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Loïc Henry

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Essais sur l'économie du changement
climatique : atténuation et adaptation du
secteur agricole

*Essays on the economics of climate change:
mitigation and adaptation in the agricultural
sector*

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Résumé

Cette thèse aborde des questions économiques liées au changement climatique, à la fois sous l'angle de l'atténuation et de l'adaptation, avec un accent mis sur les implications pour le secteur agricole. Dans le premier chapitre, je propose une analyse quantitative de la littérature économique sur le changement climatique depuis plus de quarante ans. Je mets en évidence une visibilité croissante de ce sujet au sein de la discipline. A partir d'une catégorisation textuelle des articles de la littérature à l'aide d'une Allocation de Dirichlet Latente, j'illustre sa structuration autour d'approches sur l'atténuation globale du changement climatique d'une part, et d'analyses empiriques des implications sectorielles du changement climatique d'autre part. Le deuxième chapitre examine les performances d'une taxe sur les émissions agricoles de gaz à effet de serre en présence de coûts de contrôle des émissions. A l'aide d'un modèle analytique, je caractérise la couverture partielle optimale de la taxe sur les émissions. La question est ensuite étudiée à l'aide d'un modèle d'offre agricole représentatif de l'agriculture européenne. L'application empirique montre que l'exemption des exploitations les moins émettrices en Europe permet de limiter les coûts de contrôle tout en incitant à réduire efficacement les émissions. Dans le troisième chapitre, j'étudie les stratégies d'adaptation en agriculture lorsque la modification des zones de production est rendue difficile du fait de la présence d'une Indication Géographique. Je développe un modèle théorique stylisé permettant d'analyser les modes d'adaptation en tenant compte du lien étroit entre la qualité du produit et les attributs de la zone géographique de production. Le modèle montre que la relocalisation de la production comme stratégie d'adaptation peut être rendue difficile par la redistribution des rentes qu'elle induit entre producteurs historiques et nouveaux entrants.

Abstract

This thesis addresses economic issues related to climate change, from both a mitigation and an adaptation perspective and with a focus on the implications for agriculture. In the first chapter, I propose a quantitative analysis of the economics literature on climate change for over more than forty years. I show that climate change has become increasingly prominent in the discipline. From a textual categorization of the content of articles using Latent Dirichlet Allocation, I suggest that the literature is structured around approaches on global mitigation of climate change on the one hand and empirical analyses of the sectoral implications of climate change on the other hand. The second chapter examines the performances of a tax on greenhouse gas from agriculture in the presence of monitoring costs. Using an analytical model, I characterize the optimal partial coverage of an emission tax. The issue is then investigated using an agricultural supply model representative of European agriculture. The empirical application shows that exempting the lowest emitting farms limits monitoring costs, while providing an incentive to efficiently reduce emissions. In the third chapter, I study the adaptation strategies in agriculture when modifying the production areas is made difficult by the presence of Geographical Indication. I develop a stylized model to analyze adaptation patterns taking into account the strong link between the quality of the product and the characteristics of the area of production. The model shows that the relocation of production as an adaptation strategy can be made difficult by the induced redistribution of rents between historical producers and new entrants.

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*La planète se réchauffe,
Du coup, aussitôt,
On vendait la neige.*

BOOBA

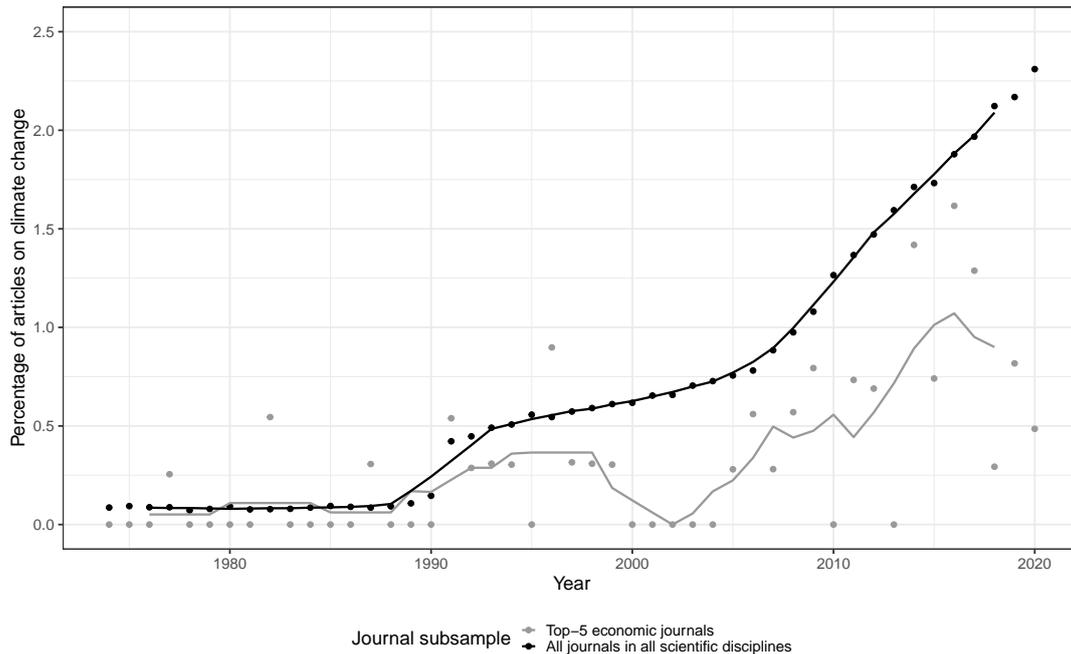
General Introduction

Climate change is the key global environmental challenge of our time. The accumulation of greenhouse gases emitted by human activities into the atmosphere modifies Earth's energy balance, and results in an increase of average temperatures, alterations in cloud cover and precipitations, and increased occurrence of extreme weather events (IPCC, 2014). Climate change is likely to affect both natural (ecosystems, water resources, biodiversity, etc.) and human-made (buildings, infrastructures, etc.) assets. This will have far-reaching, long-term, and multi-faceted impacts on many sectors of the economy, if not all.

The stakes are particularly high for the agricultural sector, which is the focus of this thesis. Agriculture is among the major greenhouse gases emitting sector. Livestock and nitrogen fertilizer use are the main sources of methane (CH₄) and nitrous oxide (N₂O), two major non-CO₂ greenhouse gases. About 10% of total net emissions in the European Union (EU) and 18% in France originate from agriculture (European Environment Agency, 2017; CITEPA, 2020). At the same time, weather is a significant input in agricultural production systems. Changes in average and extreme temperatures, precipitations, and water resources will affect agricultural yields, and put further stress on the functioning of ecosystems, with potentially large consequences on food security, vulnerability of rural households, and biodiversity (IPCC, 2019).

In the face of such a challenge, what is the role of economists and what could/should be their contribution with regard to climate change in general, and its implications for agriculture in particular?

Figure 1: Share of articles related to climate change in *top-5* economic journals and in all scientific journals.



Note: in 2015, articles on the economics of climate change represented 1% of the articles published in the *American Economic Review*, *Econometrica*, the *Quarterly Journal of Economics*, the *Journal of Political Economy* or the *Review of Economic Studies*, while they represented 1.8% of all articles published in all scientific journals. Lines represent the five-year moving average of each time-series. More details on the construction of this figure are given in Chapter 1.

Economics of climate change

In a recent column, Oswald and Stern (2019) argue that economics is, to a large extent, absent from the scientific debate around climate change. To support their view, they point out the very low number of articles dealing with climate change in leading academic journals in economics. Figure 1 depicts the share of articles on climate change published each year in *top-5* economic journals and in all journals in all scientific disciplines. It indicates that the share of articles dedicated to climate change published in *top-5* economic journals is about half of that in science as a whole.

Does this strikingly low share reflect a low interest in climate change in economics? Does it mean that economics have only a secondary part to play in the issue? It might be argued that the most pressing scientific challenge is to further our understanding of the physical and natural processes underlying climate change. This can help predict how greenhouse gases accumulate in the atmosphere, how the climate will respond to increased concentra-

tions of greenhouse gases, how this will affect temperatures and precipitations, and how climate impacts will be distributed across time and space.

Yet, if one uses the classical definition of economics as “the science which studies human behavior as a relationship between ends and scarce means which have alternative uses” (Robbins, 1932, p.15), it appears that economics has its say on the issue. After all, the economic choices of human beings in terms of production, consumption, and investment determine to a large extent how much greenhouse gases are released into the atmosphere. As long as agents have an incentive to allocate their resources to greenhouse gas emitting activities, it is likely that they will continue to do so. Tackling climate change thus requires to study the behavior of economic agents, the trade-offs they face between “ends and scarce resources”, and how policy instruments can influence their economic decisions. It also requires to better understand how billions of microeconomic choices are coordinated at the global level, notably through markets, and to assess the resulting environmental and economic consequences. Last, as climate change itself will affect the level and distribution of resources, it is also important to describe how it will impact the decision space of agents and how they can adapt to this “new normal”.

Along these lines, the economics of climate change is classically categorized into two broad fields of study: mitigation and adaptation. Regarding mitigation, economics can inform on how to best allocate resources when taking into account the environmental consequences. The objective is to design policy instruments able to minimize the costs of reaching a given environmental target (expressed e.g. in terms of total emissions, concentrations, or change in global average temperature). As for adaptation, economics can evaluate how economic agents may modify their behavior in response to climate change in order to reduce the damage they incur and/or their exposition to climate risks.

Note that the distinction between mitigation and adaptation is not as clear as it may seem at first glance. First, some evaluation of the climate related damages is needed for both. Second, the actions taken to mitigate greenhouse gas emissions may have consequences on the possibilities to adapt to climate change, and *vice versa*. However, this distinction is useful to structure the presentation of how economics in general can inform vari-

ous aspects of climate change. In what follows, I propose a synthetic overview of the contribution of the discipline to our understanding of the consequences of climate change and the associated policy recommendations before examining the implications for the agricultural sector.

The economics of mitigating greenhouse gas emissions

Climate change is a textbook example of a global externality (Pigou, 1920; Nordhaus, 1977). By emitting greenhouse gases, some agents deteriorate the welfare of other agents—possibly distant in space and in time—without bearing the consequences of their actions. This externality creates a market failure, which leads to an inefficient allocation of resources and excessive damages and justifies a policy intervention.

The standard toolbox of environmental economics can then be used to design public policies aimed at encouraging agents to reallocate their resources towards lower greenhouse gas intensive uses. Two main categories of policy instruments are available in this toolbox: regulatory “command-and-control” instruments, and economic “market-based” instruments. The former includes instruments to reduce pollution through rules or standards imposed on production methods. The second category includes instruments providing economic incentives to reduce pollution, e.g. pricing greenhouse gases emissions using a tax or an emissions trading scheme. While the first category of instruments imposes the adoption of a certain behavior, the second one aims to induce this behavior by providing the appropriate incentives.

In a stylized world, in which greenhouse gas emissions externality would be the only market failure in the economy, pricing greenhouse gas emissions is generally the instrument favored by economists (Blanchard et al., 2021). The main reason is the cost-effectiveness permitted by this type of instruments. Under e.g. a carbon tax, the emitter reduces its emissions until the cost of reducing one additional unit of emissions, i.e. the marginal cost of abatement, corresponds to the tax level. As a result, with rational economic agents making the optimal decision on their own, the mitigation effort is directed towards the actions characterized by the lowest abatement costs and total abatement costs are minimized.

The superiority of market-based instruments relative to command-and-control instruments is all the more important when the heterogeneity of abatement costs across agents is large (Newell and Stavins, 2003). When agents are characterized by heterogeneous abatement costs, setting a uniform price on all sources emissions is sufficient to ensure cost-effectiveness. To the contrary, an emission standard must be individualized to minimize total abatement costs with heterogeneous agents. In most situations, this would impose an unrealistically prohibitive informational burden for the regulator.

The classical response of economics to mitigate climate change is thus to set a unique price to all greenhouse gas emissions from all sources and sectors. The question that immediately follows is that of the value chosen to price emissions.

Following the standard reasoning in environmental economics, this value, also known as the social cost of carbon (Nordhaus, 2017), results from the confrontation of the overall marginal abatement cost and the marginal damage.

To determine the value of potential future harm caused by today's emissions, there has been an important effort in the literature based on Integrated Assessment Models (IAM), inspired by the pioneering works of Nordhaus (see e.g. Nordhaus, 2014, for a review of the approach). This approach articulates climate models and scenarios into a standard optimal growth model. The economic costs caused by greenhouse gases emissions is obtained by comparing scenarios with decarbonized activities and a stabilized climate, and a business as usual scenario. The evaluation of damages of climate change can be refined by taking into account e.g. their irreversibility, their uncertainty, or their distributional effects (Burke et al., 2015; Cai and Lontzek, 2019; Hsiang et al., 2019).

There is a large literature assessing marginal abatement costs analysis, in a variety of sectors and contexts, and using various methods (assessments of various technical options, structural micro-economic models, partial or general equilibrium models) (Kuik et al., 2009; Gillingham and Stock, 2018). They provide useful information about the abatement response to the implementation of a carbon price and their heterogeneity across agents, sectors, or countries.

Despite the consensus among economists regarding the importance of pricing green-

house gases, around 60% of the emissions in the OECD are currently not subject to any carbon price in 2018 (OECD, 2021). Even when policies are in place, entire sectors are often left out of their scope through exemptions or derogatory provisions. In addition, the price on emissions is mostly determined at the national level, with large discrepancies between countries (World Bank, 2017). In practice, we are thus still very far from a situation where a global, comprehensive, and unique carbon price could guide economic agents in making the most cost-effective decisions with regard to climate change. As a result, the flexibility among sectors and/countries is not sufficient to fulfill the ambitious climate objectives in a cost-effective manner.

Many difficulties may explain the slow and partial adoption of price instruments aimed at mitigating greenhouse gas emissions. I will hereafter focus on three possible reasons: the imperfect monitoring of greenhouse gas emissions, the uncertainty associated with abatement costs, and the potential distributional effects of mitigation policies.

First, greenhouse gases emitted by firms or households are not directly observable by the agent or the regulator. In most cases, emissions are derived from indirect observations of activity data (output, consumption, input use, etc.) combined with standardized emission factors. For instance, emissions of CO₂ from cars are not measured directly from the exhaust pipes, but calculated from the consumption of fuel multiplied by a fuel-specific emission factor (Bellassen et al., 2015). Actual emissions may then differ from measured emissions. The difference may vary substantially depending on the source or the gas considered, the level of aggregation. It may well be the case that emission factors do not reflect technical or local specificities that alter the emission process; or the emissions reporting system does not allow for reliable collection of activity data.

Second, the effect of imperfect information regarding abatement costs and damages on the efficiency of pricing or quantity to regulate pollution has been the subject of important research in environmental economics. Weitzman (1974) shows that under uncertainty regarding aggregate abatement costs, taxes and quantity regulations lead to inefficiencies, because the resulting mitigation is not optimal given the ex-post knowledge on abatement costs. In order to properly assess the social cost of carbon, it is then important to have an

accurate and detailed understanding of the adjustment techniques to reduce emissions and their respective costs. This is all the more challenging as the agents are heterogeneous.

Third, polluters being heterogeneous, pricing emissions leads to large differences in income impacts. The redistributive effect of the instrument matters and determines its acceptance. In the context of consumption, carbon taxes are shown to be regressive in most high-income countries, because lower-income households are also those whose consumption shares relies the most on carbon-intensive goods (Grainger and Kolstad, 2010; Cronin et al., 2019; Ohlendorf et al., 2021). The “Yellow Vest” protest, which led to the withdrawal of the projected increase in fuel tax in France in 2019 (Douenne and Fabre, 2021), illustrates the importance of the redistributive effects of an environmental policy for its social acceptance.

For each of the difficulties discussed above, environmental economics offers solutions. The design of policy instruments can be adapted to address the uncertainty upon emissions measurements and/or the monitoring of emissions (Millock et al., 2002, 2012; Bellassen and Shishlov, 2017); or to address the information asymmetry regarding abatement costs (Spulber, 1988; Mason and Plantinga, 2013); and to design transfers which correct the regressive distributional impacts of climate policy (Cronin et al., 2019). Accounting for these difficulties often requires to adopt a second-best approach, but it does not fundamentally change the overall economic perspective.

The economics of the adaptation to climate change

Current mitigation efforts are unlikely to be sufficient to prevent significant climate change in the coming decades. There is thus a need to assess the impacts of climate change, and the degree of flexibility that agents may use to moderate these impacts. The IPCC (2014) defines the adaptation to climate change as “the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities”. The ease and flexibility of changing decisions, as well as the magnitude of climate change impacts that are moderated, define the adaptation margin. It depends on the impacts of climate change on natural or human-made assets, which must be obtained from other disciplines.

The economic approach to adaptation then fully exploits the results of these assessments and translates them into an economic response.

This definition entails a fundamental distinction between the effects of climate change and the economic damage caused by them. Climate change effects are the physical measure of climate change, such as extreme temperature variations. The damages of climate change correspond to the economic measure of climate change, i.e. the effects of temperature variations on economic variables while accounting for agents' adjustments.

The economic environment in which the adjustment decisions are made is decisive in accurately representing and assessing the adjustments margins to a modified climate. Considering production costs, profitability of production alternatives, agents' expectations, interactions with markets and prices, infrastructures or technologies, make that a climate-related drop in productivity does not mechanically translate into a proportional decrease in supply.

Economics can study how economic agents modify their decisions in a changing environment. Agents' adjustments to changes in the conditions of production is a central question in microeconomics (Samuelson, 1947). Using for instance the envelope theorem in a microeconomic model, one can obtain theoretical predictions on the deviations from the private or social optimum in response to climate-induced changes in productivity (Guo and Costello, 2013; Hsiang, 2016).

In particular, the analysis of the market and its adjustment mechanisms is central to the study of adaptation. The market plays a central role in mediating the effects of climate change and transmitting adaptation behaviors (Anderson et al., 2019). Market mechanisms make it possible, for example, to imagine that a generalized decrease in productivity for one sector in the world could tend to increase the price of the sector's product and in return intensify the production in some places that would mitigate the pure yield loss overall. Individual decisions to adapt are thus interdependent through the market, which gives a collective dimension to adaptation.

It is rather the proper consideration of the context of the adjustment decisions that accurately determines the adjustment margins. The timing context determines whether some

inputs are fixed or variable in the face of a more or less rapid change in climate. The regulatory context is also important. Existing regulations can distort market adjustments and potentially impede adaptation. For instance, the National Flood Insurance Program in the United States offers reduce flood insurance rates and is shown to bias downward the perception of flooding risks (Kahn and Smith, 2017). The competition and market structures also determine the price and quantity adjustments on the market following a climate-induced change in costs or productivity.

The issues of putting a price on greenhouse gas emissions into practice, and of correctly modeling and valuing the margins for adapting to climate change are particularly relevant to agriculture. Let us now look at how these difficulties specifically apply to this sector.

Challenges of transitioning the agriculture to a carbon-neutral and resilient sector

Concerns about pricing emissions from the agriculture in practice

Agriculture remains to a large extent out of the scope of the main climate policy instruments. There are independent and voluntary initiatives, such as the *Label bas-carbone* in France. However, the Common Agricultural Policy, which is the overall framework for agricultural policy in Europe, does not include a binding mitigation target (Dupraz and Guyomard, 2019; Guyomard et al., 2020). The ambitious goal of the Paris agreement to keep the temperature increase below 2°C above pre-industrial levels could materialize through the implementation of the Green Deal in the European Union, which aims at making Europe carbon-neutral by 2050. However, excluding agriculture limits the inter-sectoral flexibility and raises concerns about the possibility of reaching this ambitious objective efficiently.

