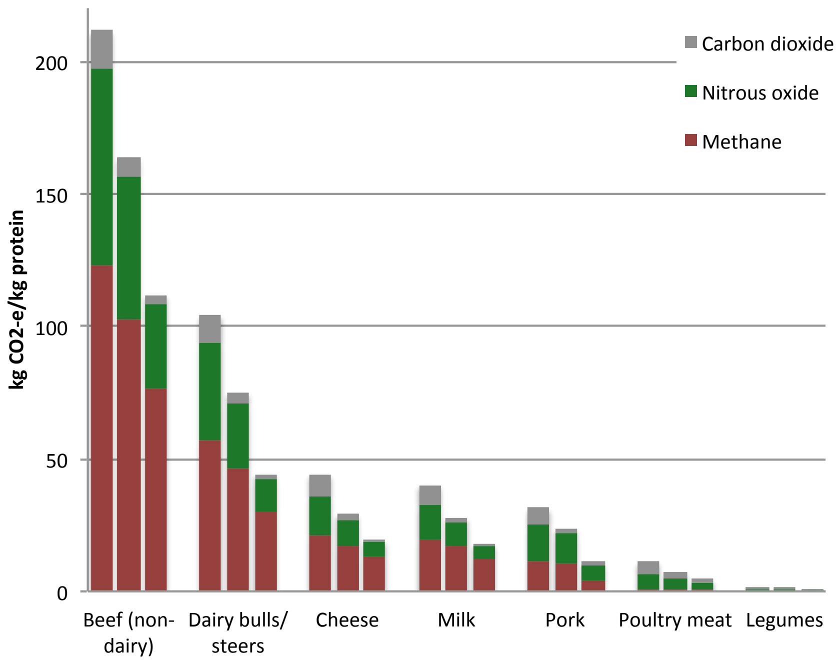

Figure 2.1: *Emission intensity per kg protein from some representative protein sources. The left bar for each category represents the current average Swedish production system, while the middle and right bars represent improved future production systems with moderate (middle) and optimistic (right) assumptions for future developments and implementation rates for emissions-reduction measures within the agricultural sector.*

food categories for which GHG emissions were estimated. Trends in food consumption were analysed, from which a reference diet for 2050 was constructed, together with a set of alternative low-emission diets. Potentials for efficiency improvements and dedicated emission-reduction measures were also estimated.

2.1.1 Object and scope

We aim to:

- Assess the expected levels of GHG emissions from the food sector in Sweden today and by 2050 from domestically produced as well as imported food.

- Assess how high these emissions can become if current trends continue and how low they can become if dedicated technical mitigation measures are implemented and if diets are altered to reduce emissions.

- We also compare these findings with the allowed emission space in Sweden for 2050 based on EU's long term climate targets.

2.1.2 Method

The study is made up of three major parts. In the first part we quantify current food demand for en average Swedish person and analyze trends for developments in food demand for resource demanding food products, mainly livestock derived products. Based on historic trends and extrapolation of these, in combination with consumption levels in USA we construct a reference diet for 2050. USA is chosen as a reference point because it is an example of another affluent country but with higher per capita levels of meat consumption that is close to the levels that linear extrapolation of historic trends point to. We also construct several alternative diets, with lower levels of ruminant meat, dairy, meat in general, and strictly vegan.

Emission intensities per food category is based on a selection of representative life cycle assessment (LCA) studies. Mitigation measures for agricultural GHG emissions are estimated based on the scientific literature. Efficiency improvement potentials are based on the scientific literature and an modeling of the cattle sector.