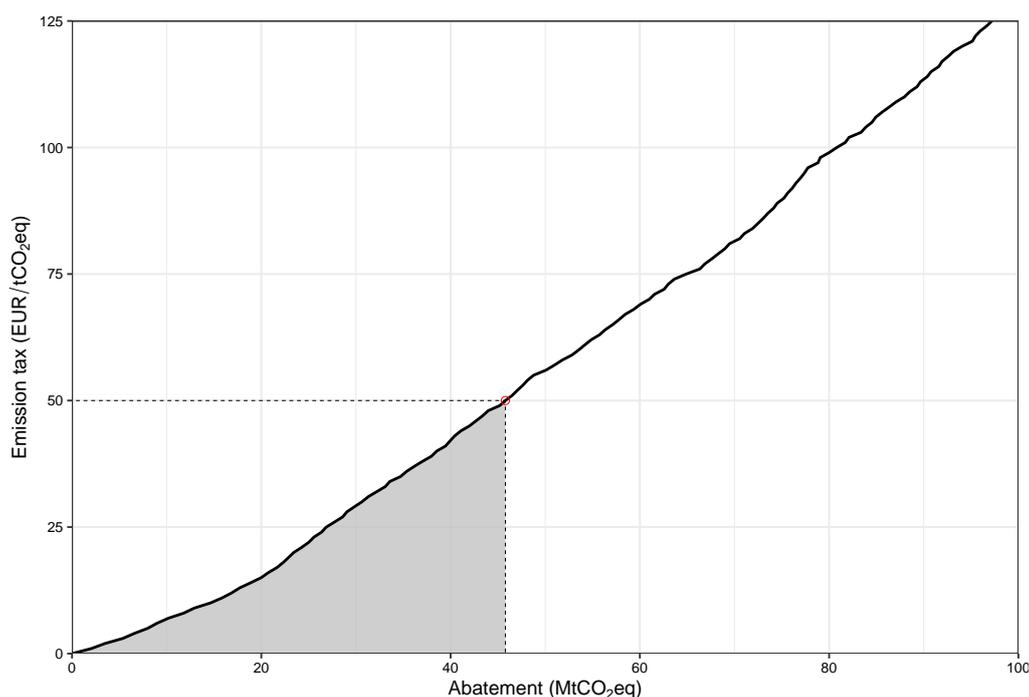
Agriculture is a sector composed of numerous farms, which are highly heterogeneous in several dimensions. They differ in locations and climatic conditions, they have varying size and their crop mixes and livestock types are heterogeneous. This implies that there are important differences in the technical and agronomic potential to modify the production

plan to a given emission norm or price. This heterogeneity confers a serious advantage to carbon pricing over regulatory instruments in the case of agriculture.

However, taking this heterogeneity into account is difficult when evaluating abatement costs. The effect of the tax on farmers depends on how emissions are initially distributed across farms and also on their ease to adjust their production plan accordingly, that is, the distribution of the abatement costs. A detailed representation of the agricultural production is required to adequately capture the heterogeneity of farmers' response to a uniform price on their emissions. The informational and technical requirements to build such a representation is important and needs a thorough approach relying on farm-level data as well as a detailed modeling of the agronomic and technological constraints. This adds technical difficulties to obtain a realistic model of the reaction of farmers to the implementation of a mitigation policy.

There are several methods to integrate this heterogeneity in abatement costs assessments in the agricultural sector (see Vermont and De Cara, 2010, for an overview of the estimation approaches of the mitigation potential in the agriculture). One method, among others, harnesses greenhouse gas emission processes into a microeconomic model representing farmers' decisions and accounting for their agronomic and technical constraints. Agricultural greenhouse gases emissions mainly come from fertilizer use and livestock. They are affected by farmers' decisions regarding land allocation, animal farming, or soil management. These decisions depend on economic dimensions regarding input or output prices. By putting a price on emissions, we modify these costs and we incentivize farmers to divert their resource allocations from emission intensive use. Depending on the sophistication of the modeling, the adjustments considered could be changes in herd size, changes in livestock feeding, or reductions in fertilizer use. As a result, the farmer will adjust its farming practices and the emission reductions undertaken will be all those requiring an effort lower than the price of the emissions. These adjustments will be made under the assumption that farmers are rational, and observe their emissions. The abatement cost is then the difference between the farmer's revenue under carbon tax compliance and that in the absence of regulation. The model used in Chapter 2 is built to capture these trade-offs with a represen-

Figure 2: Abatement supply in the EU agricultural sector.



Note: Under an emissions tax of 50 €/t.CO₂eq, the EU agricultural sector reduces its emissions of 45 MtCO₂eq, which corresponds to 11% of total emissions in the sector. Initial emissions considered amount to 406.8 MtCO₂eq. This figure is adapted from Chapter 2.

tativity of the different farming systems in the EU-27.

Then, by aggregating farmers' reactions, one can get their abatement supply, that is the quantity of greenhouse gases emissions reduced by the sector for a given emission price. Figure 2 represents this quantity of agricultural greenhouse gases emissions reduced for a given emission price in the EU and obtained from the model used in Chapter 2. It reflects the industry marginal and total abatement costs when a cost-effective policy is implemented. Aggregate abatement costs correspond to the area below the abatement curve and for a given emissions price. As an illustration, if the tax is set to 50 €/tCO₂eq, abated emissions amount to 45 MtCO₂eq, for an aggregate abatement costs of 979×10^6 € (gray area on Figure 2). By contrast, the benefits from these avoided emissions are equal to $2,290 \times 10^6$ € (area of the dashed rectangle on Figure 2). Thus, economics can inform the potential benefits from implementing a climate policy in the agricultural sector.

However, the difficulties in monitoring emissions presented above are particularly salient with respect to the agricultural sector. Agricultural greenhouse gas emissions result from microbial activities in the soil, in the digestive track of livestock, and in manure. The biogenic

nature of emissions and the multiplicity of heterogeneous sources make them complex to measure as they vary across space and time, due to differences in soil type, precipitations or temperature. Measuring, controlling and verifying agricultural emissions to guarantee the effectiveness and efficiency of any mitigation policy is challenging (Garnache et al., 2017). This argument has also been used as a justification for excluding the sector of current climate policy (Ancev, 2011).

The imperfect observation of farm-level pollution can be improved if an efficient monitoring, reporting and verification system is introduced into the policy design. The level of stringency and precision of the monitoring scheme becomes a choice variable besides the price instrument. On the one hand, more precised information regarding pollution levels improves the reallocation of resources under emission pricing. On the other hand, stricter monitoring requirements are more costly to implement. When designing the instrument, the regulator trades off costly monitoring requirements with the loss in efficiency in input allocation (Millock et al., 2002; Bellassen and Shishlov, 2017). The main outcome is that the mitigation policy instrument does not provide the first-best outcome: some pollution remain unobserved because the monitoring technology is expensive.

Here, the characteristics of the monitoring technology play a key role. An efficient one can lead to more precised knowledge at a lower cost, thus improving the effect of the instrument. For the agriculture, one available approach is to have an idea of the amount of activity, and then emissions can be counted using emission factors. This requires activity data recording farm facilities and documenting behavioral change. One advantage is that these data are also recorded to justify payments under the CAP or to comply with cooperative or private certification standards. However, there are still efforts to gather, simplify and share data, which are costly, and this will only provide an imperfect information on the level of pollution. The costs of monitoring, reporting and verifying pollution levels of farmers may form a budget constraint regardless of the policy design. Whoever bears the costs of these monitoring activities, their total amount may offset the net benefits from the emissions reduced by the tax, and be an obstacle to the implementation of a policy regulating emissions in the agriculture.

Moreover, with regards to the previous argument, the high heterogeneity of farming systems adds on difficulties in monitoring emissions. This challenges further monitoring, because it implies multiple margins of adjustments of emissions to be identified, potentially in a nonlinear fashion. Also, deriving emission factor is prone to error given this diversity. It requires high-level data on emission processes, possibly spatially disaggregated. This is likely to push the costs of monitoring systems even forward.

Finally, this heterogeneity implies that some farmers can reduce more emissions than others and that some farmers bear important abatement costs. For agriculture, the regulator might also be concerned with protecting the income of the most vulnerable farmers, depending on the distribution of the cheapest opportunities to reduce emissions across farms. Compensation schemes, transfers, or other designs which can alleviate the burden of the tax must be considered.

These elements underline some concerns regarding the application of carbon pricing instruments in the agriculture. The polluter pays principle, which is central to environmental economics would then suffer from a lack of applicability and low acceptance in the case of agriculture. It questions ways to make a carbon tax operational for the sector.

Assessing the adaptation of the agricultural supply

Agriculture is a sector where the analysis of adaptation to climate change is particularly scrutinized because it is vulnerable to climate change. Warmer temperatures are expected to decrease yields in many regions (Asseng et al., 2013; Chen et al., 2016). For instance, soy yields in the United States are likely to decrease from 30 to 80% before the end of the century depending on the climate scenario considered (Schlenker and Roberts, 2009).

In the face of climate change, two types of adjustments are usually distinguished: the intensive and the extensive margins of adaptation. The intensive margin of adaptation is obtained by adjusting a continuous choice variable in response to climate change. Such adjustments are changes in planting times, or in the quantity of fertilizer. The extensive margin considers discrete changes in reaction to climate change, such as crop allocation, or the adoption of heat-resistant crop varieties (Guo and Costello, 2013). The literature then

focuses on assessing these different adjustment margins, using econometric or statistical methods, or structural approaches.

Econometric techniques infer adaptation behaviors under climate change using historical observations. A first identification strategy is to use joint spatial variations in land values and climate, as in the Ricardian approach developed by Mendelsohn et al. (1994). But this approach is fundamentally vulnerable to omitted variables, since any unobserved drivers of land values correlated with climate bias the results. As an improvement, the panel approach makes full use of longitudinal data, and controls for time invariant confounders (Deschênes and Greenstone, 2007). However, this approach tends to capture short-run adjustment to weather fluctuations rather than long-run adjustments to shifts in climate (Mérel and Gammans, 2021). This is conceptually different since weather is the distribution of a given climate. That is, the climate is given in the short-run, but weather may fluctuate. For instance, the mean and standard deviation of daily rainfall is given in the short-run, and random events occur with more or less important deviations from the mean. In the long-run, the distribution of weather conditions is shifting. This needs long time-series data to hope identifying adjustments to changes in climate. Finally, a broader criticism on the econometric approach is whether one may adequately represent future farmers' adaptation in the long-run based on past observations (Kahn, 2014).

Other approaches use structural methods to model and derive the value of the adaptation to climate change. Such approaches use microeconomic models or general equilibrium frameworks to characterize the role of costs, or prices adjustments in mediating adaptation (Leclère et al., 2013; Costinot et al., 2016; Gouel and Laborde, 2021; Rudik et al., 2021). These models generally showcase perfect competition frameworks with key parameters calibrated on data. Then, equilibrium changes under climate-induced productivity shifts are computed to assess the adaptation margins of the economy. In contrast to the econometric approach, this method explicitly models the market adjustment mechanisms that are important for policy or developing priorities for adaptation. However, it still relies on key modeling assumptions regarding farmers heterogeneity, or market structure, which are not relevant in some contexts.

Overall, these methods tend to confirm that intensive adaptation margins exist, but are relatively small. For instance, double cropping seems to offer little adaptation margins to producers (Seifert and Lobell, 2015). Extensive adaptation margins, and in particular large-scale relocation of production, seem to provide a significant adaptation margin. Using an econometric method, Cui (2020) shows that farmers are expanding the area devoted to corn and soybean in the United States in reaction to climate change. With a structural approach, Costinot et al. (2016) explore the role of within and between countries reallocation of crops and trade to cope with climate change. Given that climate change effects are uneven around the world, this work highlights the substantial benefits from crop reallocation allowed by the heterogeneity in comparative advantage. However, this is not the case for all agricultural products. For some, such as products under Geographical Indication labels, they are defined by where they are produced. It is therefore not possible to relocate their production to areas that are little affected by climate change.

Geographical Indications structure the wine and cheese markets according to their place of production. Cheese and wine quality is partly determined by the pedo-climatic conditions occurring in their place of production, i.e. also referred as *terroir*. However, in the absence of a label, it is not verifiable by consumers even after consumption. Then, producers located elsewhere would have an interest in fraudulently claiming that their product comes from the region where the high quality originates. This information asymmetry on quality makes that producers of high quality are not willing to sell their product (Akerlof, 1970). Then, Geographical Indication are collective intellectual property rights granted to some producers in a precisely delineated exclusive area, which indicates that their product's quality is attributable to their geographical origin. They restore incentives for high-quality producers to market a differentiated product and improve consumer information on quality (Mérel et al., 2020).

Thus, the extensive margin of adaptation for agricultural production under Geographical Indication is narrow, since it cannot benefit from other places showing beneficial conditions of production. Previous approaches in the agricultural context cannot be directly replicated to this segment of the agricultural supply to analyze their adaptation. Economet-

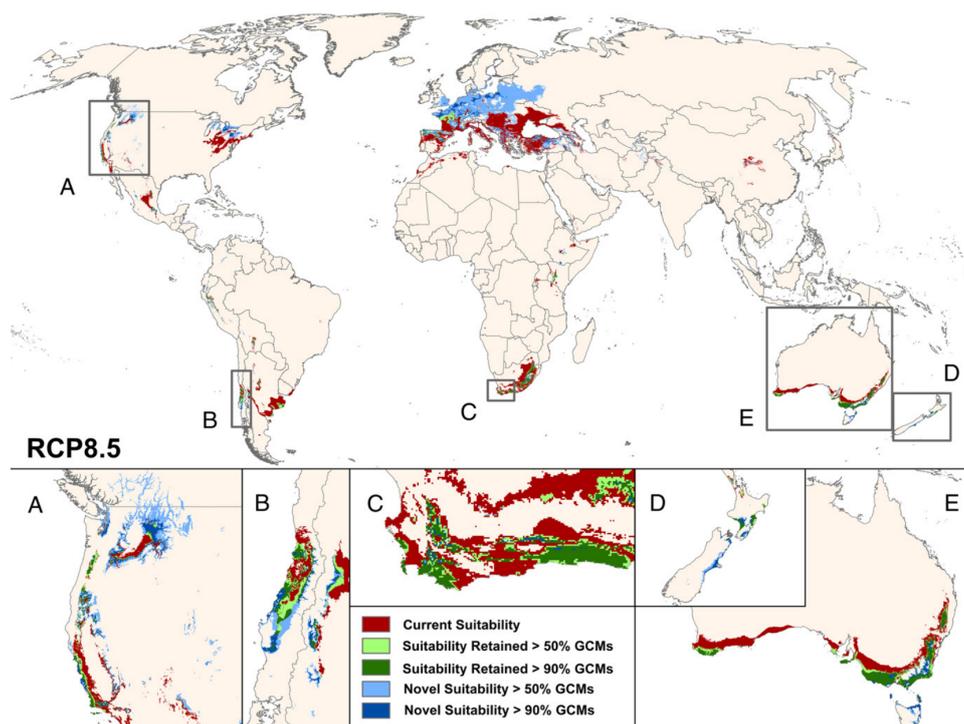
ric approaches suffer from a lack of empirical evidence on the effects of climate on the supply of quality. The few studies on the agricultural supply of quality products under climate change (or under weather fluctuations) focus, for example, on rice (Kawasaki and Uchida, 2016) or on apples (Dalhaus et al., 2020).

On the other side, the structural approach should take into account the specific market structure induced by Geographical Indication labels. They indeed provide some degree of market power to producers, as they prevent the entry of outside producers. Furthermore, by being historical markers of the wine and cheese markets, Geographical Indications can be considered as a form of an institutional barrier to adaptation. A thorough look into the political economy and the governance of these labels is needed to know whether these institutions are carved in stone or are flexible in the face of climate change. They are collectively managed by producers, which means that GI specifications are set after producers agree on the degree of supply control on their inputs. Finally, some GIs represent large area with different conditions and heterogeneous producers, that inevitably makes winners and losers under adaptation of the label specifications.

Nevertheless, production of wine is likely to importantly suffer from climate change. In a prospective exercise, which combines climate models and an agronomic model determining the suitability to produce wine in a given place depending on temperature and heat exposition, Hannah et al. (2013) show that the area suitable for viticulture will decrease from 25% to 73% in major historical wine producing regions by 2050. These projections are represented on Figure 3. It is important to emphasize that this work does not account for economic determinants of agricultural supply. For instance, whether it is economically viable for currently non-producing regions considered as suitable for viticulture in the future to effectively reorient their production depends on their opportunity costs as well as on the marketing and reputation costs.

Nearly 15% of the value of sales in the food and drink sector in France and 12% in Italy comes from Geographical Indications products. This label is one of the main public quality label for agricultural production in the European Union (European Commission, 2020). Insofar as GIs seem to improve the well-being on the market by providing high-quality prod-

Figure 3: Projections of suitability in wine production in 2050.



Note: Areas currently suitable for viticulture and with deteriorating suitability in the future are highlighted in red. Areas currently suitable as well as in the future are highlighted in green and light green. Areas not currently suitable for viticulture but suitable in the future are highlighted in blue.
 Source: Hannah et al. (2013)

ucts, and as they are particularly sensitive to climate change, the question of how adapting their supply arises. It is necessary to develop adequate tools which take all the relevant dimensions of their supply into consideration in order to investigate the question.

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Is there a shift in the economics in the face of climate change? This introductory analysis highlights enrichments brought about by the analysis of climate change. On the one hand, the economic approach of climate change has endeavored to apply and extend the already existing toolbox of environmental economics of the externality regulation in the case of greenhouse gas emissions. On the other hand, methods for analyzing the consequences of market adjustments or behavioral changes caused by climate change have been developed. These enrichments can be looked at in detail in the case of agriculture.

The objective of the research conducted in this thesis is to explore how economic approaches can help engage agriculture in an effort to mitigate greenhouse gas emissions and can improve our understanding of effective strategies for the sector to adapt to climate change. The work presented shows that the economic tools developed in relation with research on climate change are vast and that the design of mitigation policy instruments takes an important place in this literature (Chapter 1). The most prevalent mitigation policy instrument in the literature is carbon pricing (Chapter 1). If we implement the instrument as such to mitigate greenhouse gases emissions from the agriculture, the benefits of the abatement might be entirely offset because of the monitoring costs of emissions (Chapter 2). An alternative policy design is considered to save some monitoring costs while still reducing efficiently emissions (Chapter 2). Then, the economics of the adaptation to climate change has been more applied to the agriculture than any other sector, given the strong dependence of the sector on climate (Chapter 1). Here, the relocation of agricultural production to adapt to climate change is studied from a theoretical perspective, when modifying the production areas is made difficult by the presence of Geographical Indication (Chapter 3).

Contributions

A quantitative overview of the economic literature on climate change

Chapter 1 has its origin in the aforementioned statement from Oswald and Stern (2019), who call economists to increase their contributions on the understanding of issues related to climate change and to play a role in guiding policy to tackle climate change. This chapter gives an answer by quantitatively discussing the entire academic production in economics on climate change. This work aims to document how contributions on climate change in economics have evolved over time. In particular, I focus on the volume of publications, their structure by journal, and the topics addressed. With a more global objective, the idea is to understand the role of the economics discipline in the face of climate change.

To do so, I construct a corpus of articles representative of the economics research on

climate change. The main issues in the corpus construction are to define the boundaries of the economic literature on climate change, and to develop an automated technique to identify the relevant publications given the volume of the literature considered. After having developed a bibliographic data extraction protocol, I obtain a corpus of about 14,000 economic articles on climate change referenced on WoS and Scopus.

Using this corpus, I can further illustrate the low share of articles related to climate change in top-5 journals underlined by Oswald and Stern (2019) and represented on Figure 1. However, by focusing on these journals, Oswald and Stern miss the fact that economics has built up an extensive literature on the subject outside these leading journals. In particular, the coverage given by economic journals is of similar scale of that in science as a whole.

I then show that climate change keeps on spreading in the economics as a whole, by being increasingly present in economic fields historically non-specialized on the topic and in some general economics journals. In addition, the share of articles dealing with climate change in a journal is positively correlated with the impact factor of the journal. Furthermore, articles related to climate change receive more cites in average than other articles in the same journal. This bibliometric approach qualifies the statement from Oswald and Stern (2019), by showing that the profession has paid an increasing attention to climate change in the recent years.

I also provide quantitative assessments of the prevalence of particular research questions and topics in the economics of climate change. I categorize articles using their abstract into topics based on a topic model, which classifies articles from their co-occurrence of words. This approach shows the importance of analysis on mitigation policy instruments and integrated assessment models in the literature until 2005. From then, the literature has extended its scope. In particular, the share of empirical approaches on the sectoral implications of climate change in the agriculture or transportation, and the share of empirical works identifying the causal effect of growth or trade on GHG emissions patterns have increased. This illustrates how and from what angles economics has appropriated the subject of climate change.

Partial coverage of an emission tax in the agricultural sector

Chapter 2 examines the optimal coverage of a mitigation policy instrument in the presence of monitoring, reporting, and verification (MRV) costs. Although this question has been investigated in the general interest economic literature, such as in the optimal taxation field (Yitzhaki, 1979; Wilson, 1989), the present work focuses on the optimal coverage of an environmental pollution tax—assuming individual costs are unknown.

The basic problem is that all polluting firms generate environmental damage. However, taxing some firms may lead to a negative net social benefit if marginal abatement cost and administrative costs to monitor emissions exceed the avoided marginal environmental damage. Therefore, full coverage may not be welfare maximizing, and in some cases *laissez-faire* may even outperform full coverage. Thus, the regulator wishes to tax only firms for which being taxed generates a positive net social benefit. The problem is that the regulator cannot distinguish firms bringing a positive net social benefit from firms having a negative net social benefit of abatement when taxed because individual abatement and monitoring costs are generally not observable.

With my co-authors Stéphane De Cara and Pierre-Alain Jayet, we propose an alternative policy design, which adds an exemption threshold to the level of the tax. That is, the regulator sets a threshold based on some observable and non-manipulable characteristics, where firms with characteristics above the threshold are included in the tax and firms with characteristics below the threshold are excluded. Tax exemptions through a partial tax base are common in public taxation (Keen and Mintz, 2004). Exemptions also exist in environmental policy. For example, installations emitting more than a given amount are covered by the European Union Emissions Trading Scheme. We here justify these exemptions to save monitoring costs, and we seek the optimal level of these exemptions.

Using an analytical framework, the required conditions regarding abatement costs and monitoring costs heterogeneity for the existence of an optimal threshold as a first-best policy are identified. A simple formula approximating the optimal threshold based on flexible specifications for MRV costs and abatement costs is also highlighted. Because this formula relies only on aggregate or sectoral information, we argue that this method is easily imple-

mentable.

Then, we apply these theoretical insights to the question of greenhouse gas mitigation from the EU agricultural sector, which is currently exempted from emission reduction efforts. We seek to determine the coverage of an emission tax and to characterize the welfare effects of this tax scheme when applied to the sector. We use a detailed agricultural supply model at the farm-type level to derive individual and aggregate abatement supply. We calibrate MRV costs using values published for other economic sectors. By relaxing some of the required restrictions on inter-farms heterogeneity in abatement costs for the optimal threshold to exist, we can investigate how the simple formula to approximate the threshold performs in second-best settings. We finally show that only a small number of relatively large emitters of GHG should be optimally covered by a mitigation policy in the agriculture. This work then contributes to a literature which underlines the important monitoring costs of emissions in the agricultural sector (Garnache et al., 2017) and uses this to justify excluding the sector from the scope of climate policy in Europe (Ancev, 2011). The decision whether or not to regulate agricultural emissions is not necessarily restricted to *laissez-faire* or full coverage. Targeting only a fraction of the farms may limit MRV costs, while simultaneously incentivizing cost-effective reductions in emissions.

Adapting geographical indications

While shifting crops, production and processing to new geographical areas is one way of improving value loss due to climate change (Costinot et al., 2016; Gouel and Laborde, 2021). This strategy has not been considered for Geographical Indications. The third chapter examines the relocation of agricultural production as a strategy to adapt to climate change when modifying the production areas is made difficult by the presence of Geographical Indication.

In particular I examine how climate change may affect the border of the geographical area within which producers have the right to claim the label. This chapter develops a theoretical model to examine the issue. First, the historical GI area is either open to any producers having a comparative advantage or delimited by the producers' organization to max-

imize the GI industry profits. These two alternative assumptions are meant to capture the strength of the exclusivity constraint exercised by the label and to reflect the fact that existing GI labeling schemes across the world differ in the degree of market power left to producers. Then, I compare to the social optimum the outcome under both delineation systems, and recover and extends existing results in the industrial organization literature on Geographical Indications (Moschini et al., 2008; Mérel and Sexton, 2012).

Next, I study in which direction the border of the GI area is modified in a reaction to a climate-induced deterioration in the conditions of production. Does it shrink or does it expand to include producers that were previously producing the unlabeled commodity? Climate deterioration is interpreted as reducing all producers' comparative advantage in the GI product. For the open delineation case, the model shows that the result of climate change on the extent of the GI area crucially depends upon the relation that holds for the producer at the border of the GI area between the absolute value of the GI revenue change due to climate change and the opportunity cost of producing the commodity. If the opportunity cost is less than the absolute value of the change in revenue, then for a small climate deterioration the GI area extends, while for a larger such deterioration the GI area shrinks. When the producer at the border finds the opportunity cost of remaining in the GI area higher than the reduction in its revenue from producing the GI product, the GI area shrinks monotonically with the severity of the climate change. When the GI area is determined monopolistically, the same pattern is observed, but now the crucial relation is between the elasticity of quality and that of quantity elasticity, depending also on the shift of the marginal profitability caused by the climate change.

This piece of research underlines the specific adaptation patterns of products under Geographical Indication. It models the determinants of the incentives for GI producers to relocate their production. When the GI agency behaves as a monopolist, quality changes at the border are crucial in determining the potential expansions of the GI area. This illustrates the problems that some appellations may face, to decide whether or not to relocate their production in the face of climate change.

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List of Publications

Each chapter in the thesis is independent of the others. Chapter 2 is a slight adaptation of a published research article. Chapters 1 and 3 are working papers.

Chapter 1 has been accepted to the FAERE annual Conference in September 2021.

Chapter 2 is a reproduction of the **following article**, with few minor adjustments :

De Cara S, Henry L, Jayet PA (2018). Optimal coverage of an emission tax in the presence of monitoring, reporting, and verification costs.
Journal of Environmental Economics and Management, 89, 71-93.

Chapter 3 is under revision (revise and resubmit) at the *American Journal of Agricultural Economics*.

Chapter 1

A systematic review on the economics of climate change

Abstract

I analyze the production of scientific articles related to climate change published in economic journals. Using an iterative selection protocol, I identify a corpus of about 14,000 articles published between 1974 and 2020. I analyze in what journals these articles were published, the number of citations they have received, and the topics they address. The latter is based on a textual categorization of the content of abstracts using Latent Dirichlet Allocation (LDA). The findings indicate that (1) economic articles related to climate change remain predominantly published in journals in the field of energy and environmental economics, and very few are published in *top-5* economic journals, (2) the share of climate change-related articles in journals in other fields of the discipline has increased over the past decade, (3) the share of articles dealing with climate change in a journal is positively correlated with the impact factor of the journal, (4) articles dealing with climate change tend to be cited more than other articles published in the same journal. Until 2005, the corpus is dominated by articles examining mitigation policy instruments, as well as how long-term, and possibly catastrophic and/or irreversible implications of climate change can be included in welfare analyses. The last decade has seen an increase in empirical analyses of the sectoral implications of climate change (e.g., agriculture, transportation) as well as the links between growth, trade and CO₂ emissions.

1.1 Introduction

In a recent column, Oswald and Stern (2019) have highlighted the stark contrast between the potential economic consequences of climate change and the urgency of climate action on the one hand, and the strikingly low number of contributions dealing with climate change in leading journals in economics on the other. As shown in Figure 1.1, their observation is confirmed by the meager share of climate-change related articles published in *top-5* economic journals since 1974.¹ Is that to say, as Oswald and Stern suggest, that “economists are letting down the world”?

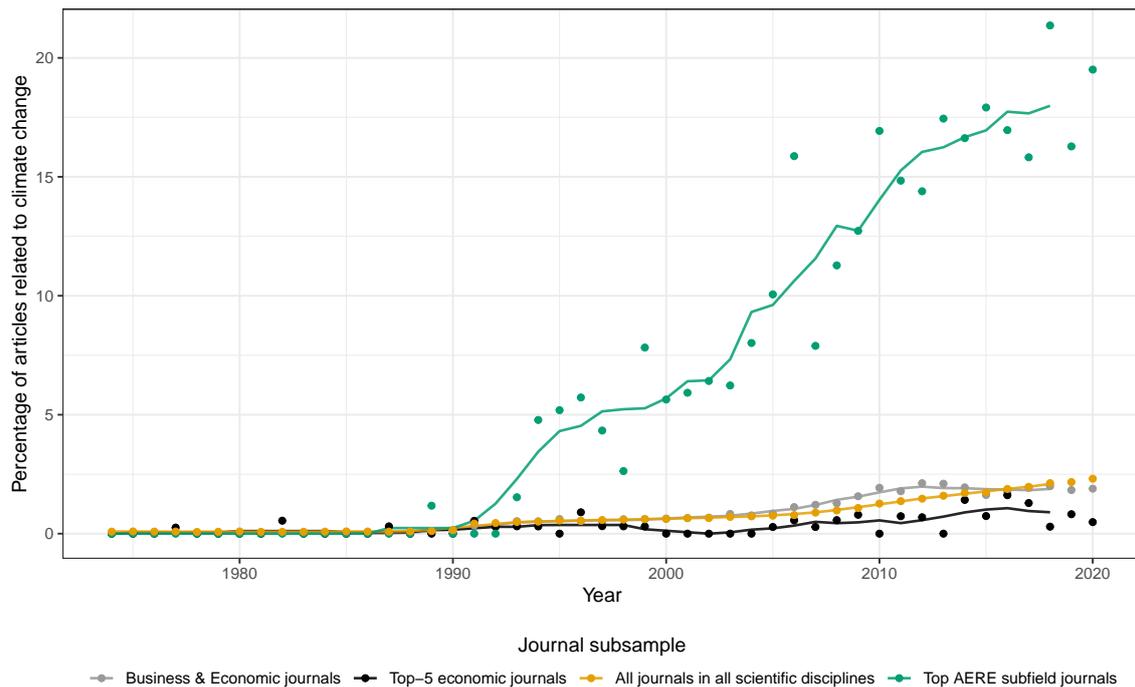
One broad objective of this chapter is to revisit Oswald and Stern’s assessment in the light of a quantitative, systematic, and in-depth analysis of the *whole* academic production in economics on the topic, i.e. beyond the only scope of what has been published in top-5 journals. This provides a broader and more complete picture of the scientific production in economics with regard to climate change.

One naive interpretation of Oswald and Stern’s assessment could be that economists, as a profession, have shown a limited scientific interest for issues related to climate change. This interpretation is in clear contradiction with the facts. The number of peer-reviewed publications in academic journals in economics related to climate change between 1974 and 2020 amounts to more than 14,000, or 2% of the total volume of the publications in the discipline over the same period. This share is, in many cases, higher than what prevails in other scientific disciplines concerned by climate change (see Figure 1.1).

When examining the production of the discipline as a whole, it thus appears clearly that economics has produced a large number of contributions on the issue, on a scale similar to that of science as a whole. Given the multi-faceted and complex nature of climate change, this production is very diverse, and characterized by a wide variety of issues addressed, methods employed, scope and scales investigated. In addition, it is likely that the contribution of economics has changed over time. The present work thus aims to document how the volume and structure—by journal, field and topics addressed—of contributions on

¹ *Top-5* journals are the leading journals in economics. These are the *American Economic Review*, *Econometrica*, the *Quarterly Journal of Economics*, the *Journal of Political Economy* and the *Review of Economic Studies*. These journals influence academic positions and policy makers (Heckman and Moktan, 2020).

Figure 1.1: Percentage of research articles related to climate change.



Note: in 2010, 1.9% of the articles in economic journals are related to climate change. I identify articles related to climate change using the WoS as the ones containing the exact expressions: “climate change” or “climatic change” or “global warming” or “greenhouse gas” or “carbon emissions” or “CO₂ emissions” or “carbon dioxide” or “climate policy”. I then separately aggregate the counts of articles by year and by category of journals, and divide these numbers with the total number of articles referenced in WoS each year in the considered category of journals. The four different categories of journals considered are: the “All journals in all scientific disciplines” category, containing all journals in WoS; the “Business & Economics journals” category with every journals categorized as economic journals by WoS; the “Top-5 economic journals” category which are the *American Economic Review*, *Econometrica*, the *Quarterly Journal of Economics*, the *Journal of Political Economy* and the *Review of Economic Studies*; and the “Top AERE field journals” includes journals considered as leading journals in the fields of Agricultural, Environmental, and Resource Economics (AERE) according to the CNRS ranking, which are the *Journal of Environmental Economics and Management*, the *Energy Journal*, *Ecological Economics* and the *American Journal of Agricultural Economics*. The lines measure the five-year moving average of each time-series.

climate change in economics have evolved over time.

Two main dimensions have been investigated in economics through the lens of climate change: (i) the correction of greenhouse gases (GHG) emissions externality and the role of the state(s) in this direction, also referred as the mitigation of climate change, (ii) the modeling of the consequences of climate change on the context in which economic agents evolve, or the adaptation to climate change. Nordhaus’ seminal works from the mid-1970s explore climate change in both direction by modeling the future impacts of climate change using a macroeconomic model and by illustrating the mitigation potential from pricing carbon emissions (Nordhaus, 1977, 2019a). This initiated the development of new tools for analyz-

ing long-term well-being in an unstable environment, in order to identify intergenerational wealth transfers needed to achieve optimal emissions mitigation pathways at a global scale (Nordhaus, 1993b; Stern, 2008). As illustrated by Vale (2016), the economic literature has progressively studied multiple economic dimensions applied to climate change, notably through the economics of insurance against catastrophic risks (Weitzman, 2009; Lemoine and Traeger, 2014), the economics of trade and climate (Fischer and Fox, 2012; Costinot et al., 2016), and the economics of the adaptation to climate change (Tol et al., 1998; Di Falco et al., 2011).

Some works synthesize subfields in the research domain extensively, for instance Viguié et al. (2021) on the interactions between adaptation and energy consumption. Other review tools and methods specific to the subject, such as Dell et al. (2014) for econometric methods using weather data or Pindyck (2013) regarding macroeconomic models integrating the economy and climate. However, no existing work provides a comprehensive quantitative assessment of the economic contributions on climate change to my knowledge.

The present quantitative overview is performed using a systematic review approach. Systematic reviews are purposefully developed to quantitatively analyze a literature in an encompassing way by (i) not setting a size limit on the bibliographic corpus, (ii) not imposing arbitrary rules to select the relevant literature, (iii) allowing reproducibility of the analysis, and (iv) investigating the literature from several perspectives by benefiting from the availability of large bibliometric data (Gough et al., 2017). Following the recommendations for systematic reviews developed in a general setting by Moher et al. (2010), I conduct a rigorous article selection protocol. I define the economics discipline as a set of economics journals, as is similarly done in other bibliometric studies about economics (Angrist et al., 2020; Advani et al., 2021). Thus, the analysis does not include publications by economists in general journals such as *Science* or *Nature*. This simplifies the identification of works on the subject, otherwise it would be difficult to separate the economic contribution in a work of general scientific interest. In addition, economists are likely to publish a significant portion of their work in economics journals. I then develop a bag-of-words approach with words from lexicons on climate change, wherein articles containing the associated words in

title, abstract or keywords are automatically classified as related to climate change. I finally identify a corpus of about 14,000 economic articles referenced in WoS and Scopus related to climate change and published between 1974 and 2020.

Then, I measure the evolution of the coverage and of the prominence of economic research on climate change. In particular, I investigate the place of the literature by studying the journals in which the articles are published. Since journals are held and edited by associations of scholars, the profession uses them as a mean to develop and structure the literature. I measure the coverage given to climate change at the journal-level to identify fields in the discipline that focus on the subject. Also, I use citations and journal impact factors to measure the visibility of the outlets where articles on climate change are published.

Finally, I investigate further the qualitative content of the economics research on climate change using a topic model. Topic models are tools developed to manage large collection of text data to discover the themes in a corpus using statistical techniques (see Gentzkow et al., 2019, for an exhaustive review of text analyses in economics including topic models). I use this approach to elicit themes structuring the economics of climate change. To this end, I implement a Latent Dirichlet Allocation (LDA) (Blei et al., 2003). LDA has been used to underline the topic treatment by journals (see e.g. Griffiths and Steyvers, 2004; Polyakov et al., 2018), or to categorize CEO behavior through their diaries (Bandiera et al., 2019), or to classify central banks communications (Hansen et al., 2018), or, unlike this work, to elicit topics in a scientific domain (Westgate et al., 2015; Sun and Yin, 2017). This method reduces the dimensionality of the corpus to better capture similarity between articles. As a result, I classify with some probabilities articles into topics, and I then determine the prevalence and the dynamics of the topics.

First, I document an increasing coverage over time given to climate change by the economics. Second, *top-5* journals leave a coverage to issues related to climate change which is significantly lower than the economic literature as a whole. By contrast, the energy economics and the environmental economics are the specialist fields on climate change, since 55% of the literature is concentrated among the top journals of these fields. Third, the last decade has seen the emergence of journals in general economics and in non-historically

specialized fields (mostly development and transportation economics) increasingly publishing on the subject. Fourth, I observe a positive correlation between the climate-change coverage and the impact factor of the journal. Fifth, articles on climate change tend to receive more citations than articles published in the same journal. This additional research impact is more pronounced in the recent years. Thus, these evidence suggests that the economics of climate change keeps on spreading to other fields, it is disseminated by visible journals and it is receiving a growing interest overall.