2.1.3 Main findings

- Current Swedish food consumption is not compatible with the long-term climate targets for the EU. The trend towards higher per capita levels of meat consumption is even less compatible with the EU climate goals.
- There is a potential for efficiency improvements and dedicated technical emission reduction measures that may play an important role for reducing food related GHG emissions. However, the extent of this potential is limited and uncertain.
- The emission reduction potential from dietary shifts is large. The emissions can be reduced to less than a third of the current level through dietary shifts alone, without jeopardizing nutritional quality.
- Reducing the amount of ruminant meat consumed (beef, mutton, goat) is the singel most effective measure for reducing food related emissions. This is also the most important measure for improvement of area efficiency in food production.
- The long-term climate targets for the EU can be reached if the amount of ruminant meat is reduced.
- A diet with reference levels of meat consumption, but entirely devoid of ruminant products (beef, mutton, dairy) carries lower GHG emissions and has higher area efficiency than a vegetarian diet rich in dairy.

2.2 Paper II: How much does meat and dairy consumption influence the cost of stabilizing the climate?

In paper II we investigate how divergent dietary developments on a global level affect energy system costs for reaching different climate targets. In paper II we continue the work from paper I by moving from a Swedish to a global focus and from emission targets to temperature targets. There is a lower level of detail for food categories in paper II than in paper I and this is mainly based on the result from paper I that emissions and area requirements for non-livestock products are very small and vary little, compared to livestock products.

2.2.1 Object and scope

The aim of Paper II is to:

- Estimate how the energy system cost for reaching a climate target depends on dietary developments.

- Calculate whether alterations to the reference diet (based on FAO projections) will be necessary if the 2°C target is to be met.

- Compere and aggregate the reduction in mitigation cost for the energy system from

  - non-energy non-CO_2 emission reductions,
  - increased bioenergy potentials from saved cropland, and
  - carbon accumulation in vegetation and soils on abandoned pastureland,

  when low-emission and area-efficient diets are realized.

- Compare the reference diet with a vegan diet, but also with a carnivorous diet with reference levels of meat consumption, but devoid of ruminant animal products, to find out how much of the mitigation cost reduction that can be realized without actually moving to an all vegan diet. To find out how climate efficient a carnivorous diet kan be.

2.2.2 Method

In paper II we calculate methane and nitrous oxide emissions for a reference diet based on FAO projections (Alexandratos et al., 2006) until 2050 and extrapolations until 2100. Emissions are also calculated for a vegan diet and a carnivorous diet with reference levels of meat consumption; however, ruminant meat is replaced with poultry meat. Bioenergy potentials for the different diets are calculated, and two carbon accumulation scenarios for abandoned pastureland are created.

These data are fed into the coupled energy-system and climate model *GET-Climate* (Azar et al., 2013) for comparison of mitigation costs for the energy system, depending on climate target and dietary developments.

2.2.3 Main findings

- A shift from a reference diet to a diet with no ruminant products reduces energy-system mitigation cost by 40–50% for reaching a 2°C stabilization target, see Fig. 2.2. These cost savings correspond to roughly three quarters of a per cent of future NPV of global GDP.

- The absolute savings are higher for more stringent targets. Dietary changes may even become necessary for strict climate targets, or if the climate sensitivity turns out to be high.

- The mitigation cost depends little on whether the ruminant products are replaced with monogastric meat, or with vegetable products. The savings are slightly higher for the latter, but it seems not to be the quantity meat that matters for climate change mitigation, but it is the quantity ruminant meat.

- The results of reduced relative mitigation costs from changed diets are robust over a wide span of climate targets.