With regard to the topic structure of the literature, the preferred estimation shows 10 topics. These topics correspond to some intuitive structure in the literature ranging from carbon pricing, impact assessments of climate change (including Integrated Assessment Models), sectoral approaches (energy, transports, agriculture and carbon sequestration), methods to evaluate the carbon content and mitigation options, or effects of growth and global supply chains on GHG emissions. Trends in the topic content of the literature showcase the prevalence until 2005 of carbon pricing, and methods to include long-term, and possibly catastrophic implications of climate change in welfare analyses. Almost 40% of the publications between 1990–2005 focus on these questions. Starting from 2005, the literature has broaden its scope to develop econometric approaches on the relationship between growth and trade on GHG emissions, and empirical analyses of the sectoral implications of climate change in the agriculture or in the transport. In addition, these results seem to underline a literature split between global analyses of climate change and systemic climate policies on the one hand, and specific sectoral analyses on the other hand.

This work contributes to quantifying and qualifying the economic research on climate change in a comprehensive way. It is part of a strand in the literature aiming at reporting the scientific effort and its diffusion in a field, by taking advantage of the access to bibliometric data and/or using statistical text analysis (Card and DellaVigna, 2013; Angrist et al., 2017; Kube et al., 2018; Lybbert et al., 2018; Angrist et al., 2020). These works also encourage discussions about potential research gaps. By identifying topics with an increasing prevalence and associations of topics under-investigated, we can underline promising research questions, as in Westgate et al. (2015) and Polyakov et al. (2018). This analysis suggests a greater

role for empirical approaches identifying the causal role of economic activities, and in particular the effect of trade and trade policy, on GHG emissions patterns. Also, there are potential interests in voluntary approaches to mitigate emissions—that is, nudges or labels—and the determinants of climate-friendly behavior—e.g. beliefs, moral or norms—in economic sectors such as transport or agriculture in order to assess the people’s willingness to support actions reducing emissions. Finally, the literature on the adaptation to climate change is over-represented in the agricultural sector, while this issue is under-investigated in association with other sectors or research questions.

The remainder of the chapter is organized as follows. In Section 1.2, I present the construction of the corpus of economic articles related to climate change. In Section 1.3, I present the major evolutions and trends in the diffusion of the economic literature on climate change. Section 1.4 focuses on the analysis of the topic model results. Finally, Section 1.5 concludes and gives further research perspectives.

1.2 Construction of the bibliographic corpus

In order to collect economic contributions related to climate change, I follow the guidelines of Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) outlined by Moher et al. (2010). This protocol has been used in other contexts in the economic literature (see e.g. Arunachalam et al., 2018; Viguié et al., 2021). It seeks to obtain a representative corpus of scientific works on a given topic, while reducing the researcher bias and improving transparency and reproducibility.

Coding by hand the economic research related to climate change is infeasible given the volume of publications considered. I employ an automated approach using key words related to climate change. First, I search for journal articles written in English, using Web of Science (WoS) and Scopus.² Editorials, books, book chapters, book reviews, and conference articles are excluded in order to obtain a standardized corpus of peer-reviewed scientific contributions. The selection is based on the content of the title, abstract or keywords of ar-

²WoS and Scopus are comprehensive databases of scientific works in all disciplines, which are commonly used for collecting references on a given topic in economics.

Table 1.1: Results of the key words query on WoS and Scopus

Matching rule	Key words and key expressions							
	climate change	climatic change	global warming	greenhouse gas	carbon emission	CO2 emission	carbon dioxide	climate policy
A. WoS								
Loose	10,592	10,685	11,328	13,493	16,980	18,430	18,538	19,801
Exact	9,066	9,096	9,749	11,711	13,281	15,552	16,045	16,561
B. Scopus								
Loose	7,333	7,422	8,301	9,753	12,591	12,697	13,047	13,962
Exact	6,599	6,639	7,535	9,014	10,693	10,847	11,708	12,042

Note: Number of research articles matching the sequential key words query using expressions contained in abstract or title or keywords. The last column for the loose matching rule shows that there are 19,801 research items which can be extracted using the following query on WoS: (TS = ((climate change) OR (climatic change) OR (global warming) OR (greenhouse gas) OR (carbon emission*) OR (co2 emission*) OR (carbon dioxide) OR (climate policy)) AND SU = Business & Economics) AND LANGUAGE: (English) AND DOCUMENT TYPES: (Article); and using Scopus we obtain 13,962 research items using the following query: TITLE-ABS-KEY-AUTH ((climate change) OR (climatic change) OR (global warming) OR (greenhouse gas) OR (carbon emission*) OR (co2 emission*) OR (carbon dioxide) OR (climate policy)) AND DOCTYPE (ar) AND LANGUAGE (english) AND SUBJAREA(ECON). The loose matching rule collects articles that contain parts of the expression, that is an article that contains “climate” and “change”. The exact matching rule collects articles that contain the exact expression, that is an article that contains “climate change”. Each keywords are added sequentially using the boolean instructor “OR”. This query was made on the 26th of February 2021. These results include doublons, which are not withdrawn here. In addition, the WoS query contains remaining publication in books, such as book chapters or handbook chapters.

ticles referenced as “Business & Economics” subject in WoS, and “Econ” subject in Scopus. The chosen key words reflect research on the economics of climate change. As there is no definitive way to classify research related to the economics of climate change, I apply an iterative approach where I gradually extend the group of key words to cover broader notions of climate change.

Table 1.1 presents the key words and summarizes the results of this sequential search query. Accounting for “greenhouse gas” or “carbon emissions” or “CO₂ emissions” or “carbon dioxide” adds a substantial number of articles. Also, some recent contributions deal with climate change while only mentioning “climate policy”, and this expression adds a consequent amount of articles when accounted for. I have also considered other key words such as “sustainable development” or “renewable energy”, which respectively add approximately 6,000 and 3,300 articles on WoS. However, I have not retained them, as they considerably expand the boundaries of the literature to articles which are not always produced with the idea of contributing to climate science.

Table 1.2: Number of articles after successive applications of selection criteria

Bibliographic database	Doublons removal	Journal articles	EconLit journals	Climate change lexicons	
				Lexicon 1	Lexicon 2
Scopus only	6,616	6,616	2,499	2,187	1,943
WoS only	12,458	11,147	7,394	6,109	4,956
Both WoS and Scopus	7,335	7,276	6,382	6,017	5,558
Total	26,409	25,039	16,275	14,313	12,457

Note: Evolution of the number of articles by bibliographic database after the successive applications of the selection criteria. The “Total” line corresponds to the sum of the research items from Scopus only, from the WoS only and those present in both bibliographic databases. There are 1,943 unique articles, only present on Scopus, which are strictly related to climate change (Lexicon 2), and which are journal articles published in EconLit journals.

Second, I voluntarily chose to retain research items that loosely match the key words, with, for example, “climate” and “change” appearing together or separately in title, abstract or keywords. It allows to enlarge the results to related articles, which contain parts of these expressions. In the following steps, I will then exclude articles which are actually unrelated using more accurate filters.

We reach 19,801 bibliographic entries on WoS and 13,962 on Scopus using our search query. Before merging the results of these two bibliographic databases, I remove the doublons. Then, I merge research items from Scopus and from WoS, using the DOI to match items present in both databases.³ After these merging operations, I obtain a corpus of 26,409 unique research items. I finally remove the research items which are not published in journals, such as book chapters, handbook chapters, and editorials which were wrongly included in the corpus, and I obtain 25,039 journal articles. Table 1.2 presents the breakdown of the number of articles by bibliographic database and the evolution of the number of articles after the application of the successive selection criteria presented below.

Third, I apply filters to this raw corpus to limit misclassification errors and select articles that are effectively related to the economics of climate change. The query using WoS and Scopus may wrongly classify articles either by including publications (i) which have a lim-

³When the DOI is not available, articles are matched according to their title. Since there are title discrepancies between both databases, I compute the string distance between the titles from Scopus and from WoS. This allows me to identify articles which have slight differences in titles between Scopus and WoS, and which are actually the same.

ited economic content, (ii) or that use the key words but are not related to climate change. First, the discipline boundaries of the “Business & Economics” (WoS) and the “Econ” (Scopus) field tags are unclear. I chose to retain articles published in journals referenced in the *EconLit* index.⁴ The *EconLit* index of journals has been used in another bibliometric study as a way to focus on journals related to economics (Combes and Linnemer, 2003). This approach leads to define the economics discipline as a group of journals, in a similar approach to Angrist et al. (2020). As a result, this filter drastically reduces the size of the corpus: among the 25,039 articles extracted in the first step, only 16,275 are published in journals referenced in the *EconLit* index. From the 1,505 journals present in the raw corpus, the number of journals decreases to 709, or 38.2% of the journals referenced in total by *EconLit*.⁵

The second filter intends to limit the inclusion of articles in the corpus that are not related to climate change. Two types of extraction errors may occur after the first step. First, some articles use the expressions present in the query but in contexts unrelated to climate change. For instance, some articles refer in their title or abstract to “changes in the climate of investment or businesses”. Second, in addition to the author keywords referenced in WoS collection, the WoS generates automatic keywords, called “keywords plus”. These keywords are assigned using a proprietary algorithm based on the articles’ cited references or bibliography.⁶ If this field can be useful to capture connected articles using a lexical field different from the one of the query, it also abusively allocates climate change keywords to articles that are actually not specifically on climate change. For instance, several articles on air pollution are integrated in the raw corpus due to the WoS “keyword plus”.

After removing ten articles unrelated to climate change in the early years of the corpus, I use a bag-of-words approach to retain articles that contain in the title, or in the abstract, or in the author keywords (the “keyword plus” field is now excluded), words or expressions from a list of words constituting a climate change lexicon. However, bag-of-words approach

⁴ *EconLit* is a library of references for economic literature developed by the American Economic Association. Its index references 1,856 journals. See https://www.aeaweb.org/econlit/journal_list.php

⁵ To have an idea of the important non-*EconLit* journals publishing on the economics of climate change and excluded of the corpus, here is a list of 6 of these journals in the top 25 of *EconLit* and non-*EconLit* journals publishing the most on climate change: *Resour. Conserv. Recycl.*, *Environ. Dev. Sustain.*, *Marine Policy*, *Technol. Forecast. Soc. Change*, *For. Pol. Econ.*, *Intern. Environ. Agre. Policy Law Econ.* and *Futures*.

⁶ Both of the author keywords and the “keywords plus” are used by WoS when using the “TS” research field tag.

is not entirely free from errors. First, the constructed bag-of-words can omit some words hence leading to miss some articles related to climate change but not using words from the lexicon. Second, this does not fully correct the inclusion of articles unrelated to climate change, that is, articles which use words of the bag of words in other unrelated contexts. To limit these biases, I consider two lexicons. The first lexicon is relatively inclusive and combines the climate change glossary which accompanies the publication of the IPCC (2014) fifth assessment synthesis report,⁷ the Environmental Protection Agency glossary of climate change terms,⁸ and the Wikipedia glossary on climate change.⁹ Then, the second lexicon is more limited and consists of the association of the words and exact expressions used to extract articles from WoS, as presented in Table 1.1. Both lexicons, numbered lexicon 1 for the former and 2 for the latter, are presented in Table 1.A.1.

Articles with words in the title, or abstract, or author keywords which contain at least one word or expression from lexicon 1 form what I call the “broadly related” to climate change corpus, denoted corpus A. This denomination reflects the idea that this corpus results from a comprehensive climate change lexicon, but it is more prone to include articles unrelated to climate change since the lexicon is large. Articles containing at least one word or expression in the title, or the abstract, or the author keywords, which are in lexicon 2 constitute the “strictly related” to climate change corpus, denoted corpus B. This corpus only includes articles using words strongly associated with climate change. Note that articles in corpus B are included into corpus A. Figure 1.2 summarises the selection process and Table 1.3 presents both of the resulting corpora.

The present chapter uses the corpora with details in the columns 6 to 9 in Table 1.3. The application of the successive filters on the raw corpus extracted from WoS consequently reduces the quantity of articles. Among the 25,039 articles extracted in the first step after doublons removal and book chapters and editorials removal, only 16,275 are published in *EconLit* journals and 21,292 are broadly related to climate change. Altogether, the two layers

⁷The IPCC glossary on climate change is accessible from the following URL: <https://www.ipcc.ch/report/ar5/syr/>

⁸See https://19january2017snapshot.epa.gov/climatechange/glossary-climate-change-terms_.html

⁹See https://en.wikipedia.org/wiki/Glossary_of_climate_change

Table 1.3: Details on the constructed corpus

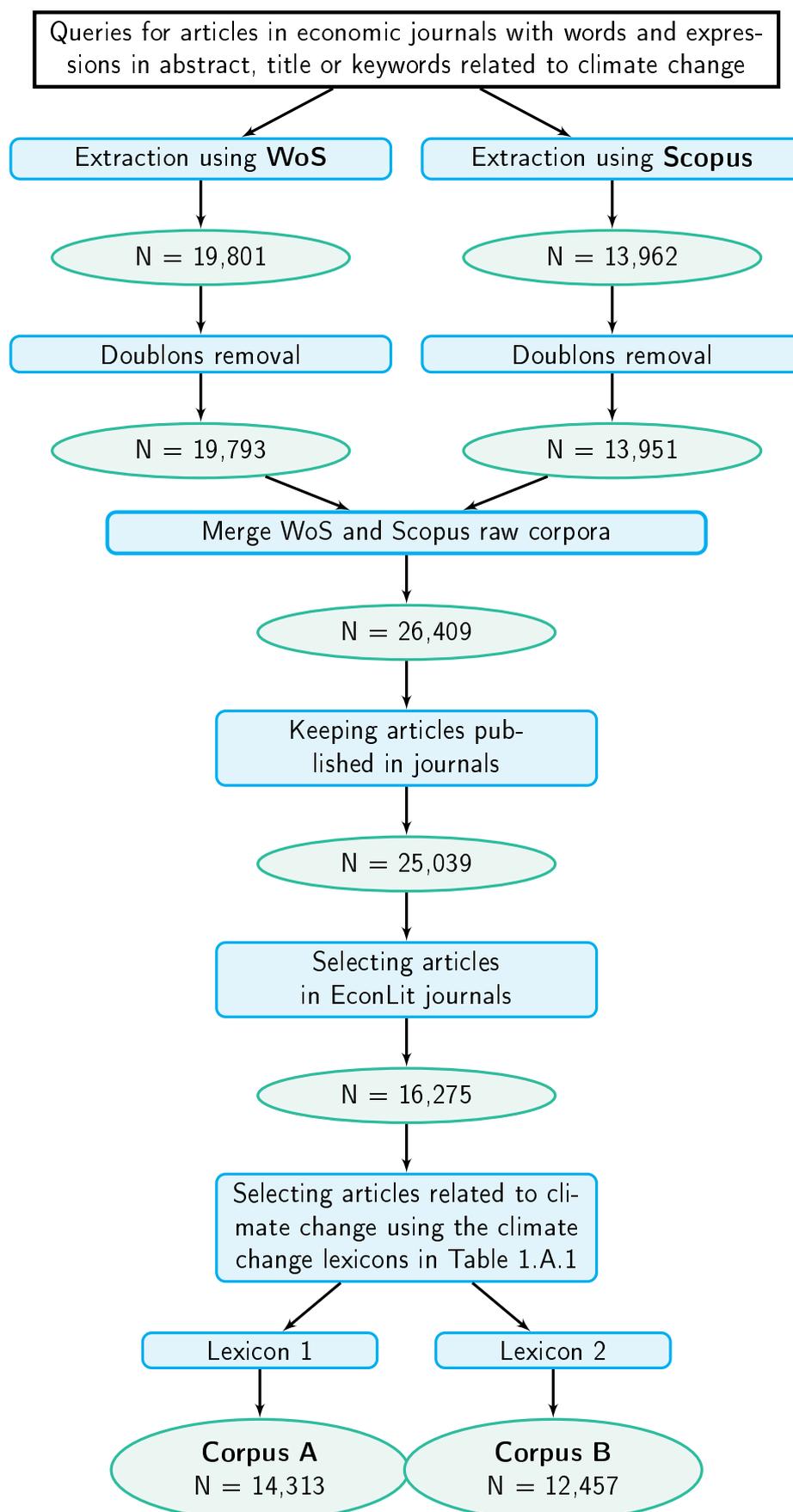
Time period	Corpus of articles in all journals				Corpus of articles in EconLit journals only			
	N_1	N_2	μ	σ	N_1	N_2	μ	σ
Merged bibliographic corpus extracted from WoS and Scopus								
All periods	25,039	24,848	27.46	58.47	16,275	16,136	30.42	59.40
Corpus A								
All periods	21,292	21,159	27.99	54.89	14,313	14,203	31.24	58.92
1974–1991	96	78	19.85	45.94	80	65	20.92	47.16
1992–2005	1,841	1,813	52.72	92.76	1,493	1,466	54.28	94.96
2006–2014	7,615	7,561	46.40	66.91	5,712	5,662	48.06	68.95
2015–2020	11,444	11,413	11.14	19.97	6,877	6,859	12.29	21.44
Corpus B								
All periods	18,628	18,506	28.88	56.41	12,457	12,357	32.24	60.52
1974–1991	81	63	19.64	46.25	72	57	20.71	47.51
1992–2005	1,674	1,647	53.00	94.60	1,362	1,336	54.62	96.60
2006–2014	6,861	6,810	46.67	67.55	5,128	5,081	48.35	69.60
2015–2020	9,760	9,736	11.26	19.93	5,769	5,757	12.43	21.28

Note: Summary statistics of the different corpora constructed. Our central corpus are the articles only published in EconLit journals which are broadly related to climate change (Corpus A). Corpus B selects articles that are strictly related to the economics of climate change. Corpus A and B are constructed by selecting articles whose abstract, titles and author keywords contain words in Lexicons 1 and 2 presented in Table 1.A.1. N_1 is the total number of articles in the corresponding corpus, N_2 is the total number of articles with available abstract, μ is the average article cites received in the corresponding corpus and σ is the standard deviation of cites received. Bibliographic data are extracted from WoS and Scopus on the 26th of February 2021. Some articles collected by WoS have no publication year and cannot be associated to a time period. These are mainly recent articles, currently pending for publication volume.

of filters lead to a number of 14,313 articles in corpus A, and 12,457 for corpus B. Also, articles published in *EconLit* journals receive more citations in average than articles of the pooled corpus of *EconLit* and non-*EconLit* journals. This increase in research impact (if research impact is proxied with citations) is significant for the whole sample, and for subsamples of recent time periods.

Finally, I construct corpora associated with the economics of the adaptation to climate change (denoted corpus C), and with the economics of the mitigation of climate change (denoted corpus D). The articles included in these corpora contain words in their title, or in their abstract, or in their author keywords, which are in the adaptation to climate change or in the mitigation of climate change lexicons, presented in Table 1.A.1. These two lexicons are directly constructed from lexicon 1, from which I assess whether each word is associated

Figure 1.2: Diagram summarizing the systematic review protocol.



to the mitigation or the adaptation to climate change. If there is an ambiguity, I chose not to allocate the expression to either of the lexicons, as in the case of “climate policy”.