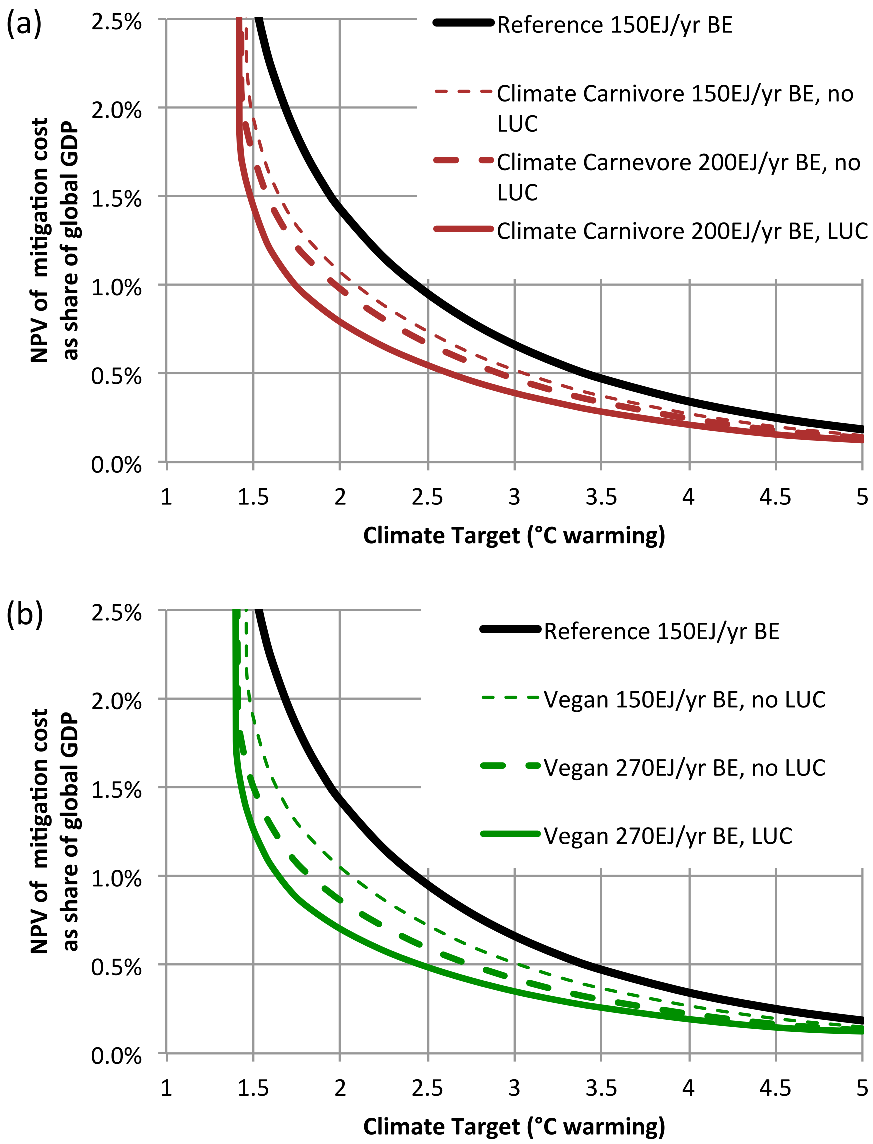

Figure 2.2: *How the mitigation costs for reaching different climate targets depend on dietary developments, bioenergy potentials, and carbon accumulation through land use change (LUC), for* (a) *reference level meat consumption, but no ruminant products, and* (b) *strictly vegan.*

Chapter 3

Equilibrium economics and land use

The European Union has endorsed a mandatory target of 10% biofuels for transport by 2020 and stated that it is appropriate with a binding target as long as the production of the biofuels is sustainable (EC, 2009). USA has a similar goal of 36 billion gallons (136 billion liters) biofuels in the transport sector by 2022, up from 9 billion gallons (34 billion liters) in 2008, implemented through the Energy Independence and Security Act (EISA) of 2007[1]. Based on these and other countries' goals of increased consumption of biofuels for transport the OECD-FAO Agricultural Outlook[2] 2011–2020 expect global biofuel production to more than double between 2008 and 2020. On an energy basis this corresponds to an increase in liquid biofuel production from 1.6EJ in 2006 to over 5EJ in 2020. BP energy outlook 2030[3] estimates the biofuel production to increase from 2.4 EJ in 2010 to no less than 9.9 EJ year^{-1} by 2030. This can be compared to the aggregate current demand for liquid fuel for transport of 75 EJ year^{-1} (Smil, 2006). In the longer perspective Pacala and Socolow (2004) propose production of 35 EJ year^{-1} of liquid biofuel by 2054, produced on 250 Mha of land, to fill one of their GHG "wedges" and reduce global emissions by 1GtC year^{-1}. There is thus no shortage in demand for bioenergy to be expected in the coming decades.