1.3 Major trends on the economic contributions on climate change

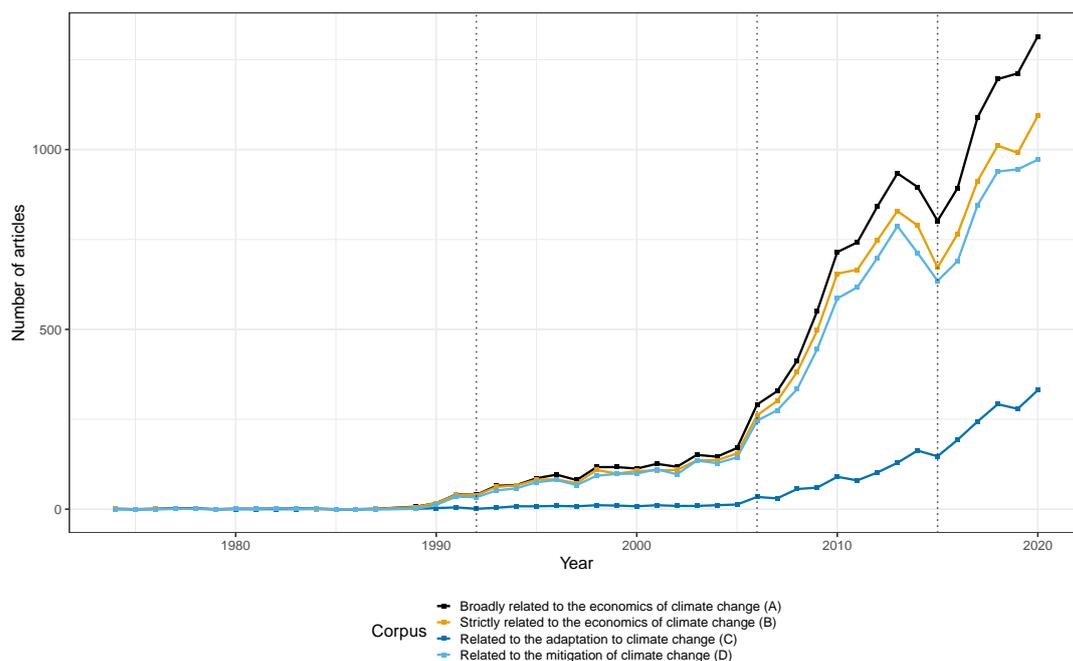
In this section, I first present some aggregate trends regarding the literature on the economics of climate change. Then, I give more details on the content of this literature, its major evolutions, while putting in perspective the contemporary history of climate science and climate policy. Then, I highlight the main journals used by the profession to publish contributions on climate change. Finally, I investigate the citation metrics of the economic journals publishing on climate change in order to assess the prominence of this research topic relative to the rest of the economics.

1.3.1 Aggregate trends on the quantity of contributions

First, we notice a global increase in the number of articles related to climate change published each year in Figure 1.3. This increase has similar orders of magnitude when concentrating on articles broadly related to climate change (black line) and articles strictly related to climate change (orange line). This finding is unsurprising given the boom of scientific publications recorded in the recent years. Nonetheless, this increase corresponds to an expansion in the coverage given to climate change by the economics overall. Indeed, the percentage of economic articles strictly related to climate change published each year has increased and now exceeds 2% (Figure 1.1, gray line).

Second, Figure 1.3 shows the strong initial interest in the economics of the mitigation to climate change until 2005 (light blue line). From then, we notice the now significant share of the economic literature on the adaptation to climate change (navy blue line). This subject currently represents around a quarter of the total economic articles on climate change published each year.

Figure 1.3: Number of articles related to climate change by year.



Note: Number of articles associated to the economics of climate change published each year in *EconLit* journals and referenced by WoS and Scopus. In 2010, 715 articles which are broadly related to climate change (corpus A) and 655 articles which are strictly related to climate change (corpus B) have been published. Vertical dotted lines represent the starting date of the time periods chosen to break down the corpus into four parts.

1.3.2 Evolutions in the content of the contributions

To present the content of the corpus, I break it down into four time periods: (a) from 1974 to 1991, (b) from 1992 to 2005, (c) from 2006 to 2014 and (d) from 2015 to 2020. I construct these periods to follow patterns in the evolution of publications related to climate change—these time periods are represented on Figure 1.3 (vertical dotted lines)—and to coincide with historical facts regarding climate policy, climate science, and influential economic articles over the period. Note that Table 1.B.4 in appendix presents the most cited articles by time period.

(a) From 1974 to 1991 The first article related to climate change and included in our corpus traces back in 1974 and studies the impact of potential climate change—here understood as a decrease in temperature—on wages using a hedonic model (Hoch and Drake, 1974). The publication year of this article also coincides with a decade during which economic scholars began to focus on the sustainability of economic growth under finite supply of resources. The famous report of the Club of Rome—entitled “*The Limits to Growth*” and

not included in our corpus—is published in 1972 (Meadows et al., 1972). In 1977, Nordhaus addresses a speech at the AEA annual meeting—published as an *AEA Papers & Proceedings* and included in our corpus—where he exposes the global externality of economic activities due to their associated emissions of GHG. In this work, he gives estimates of the social costs of GHG emissions, which he explicitly labels as carbon taxes (Nordhaus, 1977).

This first period marks the origins of the economic studies on climate change.¹⁰ Climate-related concerns remained marginal in the economic profession over this period, as illustrated by the uncertainties and dissensus regarding the reality of climate change at that time.¹¹

Then, the first IPCC report is published in 1990. It presents evidence of human-induced increase in the concentration of GHG in the atmosphere. In this regard, economists develop estimations techniques of GHG emissions from economic data (Edmonds and Reilly, 1983; Torvanger, 1991). They also study the effects of climate change on agricultural production (Adams, 1989). In addition, some scholars also initiate discussions on the economic instruments to mitigate GHG emissions and the estimation of abatement costs (Pearce, 1991). Finally, pioneering analyses on the difficulties in reaching a global agreement on GHG mitigations are published (Rose, 1990). All of these works today appear to be precursors and have initiated thematical fields that will be later highlighted in the topic model analysis in Section 1.4.

(b) From 1992 to 2005 The number of articles related to climate change published each year notably increases. The coverage left to climate change over the period also increases, that is, from an almost-negligible level in the beginning of the period to 1% at the end of

¹⁰Our corpus cannot pretend to exactly trace the starting date of the economics of climate change literature. As the corpus omits conference reports, books and working papers, it can pass by path-breaking contributions and this task goes beyond the scope of this work. Note that the *American Economic Review* re-publishes in 2019 an *IIASA* working paper written by William Nordhaus in 1975 entitled “*Can We Control Carbon Dioxide?*”, which could be a front door to properly analyze the origins of climate change economics (Nordhaus, 2019a).

¹¹In his AEA annual address, Nordhaus evokes the doubts in his profession in a metaphorical way:

“In contemplating the future course of economic growth in the West, scientists are divided between one group crying ‘wolf’ and another which denies that species’ existence. One persistent concern has been that man’s economic activities would reach a scale where the global climate would be significantly affected. Unlike many of the wolf cries, this one, in my opinion, should be taken very seriously” (Nordhaus, 1977, p. 341).

the period. Concerns related to climate change progressively diffuse over the period. Most of the research works during this time are devoted to the development of economic tools to mitigate GHG emissions in a cost-effective way. This focus is related to the operating context in climate science and climate policy. In 1992, the Rio Conference initiated international cooperation to mitigate GHG emissions. It led to the ratification of the UNFCCC in 1994, where countries agreed to stabilize GHG emissions. Then, the Kyoto protocol is established in 1997 and enforced in 2005, where countries built binding requirements and institutions—notably an international Emissions Trading Scheme (ETS)—to mitigate their GHG emissions (Nordhaus, 2019b). Thus, the need at that time to develop tools to mitigate climate change is highlighted by scholars (Nordhaus, 1993b).¹²

A notable serie of contributions over the period focuses on aggregate estimates of climate change costs and damages using Integrated Assessment Models (IAM). Nordhaus intensively contributed to this literature by building the Dynamic Integrated Climate-Economy (DICE) model, whose outputs are estimates of the social costs of carbon (see e.g. Nordhaus, 1993a,c, among others). Also, two influential articles framing and summarizing two key concepts regarding the carbon-neutrality transition have been published: Greening et al. (2000) on the rebound effect in the energy efficiency context; and Unruh (2000) on institutional determinants of the path dependance in fossil-fuel resources, also called the carbon lock-in.

Finally, we observe over this period the first notable economic works on the study of the adaptation to climate change and associated policy issues (Fankhauser et al., 1999; Adger, 2003). Also, with Mendelsohn and Shaw, Nordhaus developed the Ricardian approach to estimate damages of climate change on agriculture by accounting for adaptation behavior. This contribution has given rise to an important literature inspired by this approach (Mendelsohn et al., 1994).

¹²The following quote summarizes Nordhaus' views regarding the need of improving economic tools to tackle climate change:

“Natural scientists have pondered the question of greenhouse warming for a century. Only recently have economists begun to tackle the issue, studying the impacts of climate change, the costs of slowing climate change, and alternative approaches for implementing policies. The intellectual challenge here is daunting for those who take policy analysis seriously, raising formidable issues of data, modeling, uncertainty, international coordination, and institutional design. In addition, the economic stakes are enormous, involving investments on the order of hundreds of billions of dollars a year to slow or prevent climate change.” (Nordhaus, 1993b, p.13)

(c) **From 2006 to 2014** This third period is characterized by the exponential increase in the number of economic articles on climate change and a sharp slow-down at the end of the time period visible on Figure 1.3.¹³ There is also an increase in the coverage left to climate change over the period—rising from 1% to above 2% at the end of the period. This massive rise can be attributed to at least three concurrent factors.

First, in a report commissioned by the UK government and published in the beginning of the period, Stern (2006) criticizes the ethics of discounting the utility of future generations and recommends the use of a low discounting factor. In addition, Weitzman (2009) proposes the dismal theorem, which shows that cost-benefit analysis are inoperant in the presence of catastrophic climate-related risks. These works then fueled scientific debates (Tol, 2009; Pindyck, 2013).

Second, international climate policy faced difficulties in the same time. Countries failed to cooperate on a binding agreement for emission reduction in the aftermath of the Kyoto protocol, which expired in December 2012 (Nordhaus, 2019b). In this context, the most influential economic works over the period focus on the relationship between economic growth and GHG emissions using econometric techniques (for the most influential ones see Ang, 2007; Soytaş et al., 2007; Halicioglu, 2009; Zhang and Cheng, 2009). The importance of these works can be interpreted as the manifestation of the economic fears of countries that they will have to slow down their growth in order to reduce their emissions. In addition, the IPCC publishes its fourth assessment in 2007, in which it is included for the first time a specific working group report on impacts, adaptation and vulnerability to climate change. As societies measure the risks of facing climate change impacts over the next decades, the economic literature on the adaptation to climate change becomes substantial over the period, as seen on Figure 1.3.

Third, while limited in the energy economics and the environmental economics fields, climate change spreads to international economics, risks economics or development economics, as climate change appears to become a systemic issue (see Vale, 2016, for an in-

¹³This decrease is not due to bibliographic collection issues, as the number of overall publications referenced in WoS and Scopus has steadily increased. There is thus an apparent slow down in economic research on climate change during two consecutive years for no seemingly obvious reason.

sightful discussion on this evolution and a presentation of influential works in each fields).

(d) From 2015 until today The last period is characterized by the return of a significant increase in the number of publications by year, in a similar magnitude than the increase in the beginning of the third time period. Concerning the coverage left to climate change, the share of economic articles related to climate share slightly increases and reaches a plateau around 2.2%. The field of energy economics still occupies a significant place in the economic literature on climate change, since some of the most influential articles in the period are related to energy consumption and the development of clean new technologies (Kasman and Duman, 2015; Wadud et al., 2016).

In addition, this last period begins with the Paris agreement in 2015, which defines a target for temperature increase to be below 2°C above pre-industrial level. Some major contributions on the estimation of the social costs of carbon under the 2°C target and to better account for the preceding critiques are published (Howard and Sterner, 2017; Drupp et al., 2018; Pindyck, 2019). Also, the IPCC released its fifth assessment in 2014 and put forward adaptation and mitigation options which encompass not just technological, but also social, institutional and economic considerations. Research on the adaptation to climate change intensifies with the importing of non-economic concepts such as vulnerability and resilience (Mattsson and Jenelius, 2015). Also, we observe influential articles on the last period focusing on interdisciplinary frameworks and institutional changes to improve the governance and the efficiency of climate policies (Kivimaa and Kern, 2016; Rogge and Reichardt, 2016).

1.3.3 The journals of the economics of climate change

Journals are the main diffusion tools for research outputs in economics. Since journals are held and edited by associations of scholars, the profession uses them as a mean to develop and to structure the literature on a topic. Journals structure the economic literature both horizontally and vertically. Indeed, associations of scholars have their own journals which specialize on specific sectors and topics. As a result, this segments the economic literature

between fields and topics. Then, journals are ranked according to several metrics which intend to capture the impact and the quality of their research. The usual units of measure for scientific visibility are related to the number of citations received. I now investigate the thematical fields and the research impact of the economic journals publishing on climate change. This can assess the extent of the diffusion of the economics of climate change, through its epistemological place and its visibility.

The economic journals publishing the most on climate change First, as highlighted in the introduction, *top-5* economic journals have left a short coverage to climate change. However, this does not seem to unlegitimate the literature, given the massive and increasing amount of contributions shown in the preceding subsection. The economics of climate change literature has been constructed by bypassing the discipline's most legitimate channels and by appropriating its own channels.

Second, Figure 1.1 shows the important coverage to climate change left by leading journals in the fields of Agricultural, Environmental, and Resource Economics (AERE). Table 1.B.1 in Appendix presents all journals in the corpus as ranked by their number of articles. More precisely, journals in the field of energy economics have the highest number of articles on climate change. *Energy Policy* is by far the most publishing journal in the corpus, as it publishes more than one quarter of the articles in corpora A and B. This important share is due to the important number of volumes released every year by the journal. Adding the *Energy Economics*, the *Energy Journal* and *Resource and Energy Economics*, and gathering four of the most important journals in the field of energy economics, this share reaches 42% in corpora A and B. Journals in the field of environmental economics are the second most important publication support. *Ecological Economics*, the *Journal of Environmental Economics and Management*, and *Environmental and Resource Economics*, which are three of the most important environmental economics journals, account for 12.5% of the articles in corpora A and B.

The journals with the most important research impact on the economics of climate change

In Table 1.4, I compute the *h-index* at the journal-level for articles in each corpora. A journal

Table 1.4: Ranking of journals according to the *h-index* of articles related to climate change

Journal	(A)		(B)		(C)		(D)	
	h_i	r_i	h_i	r_i	h_i	r_i	h_i	r_i
Energy Policy	150	1	145	1	48	2	144	1
Ecol. Econ.	97	2	92	2	49	1	86	3
Energy Econ.	92	3	89	3	22	4	90	2
J. Environ. Econ. Manag.	54	4	53	4	20	5	52	4
Environ. Resour. Econ	48	5	46	5	20	5	43	6
Intern. J. Prod. Econ.	47	6	46	5	5	41	45	5
Energy J.	43	7	34	10	7	20	41	7
Resour. Energy Econ.	41	8	37	8	7	20	38	8
Transp. Res. A	40	9	39	7	9	15	38	8
World Dev.	38	10	32	11	27	3	27	14
Eur. J. Oper. Res.	36	11	35	9	7	20	32	10
Econ. Model.	32	12	30	12	7	20	30	11
Rev. Environ. Econ. Policy	32	12	30	12	13	11	28	13
Food Policy	31	14	30	12	17	8	24	16
Am. Econ. Rev.	30	15	27	15	9	15	17	27
Econ. Syst. Res.	30	15	25	18	2	85	29	12
Am. J. Agric. Econ.	27	17	26	16	18	7	19	21
Oxf. Rev. Econ. Policy	26	18	26	16	6	27	27	14
Climate Change Econ.	24	19	24	19	12	12	19	21
Environ. Dev. Econ.	24	19	24	19	14	10	19	21
Intern. J. Energy Econ. Policy	23	21	23	21	4	51	22	17
J. Bus. Ethics	23	21	23	21	3	66	16	29
Land Econ.	23	21	19	26	9	15	19	21
Agric. Econ.	21	24	19	26	15	9	16	29
J. Pol. Model.	21	24	21	23	3	66	21	18
J. Public Econ.	21	24	20	24	4	51	20	19
Transp. Res. E	21	24	20	24	3	66	20	19
...
J. Political Econ.	9	67	7	80	2	85	6	85
...
Rev. Econ. Stud.	4	155	4	147	–	–	3	151
...
Econometrica	2	235	2	219	–	–	2	195
...
Q. J. Econ.	1	342	1	321	–	–	1	281

Note: Ranking of the 25 journals with the highest *h-index* for their climate-related publications, and ranking for the *top-5* economic journals and top-AERE field journals. *Ecological Economics* has published 93 articles broadly related to climate change which have received at least 93 citations. Columns (A), (B), (C) and (D) gives the journal *h-index* by retaining articles which are respectively in corpus A, B, C and D. h_i is the *h-index* of journal i , and r_i is its rank in the corresponding corpus. The character “–” means that the journal has not published any article in this corpus. In **bold font** are represented *top-5* economic journals, and in **green bold font** are represented top-AERE field journals according to the *CNRS* ranking.

has index h if h of its N articles have at least h citations each and the other $(N - h)$ articles have no more than h citations. The h -index metric values both the volume of citations and citations per article. The ranking in Table 1.4 suggests that journals publishing the most articles on climate change are also those receiving the most citations overall. According to this ranking *Energy Policy* is still the journal which publish the most articles with the most impact, followed by *Ecological Economics* and *Energy Economics*. We also notice that the *American Economic Review* is the only *top-5* journal appearing in the ranking at the 15th rank, while it is ranked 33rd by the total number of articles in corpus A. In addition, we observe some differences between journals having the most global impact on mitigation (corpus D) and on the adaptation to climate change literature (corpus C). Some journals appear in higher positions regarding adaptation than in mitigation, such as *World Development*, *Food Policy* or the *American Journal of Agricultural Economics*. This suggests that the literature on the economics of the adaptation to climate change is not being disseminated primarily through the same journals as the economics of the mitigation of climate change, which is rather dominated by journals in energy and environmental economics.

However, a very low h -index can hide a significant general scientific impact. For instance, the *Quarterly Journal of Economics* has published only one article on climate change, but it is cited more than 120 times. In addition, the h -index is derived for a given timeframe, here for the whole timespan of our corpus. Thus, this defavorizes younger journals, and journals which recently focus on climate change.

In Table 1.B.2 in Appendix, I present the h -index ranking of journals for the 2015–2019 timespan. *Energy Policy* is still first but the classification differences with the following journals are reduced. *Energy Economics* and the *International Journal of Production Economics* are notably getting closer to *Energy Policy*. Also, this ranking highlights novel key supports in the diffusion of the economics of climate change literature in the recent years. The importance of the research published by *World Development*, the *Transportation Research* journals, and the *European Journal of Operational Research*, is highlighted. This also illustrates the diffusion of the topic beyond the historical specialization of the energy and environmental economics. Finally we can note that both the rankings in Tables 1.4 and 1.B.2 are not

so different of the ranking of journals ordered by their number of publications on the topic. The *h-index* is not satisfying for characterizing the journals' research impacts on its own, since it mainly underlines journals with an important volume of publications on the topic.

To better approach the research impact of journals in the recent years, I compute the five-year Journal Impact Factor (JIF) for articles related to climate change at the journal level. More precisely, this metric corresponds to the average cites received by journals for their articles published on climate change between 2015 and 2019. The ranking of the 25 first journals as well as *top-5* economic journals and top-AERE field journals are presented in Table 1.5. Note that Table 1.B.3 in Appendix also computes the average citations received for the whole period of the corpus. However, this measure tends to favor outlets that have long published on climate change, and this does not allow to dwell on recent trends.