If the world is to embark on a large-scale expansion of bioenergy, as the man-

[1] www.epa.gov/otaq/fuels/renewablefuels/index.htm, visited 2011-11-16

[2] stats.oecd.org, visited 2011-11-16

[3] www.bp.com/sectiongenericarticle800.do?categoryId=9037134&contentId=7068677, visited 2011-11-16

dates in EU and USA indicate, it is desirable to have an ex-ante understanding of what such a development may entail. It is difficult to calculate and agree on the impact from bioenergy on historic price changes, as was made evident in the aftermath of the recent food price hike of 2007–2008. (Persson, 2014) argues that a lack of explicit land-use modeling is one of the main shortcomings of the larger modeling efforts conducted to quantify food-price implications from increased bioenergy demand.

In paper III and IV we develop and apply a conceptual partial equilibrium model of global land use, with availability of productive land as the limiting factor. The purpose of the model is to offer an alternative and more transparent way of looking at large-scale perturbations to the global land-use system, such as from the expected future demand for bioenergy. The transparency is thought to help readers acquire a deeper understanding of the main mechanism in land-use competition and their potential effects, and at the same time avoid an overconfidence in model results, as Morgan and Keith (2008) claim may result from higher levels of detail.

3.1 Paper III: A conceptual partial equilibrium model of global agricultural land use

In the third paper we develop a conceptual agricultural land-use model that to a large degree can be explored analytically. The limiting factor in the model is availability of productive agricultural land. The main purpose of the model is to be as transparent as possible, but still realistic enough to capture important mechanisms.

3.1.1 Objective and scope

The purpose of paper III is to:

- Present a conceptual model of global land use, simple enough to be analytically explored, but complex enough to capture important driving mechanisms for productivity based land-use competition.
- Show how crops are optimally distributed on land and what characteristics that determine the distribution.
- Derive differentials for how different crop prices depend on each other at equilibrium.

The possibility of analytical exploration—we argue—enables a deeper understanding of how mechanisms work.

3.1.2 Model description

Global land is assumed to be graded in a continuous and strictly declining manner from the most productive land to the least productive land, which is depicted in Fig. 3.1.

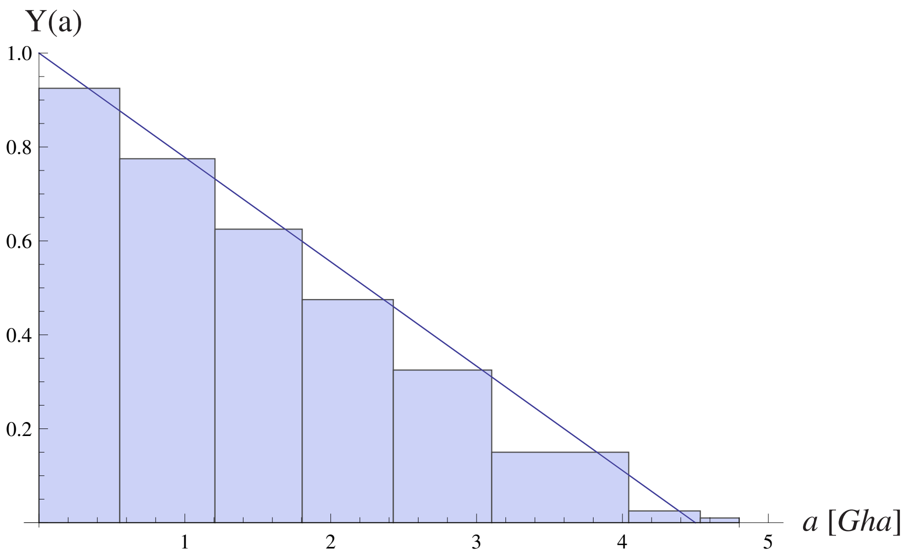

Figure 3.1: *Representation of global agricultural land with decreasing productivity. The bars represent data for Suitability for rain-fed crops (maximizing technology mix) from (Fisher et al., 2002) and the curve represents an approximation used in paper II.*