This ranking is different both from the *h-index* ranking over the period in Table 1.4 and from that of the last five years in Table 1.B.2 in Appendix. The specialist journals of climate change economics are here disadvantaged. Energy economic journals and environmental economics journals appear to have a relatively low average impact for their works published in the recent years. Only the *International Journal of Production Economics* appears both in the top-25 journals with the most articles published on climate change (Table 1.B.1) and in the top-25 journal regarding the five-year JIF.

By contrast, this ranking tends to promote journals having published few articles on climate change but getting an important impact. This is the case for some general economic journals, which have the highest impact when publishing articles on climate change although their publications on the subject are scant. Set aside journals with less than two articles published in the last five years and non-core economic journals, these are the *Journal of Political Economy*, the *Review of Economics and Statistics*, *Research Policy*, the *American Economic Journal: Economic Policy*, the *Economic Journal*, the *American Economic Review* and *Economic Modeling*. Interestingly, the *Journal of Political Economy* has published 8 of its 10 articles related to climate change in the last five years, and they have received the largest average echo in the literature. To a lesser extent, this is also the case for the *American Economic Review* which has published a quarter of its articles on the economics of climate

Table 1.5: 5-year Journal Impact Factor of climate change articles

Journal	N_i	(A)		(B)		(C)		(D)	
		JIF_i	r_i	JIF_i	r_i	JIF_i	r_i	JIF_i	r_i
J. Political Econ.	8	76.8	1	80.3	1	100.0	2	79.6	2
Rev. Econ. Stat.	5	60.6	2	40.2	6	68.0	4	58.8	6
Research Policy	20	53.5	3	18.6	45	–	–	68.9	3
Contemp. Account. Res.	1	50.0	4	50.0	2	–	–	50.0	7
Intern. J. Prod. Econ.	84	44.5	5	45.3	4	50.7	6	45.5	10
J. Applied. Econometrics	1	37.0	6	–	–	–	–	37.0	11
J. Econ. Persp.	4	36.8	7	36.8	9	22.0	19	36.8	12
Am. Econ. J. Econ. Pol.	12	36.2	8	37.1	8	139.0	1	36.2	13
Trans. Res. E	25	34.2	9	38.3	7	43.0	7	34.4	14
Econ. J.	7	34.0	10	42.6	5	–	–	29.0	22
J. Mark.	1	34.0	10	34.0	10	–	–	–	–
J. Global Econ. Anal.	10	33.6	12	33.6	12	8.5	68	65.2	5
Econ. Sys.	1	33.0	13	33.0	13	–	–	33.0	18
J. Econ. Psychol.	2	32.5	14	32.5	14	–	–	17.0	45
Am. Econ. Rev.	13	31.9	15	30.2	18	10.7	52	49.7	8
Manag. Sci.	6	31.8	16	34.0	10	21.0	21	34.0	16
Emerging Mark. Rev.	2	30.5	17	30.5	17	–	–	30.5	19
Account. Rev.	1	30.0	18	30.0	19	–	–	30.0	20
J. Dev. Econ.	8	29.8	19	28.5	22	25.4	17	–	420
J. Bioecon.	5	29.6	20	32.2	15	12.3	45	100.0	1
Econ. Model.	42	29.4	21	31.7	16	7.7	76	33.7	17
Transform. Bus. Econ.	3	28.7	22	28.7	21	–	–	67.0	4
J. Econ. Stud.	5	28.0	23	28.0	23	54.5	5	34.2	15
Res. Int. Bus. Finance	3	26.7	24	26.7	25	30.0	12	26.7	23
Cambridge J. Econ.	2	24.5	25	24.5	26	–	–	6.0	134
...		
Ecol. Econ.	352	14.8	61	15.5	53	15.2	37	15.1	49
...		
Am. J. Agric. Econ.	36	13.4	65	15.1	54	14.6	40	14.6	53
...		
J. Environ. Econ. Manag.	116	12.4	70	12.5	63	15.3	36	11.8	64
...		
Energy J.	68	6.5	154	6.8	143	2.5	143	6.7	128
...		
Econometrica	1	6.0	159	6.0	152	–	–	6.0	134
...		
Rev. Econ. Stud.	2	3.0	247	6.0	152	–	–	3.0	207

Note: 5-year Journal Impact Factor for their articles related to climate change published between 2015 and 2019. The *Journal of Political Economy* has published 8 articles broadly related to climate change in the last five years (2015–2019), which have received in average 76.8 citations, and the journal is ranked first. Columns (A), (B), (C) and (D) gives the 5-year JIF by retaining articles which are respectively in corpus A, B, C and D. N_i is the number of articles published between 2015 and 2019 which are broadly related to climate change, JIF_i is the average cites received by these publications for journal i as measured by WoS in 2021 (or Scopus if not available in WoS), and r_i is the journal ranking in the corresponding corpus. Note that 455 journals have published at least one article in corpus A between 2015 and 2019. The character “–” means that the journal has not published any article in this corpus. In **bold font** are represented *top-5* economic journals, and in **green bold font** are represented top-AERE field journals according to the CNRS ranking.

change in the last five years which also have led to a significant impact. Thus, to qualify the picture drawn by Oswald and Stern (2019), “economists are [not so much] letting down the world” from a purely quantitative point of view. These results suggest that general economic journals and some *top-5* journals, such as the *Journal of Political Economy* or AEA journals, tend to take a significant place in the economics of climate change, both by their number of contributions and their research impact.

1.3.4 The relative prominence of climate change economics

The research impact of specialist journals in the economics of climate change It remains to assess whether this topic stands out from the rest of the economic literature. To this end, I investigate whether the topic is rather located in high-impact or low-impact journals relative to the whole economic literature. This has some importance, as the diffusion of climate-related concerns in economics does not also depend on the coverage given to the subject, but also on whether the place occupied by the topic is visible and credible in the eyes of the profession.

In this perspective, I compare the overall research impact of journals publishing the most on climate change with the rest of the economic journals. Table 1.6 compares the journals as grouped by their number of articles on climate change. I construct four groups of journals, according to (i) whether they do not publish articles on climate change during the considered time period, called the “NP” group; (ii) whether they rarely publish articles on climate change, denominated the “Barely” publishing group; (iii) whether they sometimes publish articles on climate change, denominated the “Sometimes” publishing group; and (iv) whether they often publish articles on climate change, denominated the “Regularly” publishing group. For these four groups of journals, I measure their research impact using the average cites received by all of their articles, that is, the total number of cites received by the journal divided by the total number of articles published in the journal over the period. In addition, the average Journal Impact Factor (JIF) is given as derived by the Journal Citation Report (JCR) for the years 2018 and 2019. These statistics are then aggregated for the

Table 1.6: Research impact of journals specialized on climate change and the rest of economic journals

Time period	Journal group	CC-related articles			Total number of articles		CC coverage		Cites by article		JIF (2020)	
		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
		N	min	max	μ	s	μ	s	μ	s	μ	s
1980–2020	NP	142	0	0	419.1	43.2	0.000	0.000	10.2	1.7	1.44	0.13
	Barely	480	1	9	707.9	32.3	0.010	0.001	12.7	0.9	1.63	0.07
	Sometimes	125	10	54	1474.5	146.5	0.035	0.005	18.3	2.3	2.08	0.14
	Regularly	31	55	3854	2573.9	529.2	0.199	0.036	22.2	1.9	3.00	0.27
2010–2019	NP	121	0	0	272.5	20.5	0.000	0.000	7.3	0.9	1.46	0.13
	Barely	419	1	8	352.2	13.6	0.011	0.001	8.6	0.5	1.68	0.07
	Sometimes	104	9	45	690.2	68.8	0.046	0.005	11.7	1.3	2.05	0.16
	Regularly	28	46	2492	1342.5	316.3	0.244	0.036	17.4	1.6	3.09	0.29
2015–2019	NP	161	0	0	163.0	9.5	0.000	0.000	4.8	0.4	1.62	0.13
	Barely	352	1	6	194.1	7.7	0.016	0.001	4.8	0.3	1.68	0.08
	Sometimes	81	7	34	415.9	43.4	0.062	0.007	6.6	0.5	2.03	0.14
	Regularly	22	36	1032	817.5	180.0	0.264	0.044	10.6	1.1	3.27	0.34

Note: This table compares bibliometric information between groups of journals based on their degree of specialization on the economic research on climate change, and for three different time spans. The “NP”, “Barely”, “Sometimes” and “Regularly” groups of journals gather journals indexed by *EconLit* and with available bibliometric data on the JCR, and which respectively (i) have not published any article broadly related to climate change during the time period, (ii) are in 75% of the economic journals (among the journals who have published at least one article on climate change) with the fewest publications on climate change during the period, (iii) are between the 75th and 95th percentiles of the journals publishing the most on climate change, and (iv) are in the top 5% of journals publishing the most on climate change. N measures the number of journals in the category, min and max gives the minimum and maximum number of articles on climate change published by journals in the given category, and μ and s gives the mean and standard deviation of (respectively) the total number of articles by the journals, of the coverage left to climate change, of cites received by all articles in the journal, and of the Journal Impact Factor (JIF). Bibliometric data at the journal level and for a given time period are extracted from the JCR.

whole time period,¹⁴ the last ten years and the last five years.

We notice that the journals regularly publishing articles on climate change tend to receive more citations overall and have higher JIF than journals less (or not) publishing on climate change. We can reject the equality of means in cites received between the “Regularly” and the “Sometimes” category at the 5% level, except for the 1980–2019 time period. The differences of means in JIF are all significant at the 5% level. Note that when using the five year journal impact factor to account for the long lasting publication process in economics, we also observe significant differences at the 5% level, meaning that journals regularly publishing on climate change are also journals with a higher research impact over the last five

¹⁴Bibliometric data at the journal level on JCR are available starting from 1980, which thus excludes articles on climate change in our corpus published between 1974 and 1979.

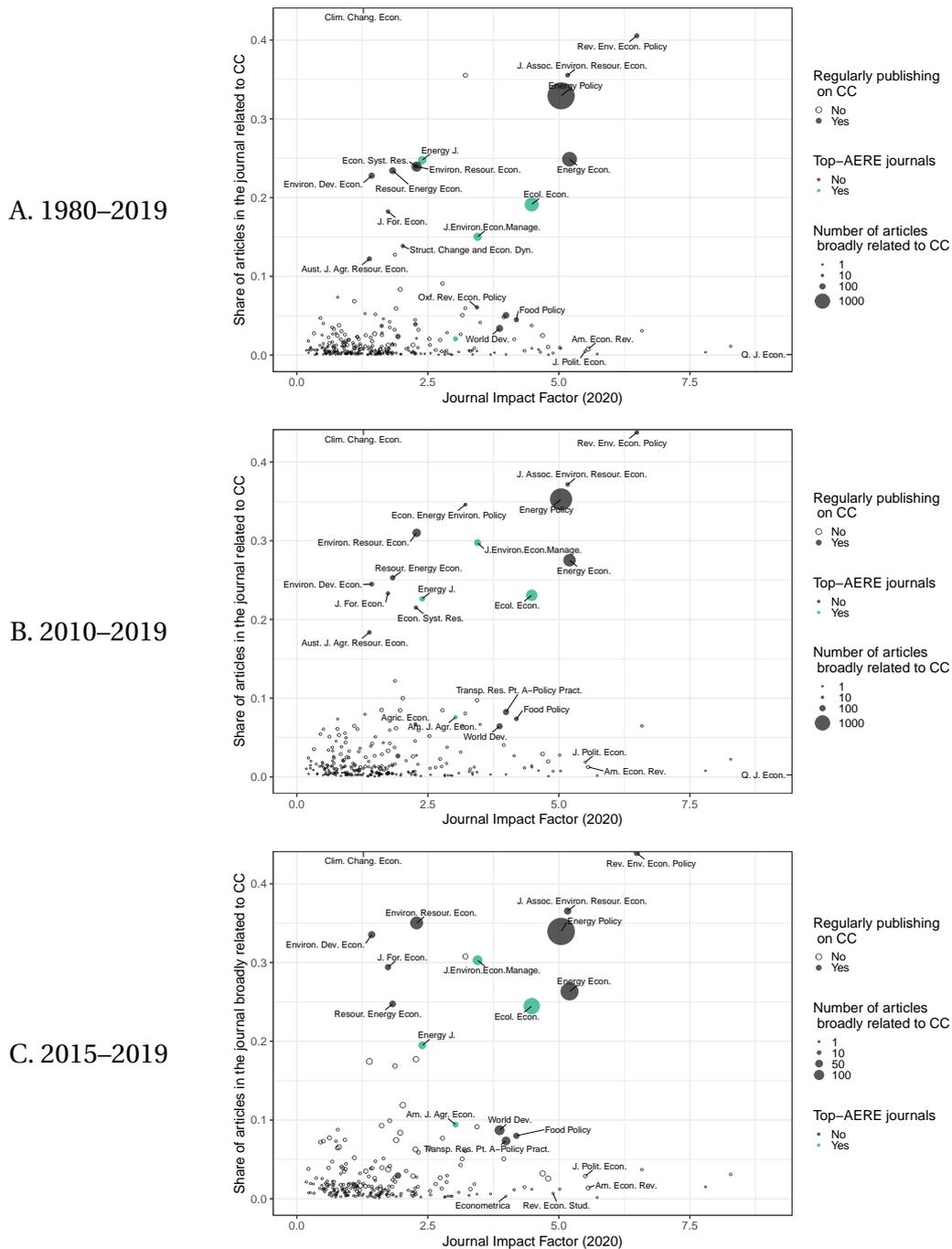
years. In addition, these differences are more pronounced in the last five years than in the last ten years and than over the whole period. This suggests that climate change is getting published by journals having higher research impacts than the rest of economic journals in the recent time periods. By contrast, significant differences in research impacts between the “Sometimes” and “Regularly” groups are not noticeable over the whole time period. This may suggest that climate change has been diffused in the past by economic journals with similar visibility than those in economics overall. This could advocate that climate change tends to become a research topic that attracts journals with higher research impact in the recent years.

Figure 1.4 allows to visualize this positive relationship between the coverage left to climate change by journals and their Impact Factor. Journals in the “Regularly” group are shaded in dark or green. The subsample of journals regularly publishing on climate change is made of journals with a higher JIF in average, that is, points are further to the right along the *x-axis*. We can also notice the global increase with respect to time in the coverage left to climate change at the journal level. We can notice an upward shift from the top panel, focusing on the entire time period, to the bottom panel, focusing on the last five years. This suggests that journals are giving more and more place to climate change in their editing process in the recent years.

The relative impact of research on the economics of climate change Then, I question whether the economic contributions on climate change have relatively more impacts than the rest of the publications in the same journals. On Figure 1.5, I compare the cites received at the journal-level between articles related to climate change and all articles. To compare citations across years in a given journal, I use the age-adjusted cites, that is, the average number of cites received each year by the journal for the articles published a given year. This metric furnishes a comparable unit of research impact across years, and it is easily computable given the available bibliometric data. I then aggregate these metrics for the four time periods as defined in Subsection 1.3.2.

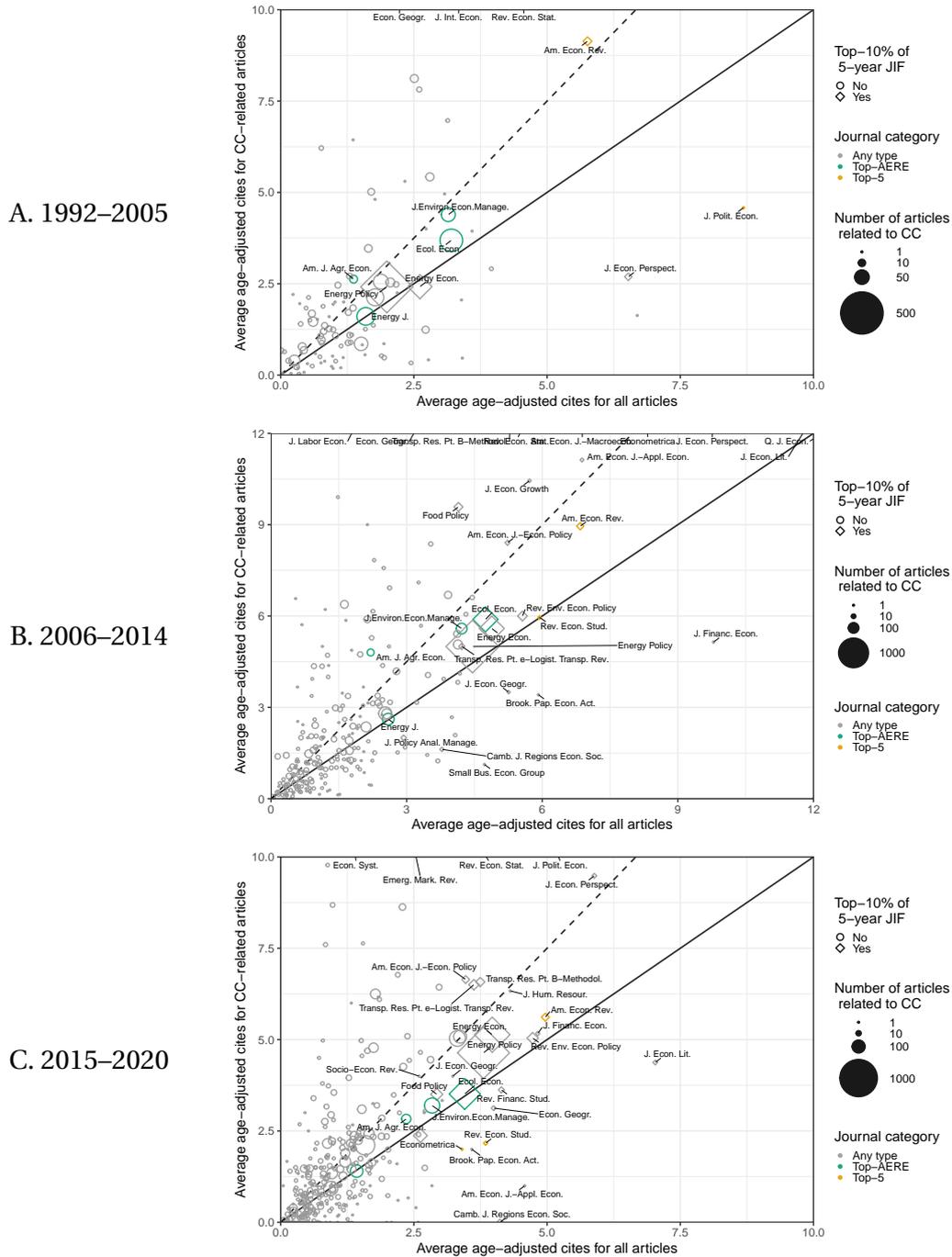
Figure 1.5 suggests that, for the majority of journals, climate change tend to receive a surplus of cites relative to the rest of the economics. For the three time periods considered,

Figure 1.4: Coverage left to climate change and Journal Impact Factor by journal.