On this land there is a distribution of agricultural land uses i, characterized by different crop specific potential yields η_i, crop specific harvest dependent costs β_i, and area dependent costs $\hat{\alpha}_i = \alpha_i + \gamma_i$, where α_i is the variable cost for inputs and γ_i is a fixed cost that must be spent per area in order to get any yield at all. The crop specific yields are assumed to be the land productivity $Y(a)$, but the (lower) potential is easier to achieve on land of lower quality, $y_i(a) = \eta_i(\alpha_i/Y)Y(a)$. Each crop can thus support a willingness to pay for land π_i according to

$$\pi_i(\alpha_i, a) = (p_i - \beta_i)\,\eta_i(\alpha_i/Y(a))\,Y(a) - (\gamma_i + \alpha_i) \qquad (3.1)$$

and the land rent at each a is set by the crop with the highest willingness to pay for the land

$$r(a) = \max_{i,\alpha_i} \pi_i(\alpha_i, a)\,. \tag{3.2}$$

The demand function is assumed to be unbounded at low quantities and decreasing with increasing quantities. The crops are assumed not to be connected an the market, i.e., there is no cross-price elasticity between any of them. There is also no shortage of labor in the model.

3.1.3 Main findings

- Crops are distributed on the land according to their respective fixed area dependent costs γ_i. This means each crop type is clustered to a span of land of similar quality, and the crops with the highest γ_i end up on land of the best quality, while crops with low fixed area dependent costs end up on land of low quality. Crops with high area dependent costs profit more from reduced areas and can thus support high land rents, while crops with low such costs are more profitably grown on larger areas with lower yields and lower land rents.

- There is a unique land-rent equilibrium solution for each set of crops.

- Analytical price connections between crops from the competition for land are derived.

3.2 Paper IV: Why large-scale bioenergy production on marginal land is unfeasible: A conceptual partial equilibrium analysis

The fourth paper is based on the application and further development of the conceptual agricultural land-use model developed in paper III.

3.2.1 Goal and scope

The aim of paper IV is to:

- Produce qualitative pictures of economic impacts from competition for land from large-scale bioenergy production by applying the conceptual land-use model developed in paper III.
- Analyze food price effects from land rent increases, due to large-scale introduction of bioenergy.
- Compare the food price effects from different bioenergy scenarios, such as market based land allocation, versus bioenergy limited to land of low quality.
- Subject the model to extensive parameter analysis to show which parameters that are most crucial for the conclusions drawn from the model.

3.2.2 Method

The land-rent model developed in paper III is applied to one reference scenario with no bioenergy demand, and to three stylized bioenergy scenarios with exogenous demand of 120EJ per year. The first two are based on high yielding bioenergy crops that are allowed to compete with food for land, versus are limited to land of low quality. The third bioenergy scenario is based on agricultural food crops as feed stock. The calculations are made for one case with zero deforestation and one with complete deforestation. Apart from bioenergy (BE) feedstock there are two agricultural land uses: intensive crop (IP) production, and extensive crop and forage (EP) production, including pastures.

Data on yields, production costs and price elasticities are drawn from the literature, in combination with some assumptions. An extensive parameter analysis is performed for all parameters in the model.

3.2.3 Main findings

- Price increases on food from increased land-use competition are significant for all cases investigated when deforestation is not allowed. This is a result from that land prices increase significantly at all levels in response to large-scale introduction of bioenergy, regardless of crop distribution, see Fig. 3.2.
- Intensively produced food crops are significantly affected in all cases, but at a level less than half the impact on extensively produced forage and food crops. This can be explained since land rent makes up a smaller share of the production cost for intensive production and a relative increase in land rent thus has a smaller relative effect on the total production cost, than for extensive production that uses larger areas of land for each unit produced.
- Allowed deforestation would reduce the land rent costs—and thus production costs—for all cases.
- Market conditions would place bioenergy production on land of lower quality than intensive food crops, but on better quality than extensive crop production or pasture, raising land rents at all levels and pushing the extensive food production onto land of lower quality. This, of course, depends on production costs for the different systems.
- The price effect, on intensively produced food crops, can be somewhat mitigated if bioenergy production is limited to land of lower productivity, see Fig. 3.2c. This results in a very strong increase in land rent for the land where bioenergy production is allowed, and an even higher willingness to pay for land of better quality. Incentives for land owners to cheat and not follow such a restriction would be very strong and implementation of such a scenario would thus be difficult, if not impossible.
- Bioenergy production from food-type crops (such as maize ethanol) results in much larger price changes for all intensively and extensively produced food and forage crops alike, stemming from radically increased land-use competition and thus much higher land rents, Fig. 3.2d.
- There is, however, room for a large-scale introduction of bioenergy without a significant effect on food prices if deforestation is allowed at a substantial scale. Allowing for deforestation without introducing bioenergy at a large scale would certainly lead to a significant fall in food prices. Bioenergy always raises competition for land and thus land rents compared to developments without bioenergy.

- The extensive parameter analysis shows that all price increases fundamentally depend on some crucial parameters. The most important parameters are: The total availability of productive land; Total quantity bioenergy demanded; Potential yields for all crops but specifically bioenergy crops; and price elasticity for extensively produced forage and food crops. Price elasticity of demand is the most sensitive parameter for the price effect, but according to the literature, difficult to estimate.

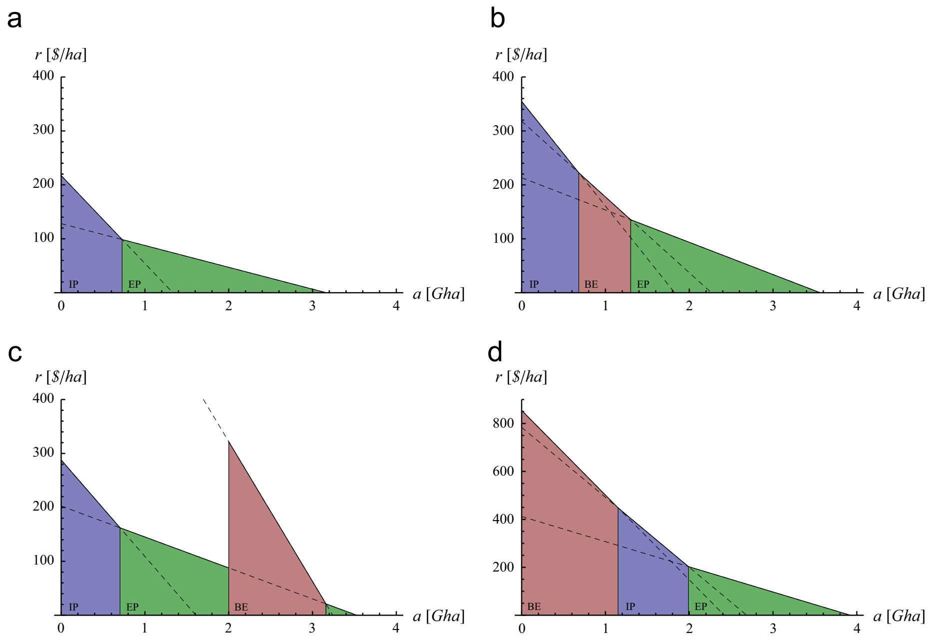

Figure 3.2: *Estimated land rents and land use in the base case (a) and the three bioenergy cases (b)–(d). Lines represent willingness to pay for land from a given crop for land of each productivity level. At each a, the crop with the highest willingness to pay sets the land rent, when there are no constraints on which crop is allowed. Colored areas indicate which crop is produced on the each piece of land. The size of each area depict the aggregate land rent payments. Note that extensive production (EP) is produced on both intermediate land and, to a small extent, on the least productive land in panel (c). Also note the different scale on the vertical axis in panel (d).*