Note: *Energy Policy* is a journal regularly publishing on climate change (point is filled and shaded). It has devoted 36% of its articles to climate change during the 2010–2019 time period, and it has a Journal Impact Factor (JIF) of 5 in 2020. Coverage is measured by dividing the number of articles broadly related to climate change (corpus A) with the total number of articles published during the period. The JIF (x-axis) is measured in 2020 by the Journal Citation Report (JCR). Panel A. aggregate these measures for years 1980–2019, panel B. for 2010–2019 and panel C. for 2015–2019. Points filled and shaded (dark or green) corresponds to the top 5% of journals publishing the most on climate change, that is the “Regularly” publishing group of journals in Table 1.6. JIF data are collected using the JCR. Note that journals with missing impact factor are not represented, as well as journals not publishing on climate change. *Climate Change Economics* have a coverage left to climate change of 95% for the 1980–2019 time period, 90% for the 2010–2019 time period and 92% for the 2015–2019 time period.

Figure 1.5: Comparison of cites between articles related to climate change and any articles by journal.



Note: Comparison of average age-adjusted cites by journals between articles related to climate change and any articles, for different time periods. The *Journal of Economic Perspective* receives in average 10 cites by year for any of its articles published between 2006 and 2014, while it receives in average 14.5 cites by year for their articles broadly related to climate change. Journals above the dark dotted line receive 50% more cites for their articles related to climate change than any of their articles. Age-adjusted cites are obtained by computing the weighted average (by the number of articles each year) of cites received for articles published a given year divided with the number of years since publication. These measures are then aggregated for the 1992–2005 time period (panel A), for the 2006–2014 time period (panel B), and for the 2015–2020 time period (panel C). Data on citations by journals are collected using the JCR.

39.5%, 37.5% and 37% of the journals publishing on climate change receive fifty percent more cites by year for their articles related to climate change than for the rest of their articles. By contrast, 39%, 37.5% and 44% receive less cites by year for their articles related to climate change. In this direction, Kube et al. (2018) documents higher citations for articles on climate change in the *Journal of Environmental Economics and Management* relative to other subjects in the same journal. The Figure also highlights some journals, which regularly receive a significant citation premium for their articles on climate change. Across time periods, these are journals such as the *Review of Economics and Statistics*, journals of the *Transportation Research*, *The American Economic Journal: Economic Policy*, the *Journal of Economic Perspectives* (for the last two periods), the *Journal of Political Economy* (for the last time period). These journals are not specialized in the economics of climate change and they can be identified as publishing breakthroughs in the literature.

In Table 1.B.5 and in Figure 1.C.1 in Appendix, I document that journals systematically receive more cites for their articles related to climate change than for the rest of their articles in average. By testing for differences in means in age-adjusted cites each year, between climate-related articles and any articles at the journal level, we observe that this surplus of cites tends to be significantly bigger at the 5% confidence level from 2005 (except in 2007, 2010 and 2013).

1.4 The topic structure of the economics of climate change

In the present section, I investigate the structure of the economic research on climate change. To this end, I use a topic modeling tool, called Latent Dirichlet Analysis (LDA), which is based on statistical text analysis and text mining techniques. This method is used to elicit themes and topics in large collections of documents (Gentzkow et al., 2019). The main intuition behind LDA is that each article is a mixture of topics, and each of the topics are characterized by a proportion of co-occurring words defining the topics' vocabulary. The LDA algorithm results in assigning every articles of the literature to some topics with some probabilities, hence eliciting the semantic construction and the different research fields in the

economics of climate change. This method can be useful to investigate trends and evolutions of specific topics and identify potential research gaps. I first present in detail the LDA method, I then present the different measures of topic trends, similarity, specificity and research directions, and I finally analyze the results of this approach.

1.4.1 The Latent Dirichlet Allocation topic model

LDA is a topic modeling technique developed in Blei et al. (2003), which have then been applied to uncover the topics and themes on which journals or scientific fields have published on (see e.g. Griffiths and Steyvers, 2004; Westgate et al., 2015; Sun and Yin, 2017; Polyakov et al., 2018).

A research article can deal with multiple topics, and the words appearing in that article reflect the particular set of topics it addresses. The intuition behind LDA is that articles exhibit multiple topics, and each topic is defined as a probability distribution over words. In other words, a topic is a set of words co-occurring with a relatively high probability and can be interpreted as a meaningful combination of ideas within our sample of articles. These topics are assumed to be pre-existing, and each article is a mixture of the latent (unobservable) topics with some probabilities.

Following Blei and Lafferty (2009); Blei (2012), LDA describes an imaginary random process based on probabilistic sampling rules, from which the documents are generated from. We only observe the words in every articles and LDA infers the topics and topic proportions per article, by applying statistical inference techniques. This process aims to answer the question: Which hidden structure or topic model is most likely to have generated these research articles? The generative process is formally defined as follows:

1. First, the term distribution for each topic is determined. Each topic is a probability distribution over a fixed vocabulary of size W , that is, with total number W of words. In this stage, for each topic k among the fixed number K of pre-existing topics, a vector β_k of size W containing the proportion of each word in the topic is determined.¹⁵ β

¹⁵Technically, the model assumes that the topics are generated first, before the documents. Then, in practice, the number of latent topics K has to be pre-defined and allows adjusting the degree of specialisation of

is then a random matrix where $\beta_{k,w}$ represents the probability of word w occurring in topic k . LDA assumes that the distribution of words over topics β is determined by a Dirichlet distribution, that is,

$$\beta \sim \text{Dirichlet}(\eta),$$

where η is the prior parameter governing the distribution of words in each topic. This parameter has a single value for every topic and word, as in Griffiths and Steyvers (2004).

2. Then, we define the topic distribution for the articles, that is the proportion of topics within each article. This proportion is determined by a random variable denoted θ . θ is a random matrix, where $\theta_{a,k}$ represents the probability of topic k occurring in article a . LDA assumes that the proportions θ of the topic distribution per article is determined by a Dirichlet distribution, that is,

$$\theta \sim \text{Dirichlet}(\alpha),$$

where α is the prior parameter governing the distribution of topics in each article. This parameter has a single value for every article and topic as in Griffiths and Steyvers (2004).

3. Then, for each of the word positions n in a given research article a :
 - (a) Randomly choose a topic from the distribution over topics θ_a determined in step 2. This topic assignment for the n th word of the a th article is denoted $z_{a,n}$, where $z_{a,n}$ is an integer between 1 and K , and is drawn from a multinomial distribution so that $z_{a,n} \sim \text{Multinomial}(\theta_a)$.
 - (b) Randomly choose a word from the corresponding distribution over the vocabu-

the latent topics. One can vary the number of topics and modify their resulting specificity, and finally choose the number of topics which fits better the corpus of documents. The fitting quality is generally a human interpretation made from the topic coherence, which consists in assessing the meaning coherence in the topic semantic (Chang et al., 2009). This is generally done by looking at the list of words occurring with the highest probability in every topics.

lary conditioned on the topic. The word $w_{a,n}$ is the n th word in article a . $w_{a,n}$ is an element from the fixed vocabulary and is drawn conditionally on the topic chosen with probability $p(w_{a,n} | z_{a,n}, \beta)$.

This statistical model reflects the intuition that each document exhibits the topics with different proportion (step 2); each word in each document is drawn from one of the topics (step 3(b)), where the selected topic is chosen from the per-document distribution over topics (step 3(a)). Then, the LDA automatically discovers the topics from the collection of research articles. The central computational problem is to use the observed distribution of words in research articles to infer the hidden topic structure. The algorithm seeks to estimate the following joint distribution

$$p(\beta, \theta, z, w | \alpha, \eta) = \prod_{k=1}^K p(\beta_k | \eta) \prod_{a=1}^A p(\theta_a | \alpha) \left(\prod_{n=1}^W p(z_{a,n} | \theta_a) p(w_{a,n} | \beta_{k,n}, z_{a,n}) \right). \quad (1.1)$$

LDA estimates the topic-word posterior distribution, denoted $\hat{\beta}_k$, and the per-article topic posterior distribution, denoted $\hat{\theta}_a$, using a log-likelihood maximization. However, given the strong dependancies between topics, terms and research articles, the number of potential structure grows exponentially and the conditional distributions in Equation (1.1) are not tractable. The estimation requires an algorithm to approximate the distributions. We here use the Gibbs sampling approach. This is a Monte-Carlo method which begins by randomly assigning topics. Then, on subsamples, it derives conditional distributions and assigns the words to the topics with some probabilities. This process is iterated several time, until reaching a good approximation of the observed distributions. Then, the main outputs used in the analysis of results of LDA are the posterior distribution of words in each topic, $\hat{\beta}_k$, and the posterior topic content distribution in each article, $\hat{\theta}_a$ (for more details see Griffiths and Steyvers, 2004, which developed the Gibbs sampling approach in the LDA context).

I apply LDA using the abstracts of articles in corpus A, that is, the articles broadly related to climate change. I use article abstracts instead of article full-texts because (i) abstracts are directly available, (ii) it reduces the computational burden and (iii) it simplifies the analysis

as text cleaning on full text would be more difficult.¹⁶ Before applying the LDA, I conduct some text preprocessing using `tm` on R (Feinerer et al., 2008). These manipulations are made to reduce the dimensionality of the data to a manageable level, and to retain words conveying the most meaning. First, I remove stop words, which are very common words using a predefined list ($n = 175$ and are for instance “some”, “what” or “have”), and words with two characters. Second, I remove words that occur only once, to discard very rare words and potential spelling mistakes. Third, I stem the words, that is, I reduce words to their most basic forms, e.g. “climate”, “climatic” are all replaced by the common stem “climat”. Finally, I filter to exclude highly common and rare stemmed words using the “term-frequency inverse document frequency” (tf-idf) (Gentzkow et al., 2019). This metric weights words that are unique to articles more than the others, so that the LDA procedure responds to the most informative text. For the word w in the abstract of article a denoted w_a , term frequency, denoted tf_{w_a} , is the count c_{w_a} of occurrences of w in a . Inverse document frequency, denoted idf_w , is the log of one over the share of documents containing w : $\log(n/d_w)$ where $d_w = \sum_{a=1}^n \mathbb{1}_{c_{w_a}>0}$ and n is the total number of documents. Finally, tf-idf is the product $\overline{tf}_w \times idf_w$, where \overline{tf}_w is the average value of term frequency of word w across articles. Very rare words will have low tf-idf scores because \overline{tf}_w will be low. Very common words that appear in most or all documents will have low tf-idf scores because idf_w will be low. Using this approach, I keep words that occur frequently in some documents but do not appear in others, which provide information on the differences between documents. I decide to exclude the 25% of the words with the lowest tf-idf.¹⁷

LDA is performed using `topicmodel` in R (Grün and Hornik, 2011) using 13,989 abstracts of articles in corpus A. The total of abstracts is slightly lower than the size of corpus

¹⁶Text analysis and topic models are sensitive to the size of the documents and the size of the vocabulary. Given that our corpus of research articles is relatively important and almost exhaustive, the results using full-texts might be similar. Indeed, it has been shown in the context of the literature on fishery, that using abstracts allows to recover similar topic distributions as when using full text when the corpus is large (see Syed and Spruit, 2017, where they have similar results using abstracts with a corpus of 15,000 abstracts relative than their full-text corpus, while their results are different with 4,000 abstracts).

¹⁷Text analysis using unsupervised technique can be sensitive to preprocessing steps (Denny and Spirling, 2018). I also run the algorithm while changing the tf-idf cutoff, that is, keeping 50%, 25%, and 10% of the words with the highest tf-idf. I respectively find number of topics leading to coherent meanings between 7 and 9, between 5 and 7, and between 4 and 6, under the 50%, 25% and 10% cutoff rule respectively, suggesting that we are losing information and diversity when removing words with lower tf-idf.

A ($N_A=14,313$) since 214 articles have no abstract (this is the case for instance of the articles published in *AEA Papers and Proceedings*), and 110 abstracts are excluded after the text preprocessing steps. Then, I estimate several LDA models with different number of topics, that is, with K varying from 2 to 30. To chose the number of topics, I assess the topic coherence between estimations by combining the use of the Akaike Information Criterion (AIC), that is, a measure of the posterior log-likelihood function with a penalty term increasing as the number of topics increases, and the evaluation of the most meaningful grouping as in Polyakov et al. (2018). The AIC is minimized for 9 topics, and 8 and 10 topics leading to close AIC (see Figure 1.C.3 in Appendix). After comparing the contents of these three alternative grouping structures, I finally chose 10 topics as it results in the most meaningful grouping of words and articles. I assign names to the topics by inspecting the words with the highest probability of occurrence in each topics, that is, the words w with the highest $\hat{\beta}_{k,w}$ in each k , and by inspecting the titles and abstracts of the articles having the highest derived proportion of a given topic, that is, the articles a with the highest $\hat{\theta}_{a,k}$ in each k .

Three main structural characteristics of LDA must be underlined beforehand. First, the order of words in the articles does not matter. This is a reasonable assumption given that I aim at uncovering the semantic structure of the articles, not the language structure. Second, the order of articles does not matter. To levy this assumption so as to analyze the evolutions of the topics across years in a dynamic perspective, one can use the dynamic topic model (Blei and Lafferty, 2006). Third, topics are not correlated, meaning that topics occurrences do not exhibit correlations. One could use a correlated topic model in a further analysis to see how it affects our perceptions of the structure of the literature (Blei and Lafferty, 2007).

1.4.2 Discovering the ten topics

The wordclouds in Figure 1.6 detail the content of the topics obtained by our LDA estimation. Sizes of words are proportional to their probabilities in respective topics. Some topics are dominated by one or two words that has a much higher probabilities than other words. For example, for the topic “Carbon pricing”, the word “tax” dominates. By contrast, other topics are defined by several words with similarly high probabilities, that is, the “Energy

transition” topic with the words “nuclear”, “wind”, “solar” almost equivalently represented. This also suggests that some topics are quite homogeneous, and others are more heterogeneous with a higher potential for overlaps with other topics.

These word distributions show some specific research areas in the economics of climate change. This mapping of the field can be studied further while looking at (i) articles with the highest content in the topic (those are articles with the highest $\hat{\theta}_{a,k}$ for each k) and at (ii) most cited articles assigned in each topic. For the latter, an article is assigned to the topic for which it contains the highest content. Formally, for a given article a , the assigned topic is $z_a = k$ if $\hat{\theta}_{a,k} \geq \hat{\theta}_{a,j}$ for any $j \in 1, \dots, K$. In Table 1.B.6 in appendix, I present the 5 most cited articles by topic, as well as the share of the assigned topic in their content ($\hat{\theta}_{a,k} | z_a = k$). Note that a high share of the assigned topic—that is, close to 1—means that the article feats very well in the topic, while a low topic share means that the article is poorly classified *or* is at the intersection of other topics. The ten topics can be briefly described as follows:

- The “Carbon pricing” topic contains words on GHG emissions pricing, the design of climate policies to account for leakages, border adjustments, or revenue recycling. Most cited works in this topic focus on the design of mitigation policy instruments, such as Menanteau et al. (2003); Sinn (2008).
- “Impacts of climate change” combines with high probability words on the economic modeling of climate change, integrated assessment models, the catastrophic and irreversible impacts of climate change, insurance, and cooperation or agreements. Articles fitting into this topics are developing tools to integrate long-term, heterogeneous, and possibly catastrophic and/or irreversible implications of climate change into welfare analysis (such as IAM models), and approaches to design global mitigation agreements and global cooperation (see e.g. Weitzman, 2009; Nordhaus and Yang, 1996).
- “Emission inventories and mitigation options” contains words related to industries, countries and their carbon equivalent emission content. Most cited articles fitting well into this topic focus on the accountability of emissions and the efficiency of mitigation

options at the sector level. (Greening et al., 2000; Peters, 2008).

- The “Energy transition” topic includes with high probability words on renewable energies, their diffusion and their economic efficiency. Articles assigned to this topic focus on the reduction of GHG emissions of energy infrastructures and on promoting innovations and diffusion of renewable energies (see e.g. Unruh, 2000; Jacobson and Delucchi, 2011). (York et al., 2003; Halicioglu, 2009; Zhang and Cheng, 2009; Soytas et al., 2007; Ang, 2007).
- “Carbon sequestration and bioenergy” combines words related to nature based solution to mitigate GHG emissions. Most cited articles fitting in the topic are related to policies designed to increase carbon sequestration, reducing deforestation, or to measure the effects of the supply of biofuels (see e.g. Pattanayak et al., 2010; Havlík et al., 2011).¹⁸
- The “Resilient communities and livelihoods” includes with high probability various words related to housing, health, income sources, sustainability and environmental amenities. The most cited articles focus on household’s well-being in the face of climate change impacts and under mitigation efforts (residential heating and cooling), and the effects of climate change on income and poverty (see e.g. Adger, 2003; Isaac and van Vuuren, 2009).
- The “Transport and cities” topic includes works on urban infrastructures and transport networks efficiency, the emissions intensity of transport mode, as well as the diffusion of electric vehicles (see e.g. Poumanyong and Kaneko, 2010; Egbue and Long, 2012).
- “Agriculture and food” showcases words with high probability related to farming practices, water supply, agricultural productivity, weather events and diets. Most cited articles fitting well in the topic focus on the mitigation and adaptation to climate

¹⁸Note that Holtz-Eakin and Selden (1995) is the example of a poorly classified article, since the word “fire” plays a key role in assigning the article in this category. Indeed, the topic modeling approach cannot handle homonyms if some of their meanings are sparsely used.

change of the agricultural and food-processing sector, as well as works on diets (see e.g. Mendelsohn et al., 1994; Hanjra and Qureshi, 2010).

- The “Climate-friendly behavior” topic associates with high probability words with heterogeneous meanings, which are related to firms, finance, governance, moral and beliefs. In terms of works, the most cited articles associated to this topic focus on the management and governance of climate transition, on green finance, on the determinants of pro-climate change behavior and the tools to nudge individuals and firms to innovate and to account for their environmental impacts (see e.g. Norgaard, 2010; Kahan, 2012).
- “Growth, trade, and CO₂” showcases country and continent names as well as words related to trade and development. In terms of content, this topic includes empirical studies on the causal relationship between growth and GHG emissions as presented in Subsection 1.3.2, and also works on the GHG emissions embodied in exports/imports, or on the energy efficiency in global value chains.

As an overall summary of LDA results, the topics in climate change economics show some consistency in the use of words, which, sometimes, correspond to clear fields of the literature. For instance, the presence of the energy, transport and agriculture clusters illustrate the rather independence of studies on the implications of climate change for these economics sectors. Some other topics are related to economic methods and concepts, which are cross-sectoral. The “Growth, trade and CO₂”, the “Emission inventories and mitigation options”, or the “Impacts of climate change” topics assemble works with rather similar methods, which are respectively empirical and econometric techniques to underline the causal relationship between growth and GHG emissions, bottom-up models of economic systems and their GHG emissions capturing technological details and substitutions, or macroeconomic models interacting global economic activities and global climate. Overall, LDA characterizes a representative landscape of the economics of climate change, which could be used as a classification scheme. The interesting aspect of LDA relies on the potential for topics to overlap and drawing similarities, which the following analysis is going to

underline.

1.4.3 Methodology to measure topic trends, topic similarity, topic specificity and to identify research directions

I use various measures borrowed from articles using LDA in other contexts (see e.g. Westgate et al., 2015; Sun and Yin, 2017; Polyakov et al., 2018), to elicit the dynamic of topic distributions, the topic similarities and specificities, the topic popularity and the research directions.