Chapter 4

Poverty effects of rising food prices

4.1 Background

Historically there has been a global trend of falling food prices from the early 1960s until the mid 1980s, when food prices leveled out, followed by a rapid price spike in 2008 and then again in 2010–2011. These price spikes are on par with the one following the first oil crises in 1973–1974. This development can be seen in Fig. 4.1.

The world had thus gotten used to low and stable food prices, at a time when the global population doubled and living standards have improved in many parts of the world. The number of undernourished people in the world has (been relatively stable and) slowly declined during this time, despite the rapidly growing population. The number of undernourished has, however, started to increase in recent years, in response to the rapidly increasing food prices, from a low of about 825 million in 1995–97 to over a billion (1.023) in 2009, with most of the increase in 2007–2009 (FAO, 2009, p. 11) and then down in 2010 to the same level as in 2008 of 925 million (FAO, 2010).

Finding out what negative side effects there may be from a large-scale bioenergy introduction is not a trivial task, and to quantify them is even more daunting. A large-scale introduction of bioenergy over the coming decades can be expected to raise land values and thus production costs for all agricultural products, which means that food prices can be expected to rise. A justified question is thus what the welfare impacts on the world's poor would be if food prices increase even further.

Investigating what the welfare effects on poor households may be if food

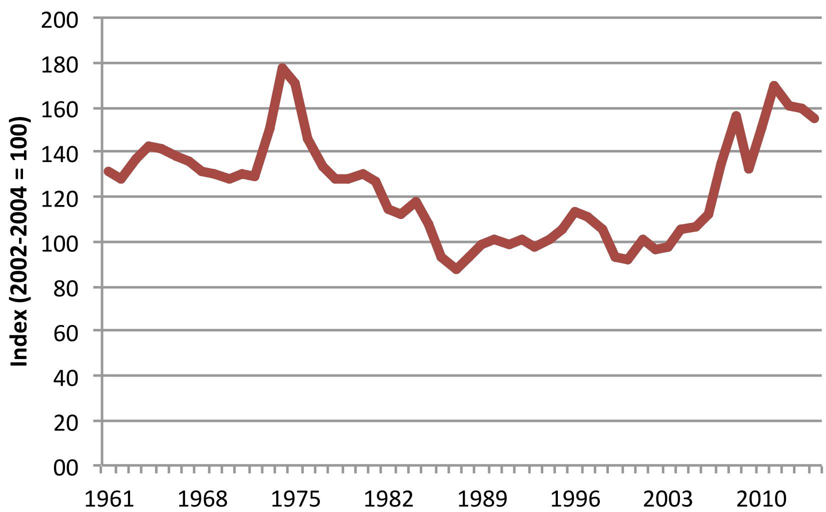

Figure 4.1: *Food price index. Source: FAO (2014)*

prices change is difficult. There are many factors that make such an exercise complicated, e.g. a general lack of data, especially for developing countries where most of poor and food insecure people live; and there are dynamic higher order effects—farmers change their behavior in response to price incentives—but it is difficult to know how much and in which directions. Generally, there is a lack of information regarding best agricultural practices, in combination with difficulty in getting access to credit for making investments for poor subsistence farmers in developing countries. These conditions make it difficult for such people to change their behaviors, but this also makes it more difficult to predict how people can be expected to respond to changing prices.

A second best approach then is to look at a static picture of peoples' net food position, i.e., if they produce more food than they consume, or vice versa. Whether a household has the position of a net producer or a consumer, and by how much, is fundamental for that household's ability to benefit from, or be harmed by, increasing prices on agricultural products, at least in the short term, when dynamic higher order effects—such as changing crops or area cultivated—can be assumed to have less impact.

4.2 Paper V: The effect of food-price movements on African households

In paper V we hence investigate the net food positions and their magnitude, for households in the four Sub-Saharan African countries/regions Ghana, Malawi, Kagera in northeastern Tanzania, and South Africa, to estimate their vulnerability to rising food prices.

Much work on vulnerability to changing food prices has already been done, see e.g. Aksoy and Isik-Dikmelik (2008), FAO (2008a), Levinsohn and McMillan (2005), Minot and Goletti (1998), Sahn (1988), Weber et al. (1988), and Zezza et al. (2008), who estimated net food positions and vulnerability by focusing on one or a few staple crops. The focus on few staple crops can be justified for at least three reasons. Firstly, staple crops are the most important ones from a nutritional perspective. Secondly, many of the studies have been conducted with a focus on trade policies, where changing prices mainly affect specific crops, and thirdly, collecting data for a few staple crops is much less work demanding—and less expensive—than conducting complete household surveys that include all food products.

The work in paper V is, however, focused on areas where comprehensive data from the Word Bank's Living Standard Measurement Studies (LSMS) were available, which are based on thorough interviews regarding most economic aspects of the living conditions of a statistically significant sample of each population.

4.2.1 Goal and scope

The aim of the paper V is:

- To estimate the shares of household budgets spent on food in four sub-Saharan African countries/ regions (Ghana, Malawi, South Africa, and Kagera in Tanzania).
- To estimate the static real income effect of changing food prices on households in these countries/regions in order to estimate how large shares of the populations that would benefit or lose from rising prices.
- To analyze how the number of food items included in such a food-price–poverty assessment affects the results.

4.2.2 Method

The work is based on comprehensive data from four World Bank LSMS for Ghana (GSS, 2005–2006); the Tanzanian region of Kagera (E.D.I., 2004); Malawi NSO (2004-2005); and South Africa SALDRU (1994). These detailed data sets are investigated with the use of two established indicators for vulnerability to food price changes. The first is the share of a household's income that is spent on food, here called *food over expenditures* (FOE), and the second is net benefit ratio (NBR), which is adopted from Deaton (1989, 1997).

The first indicator is defined by

$$\text{FOE} = \frac{\text{auto-consumed food} + \text{purchased food}}{\text{total expenditures}}, \tag{4.1}$$

where auto-consumed food consists of all food products produced and consumed within the household.

The latter indicator is calculated as follows,

$$\text{NBR} = \frac{\text{sold food} - \text{purchased food}}{\text{total expenditures}}, \tag{4.2}$$

where we have expanded on Deaton's approach by allowing for different prices for sold and purchased goods of the same type, as these activities and prices may differ throughout the year.

To offer yet another view of how choices of crops studied may affect the results we present the economic values for all staple foods (disaggregate) and other food (aggregate) for the urban and rural populations, respectively, divided into terciles based on NBR.

4.2.3 Main findings

The share of net buyers in all regions/countries is high for both rural and urban populations, which is in accordance with previous studies that look at main staples. However, both the shares of net buyers and the extent to which they are net buyers are larger in our study than in other studies published looking at the same countries, such as FAO (2008b) and Zezza et al. (2008).

A likely explanation for the difference is the inclusion of all food products in our study compared to e.g. only rice and maize in Zezza et al. (2008). By taking the example of rural Malawi, non-staples make up large and relatively similar shares of auto-consumed and sold food, but dominate the category purchased food. That they (non-staples) make up large shares of the food economy can explain why their inclusion alters the magnitudes of the indicator values. The magnitudes of the indicator values is not important when only looking at the net position of population groups, but it is when studying how price changes may affect them. That non-staples make up dominating shares of purchased food, however, not only alters the magnitude of the indicator values, but also the net positions of the population samples.

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