Topic trends To explore the topic trends, I aggregate the topic content by year to compute the size of topic k on a given year, as in Griffiths and Steyvers (2004). The topic quantity at time t of topic k , $N_{k,t}$, is defined as follows:

$$N_{k,t} = \sum_{a=1}^{N_t} \hat{\theta}_{a,k} \times \mathbb{1}(t_a = t), \quad (1.2)$$

where t_a is the publication year of article a , $\mathbb{1}(t_a = t) = 1$ if a is published on year t and 0 otherwise, and N_t is the number of articles in the corpus published on year t . $N_{k,t}$ measures the prevalence of topic k in articles published on year t . Comparing this metric across years and topics can shed light on the dynamics of topics over time, and underline hot and cold topics. We can also use the composite topic-year proportion by dividing $N_{k,t}$ with the number of articles published on t , so that $N_{k,t}/N_t$ measures the proportion of topic k in the literature on year t .

Instead of aggregating by years, one can aggregate the quantity of topic by journal, or group of journals—e.g. *top-5* economic journals as below—to measure the topic prevalence in journals. The quantity of topic k in the group of journals j , denoted $N_{k,j}$ is defined as follows:

$$N_{k,j} = \sum_{a=1}^{N_j} \hat{\theta}_{a,k} \times \mathbb{1}(j_a = j), \quad (1.3)$$

where j_a is the journal group of article a , $\mathbb{1}(j_a = j) = 1$ if a is published in journal group j

and 0 otherwise, and N_j is the total number of articles related to climate change published by the group of journals j .

An alternative measure of the topic distribution is to use the citations received by the topic. This gives the “demand-side” of the topic. To attribute a cite from a research article to a topic, we can multiply the cites received by an article with the topic proportion in the article. Using age-adjusted cites to compare the cites received by year and limit the influence of old articles and old topics, the quantity of cites received by topic k on year t , denoted $TC_{k,t}^{AA}$, is

$$TC_{k,t}^{AA} = \sum_{a=1}^{N_t} TC_a^{AA} \times \hat{\theta}_{a,k} \times \mathbb{1}(t_a = t), \quad (1.4)$$

which gives the amount of cites received by topic k each year for articles published on year t . To limit the topic size effect in the corpus, we can compute the average cites received each year by the topic on year t , that is $TC_{k,t}^{AA}/N_{k,t}$, where $N_{k,t}$ is defined as in Equation 1.4.

Topic similarity As topic is a probability distribution over words, I can measure the distance between the topic distributions. This metric can underline how the semantics of two topics are closed to each others. In the spirit of Sun and Yin (2017) and Polyakov et al. (2018), I use the Jensen-Shannon Divergence (JSD) to measure the distance between a pair of topics. JSD is a metric used to measure the difference and similarity between two probability distributions. For a given pair of topics k and j in $\{1, \dots, K\}$, with $k \neq j$, the Jensen-Shannon Divergence is defined as follows:

$$JSD(\hat{\beta}_j, \hat{\beta}_k) = \frac{1}{2} [KLD(\hat{\beta}_j, \bar{\beta}_{j,k}) + KLD(\hat{\beta}_k, \bar{\beta}_{j,k})], \quad (1.5)$$

where $\bar{\beta}_{j,k} = \frac{1}{2}(\hat{\beta}_j + \hat{\beta}_k)$ and $KLD(\hat{\beta}_j, \bar{\beta}_{j,k}) = \sum_{w=1}^W \hat{\beta}_{j,w} \log\left(\frac{\hat{\beta}_{j,w}}{\bar{\beta}_{j,k,w}}\right)$ is the Kullback-Leibler divergence. Finally, to measure the distance between a pair of topics, I use the Jensen-Shannon distance, which is the square root of the Jensen-Shannon divergence (Endres and Schindelin, 2003):

$$d_{jk} = \sqrt{JSD(\hat{\beta}_j, \hat{\beta}_k)} \quad (1.6)$$

With the given matrix of distance between all pairs of topics, I then perform hierarchical clustering, using Ward's Agglomerative Hierarchical Clustering Method (see Murtagh and Legendre, 2014, for more insights on the implementation using R). This approach minimises within-group dispersion at each junction using a sum-of-squares criterion. It aims at finding compact and spherical clusters. Using dendograms, I can observe groups of topics having similarities or differences in terms of language used.

Topic generality and specificity We can further interpret the meaning of each reserch topic, by assessing whether a topic reflects a broad theme common to many articles within the corpus, that is a general topic, or describe a restrictive theme, that is a specific topic. To measure topic specificity versus generality we can inspect the distribution of the topic proportion in research articles by topic as in Westgate et al. (2015) and Polyakov et al. (2018). If we compare the average topic proportion in articles assigned to the given topic, that is articles having the highest proportion in that topic, and the average topic proportion on articles which are not assigned to the topic, we get an idea on how the topic is restricted (specific) to some articles or is infused (generalized) in the corpus.

Identifying research directions One objective of systematic literature review is to identify future research directions. There are inherent difficulties and ambiguities in this form of prediction given that research breakthroughs may hardly come from an automated process uncovering the literature structure. Progress might indeed happen through spontaneous novel insights. Nonetheless, given the almost exhaustive overview given by this approach, it is possible to underline productive research efforts and gaps in the literature.

Some influential ideas emerge by connecting popular but disparate concepts. Some holes can structure the literature and networks can be bridged by contributions linking the questions, as suggested by (Chen et al., 2009). In our context, we can identify pairs of top-

ics which are poorly connected and both benefiting from a growing interest, in a similar approach to Westgate et al. (2015) and Polyakov et al. (2018). To identify the connection between topics, I compute the co-presence of topics, which is the correlation between topic proportions for every pair of topics. For given topics j and k , the co-presence is

$$P_{j,k} = \sum_{a=1}^A \hat{\theta}_{a,j} \times \hat{\theta}_{a,k}, \quad (1.7)$$

with A the number of research articles. The resulting matrix of co-presence measures the joint presence of every topic pairs in the corpus. By analyzing this metric along with the previous topic trend analysis, potential research directions can be highlighted.

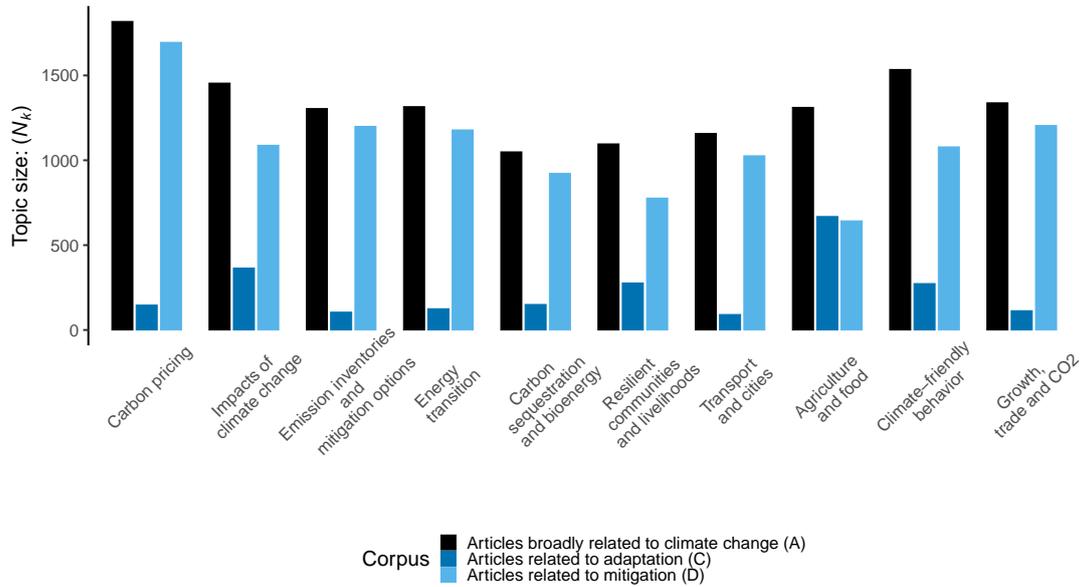
1.4.4 Insights on research topics in the economics of climate change

The size of the research topics In Figure 1.7, I represent the overall size of topics and the average age-adjusted cites received by topics, by aggregating across years the measures in Equations (1.2) and (1.4). The size of topics are rather homogeneous. “Carbon pricing” is relatively larger in size, suggesting its major place in economic research on climate change of studies on mitigating GHG using market-based instruments. The economics of the adaptation to climate change is strikingly represented into the “Agriculture and food” topic. This can be explained by the fact that agriculture is a sector with a significant share in GHG emissions worldwide *and* directly facing major impacts of climate change.

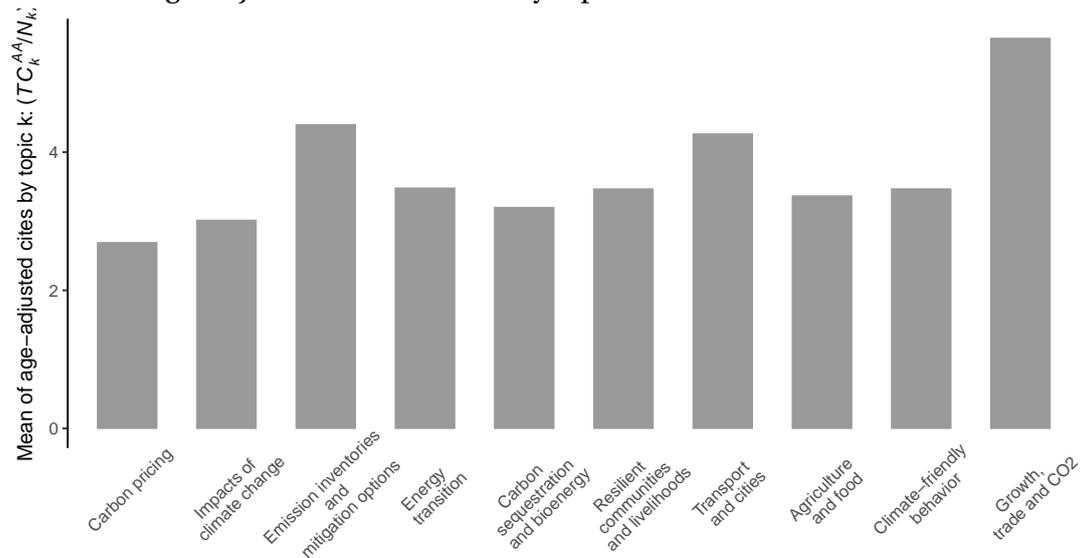
Regarding cites received, we can notice three groups of topics: “Growth, trade and CO2” which is highly cited; the importantly cited topics with “Emission inventories and mitigation options” and “Transport and cities”; and the moderately cited composed of the other topics. The significant interest received for the “Growth, trade and CO2” topic underlines the relatively larger interest in economics for evidence regarding the causal relationship between growth, global value chain and GHG emissions, and the effect of globalization and trade on the environment. Also, the average level of citations is separated from the level of publications, as for the “Carbon pricing” topic. As underlined by Polyakov et al. (2018) in the context of *Environmental and Resource Economics*, there is an important demand for pub-

Figure 1.7: Topic prevalence and mean age-adjusted cites per topic.

A. Topic prevalence



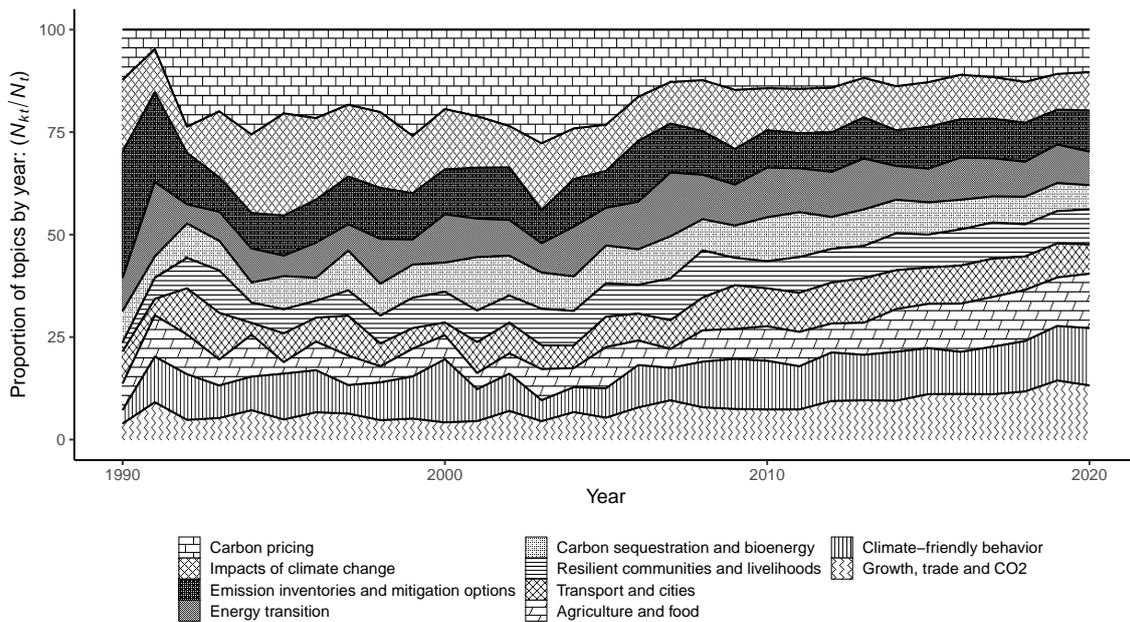
B. Mean of age-adjusted cites received by topic



Note: Topic prevalence (panel A) as measured in Equation (1.2) but aggregated over years, and mean of the age-adjusted cites per topic (panel B) as measured in Equation (1.4) but aggregated over years. These measures are differentiated between the corpus of articles related to the adaptation of climate change and those related to the mitigation of climate change. “Energy transition” represents around 1,300 articles, with a vast majority of them being related to the mitigation of climate change. In average, this topic receives 3.5 cites per year.

lishing research on this topic in order to support policy to mitigate GHG emissions, while receiving at the same time a lower interest outside the field.

Figure 1.8: Dynamics of topics.



Note: Topic trends measured by the prevalence of topic by year, as in Equation (1.2) where $N_{k,t}$ is divided with the number of articles published on year N_t . **Lecture:** In year 2000, more than 20% of the articles published on the economics of climate change have for primary focus carbon pricing, while 5% of the articles focus on the relationship between growth, trade and GHG emissions.

Trends of the research topics on climate change Figure 1.8 shows time-series patterns on the prevalence of topic, that is, $N_{k,t}/N_t$. The language of climate change economics have changed over the last three decades. These changes in language reflect evolutions in how research is conducted. The economics of climate change has clearly broadened its scope over time to reach a variety of economic questions and sectors. Between 1990–2005, half of the published articles on the economics of climate change are associated to the three topics on top of Figure 1.8. This underlines the primary focus in the literature on economic tools to price GHG emissions, on economic methods to measure future climate-induced damages in global welfare analyses, and on per-sector assessments of the economic efficiency of mitigation options.¹⁹

On the other hand, the four topics in the bottom of Figure 1.8 have consistently increased over time, starting from an aggregate share of approximately 25% between 1990 and 2005 to doubling their share and now almost representing half of the economic literature on climate

¹⁹Note that in Figure 1.C.2, I present the trends of the absolute topic quantity, $N_{k,t}$ as defined in Equation (1.2). Given that the economic research on climate change exponentially expands during the period, all topics observe an increase during the period. However, we still notice the relative early prevalence of the “Carbon pricing” and “Climate change impacts” topics, and the recent rapid increase of the quantity of research in “Growth, trade and CO2” and “Agriculture and food”.

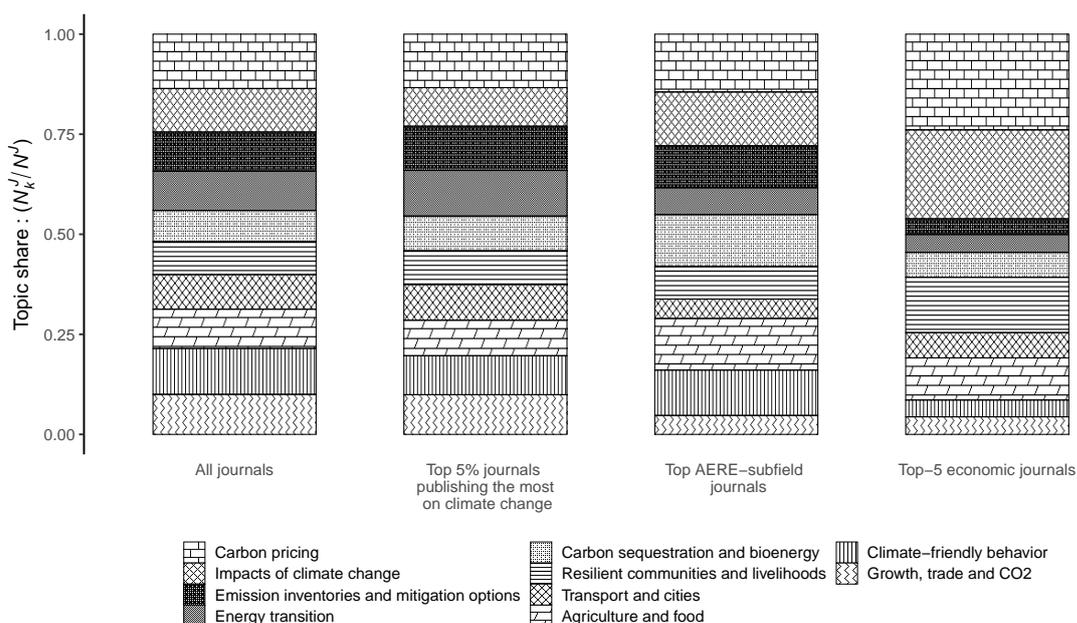
change. This illustrates the opening of the climate change economics literature to empirical analyses of the sectoral implications of climate change in the agricultural and transportation sectors. In addition, there is a growing literature on how growth and development is associated to GHG emissions, and the interaction between trade and carbon emissions. Finally, the increasing share of “Climate-friendly behavior” may illustrate the increasing number of contributions on behavioral barriers to a carbon-neutral transition, or about the role of beliefs, ideology and governance to nudge citizens or firms to innovate or to adopt climate-friendly practices.

Topic treatment of journals Figure 1.9 shows the proportion of topics by groups of journals. I measure the topic proportion at the journal-level by dividing $N_{j,k}$ in Equation (1.3) with the total number of articles published in the journal group N_j , where I here consider j as either the whole sample of journals, or the top 5% of journals publishing the most on climate change (the “Regularly” publishing group in Table 1.6), or the top AERE-field journals, or the *top-5* economic journals.

From Figure 1.9, *top-5* economic journals have a different distribution of topics than the other groups of journals, which have similar topic distributions between each others. This suggests that *top-5* journals have a different publication policy on economic issues related to climate change. In particular, half of their content related to climate change focuses on carbon pricing and global welfare analyses in the presence of very long-term and uncertain impacts. This finding may be unsurprising, given that field journals may attract research articles on economic sectors, such as transportation economics and energy economics journals. This can explain the distortion in topic distributions across journals. However, this is not entirely verified for issues related to climate change and agriculture, since *top-5* journals give a comparable share to this topic.

Above all, it shows which topics has participated in making significant advances for the rest of the economics as a discipline. *Top-5* journals are known to have a highly selective publication process, with publications often becoming major references in their respective field. To the eyes of the profession, the most important methodological advances in economics, which comes from research on climate change, are about the design of mitigation

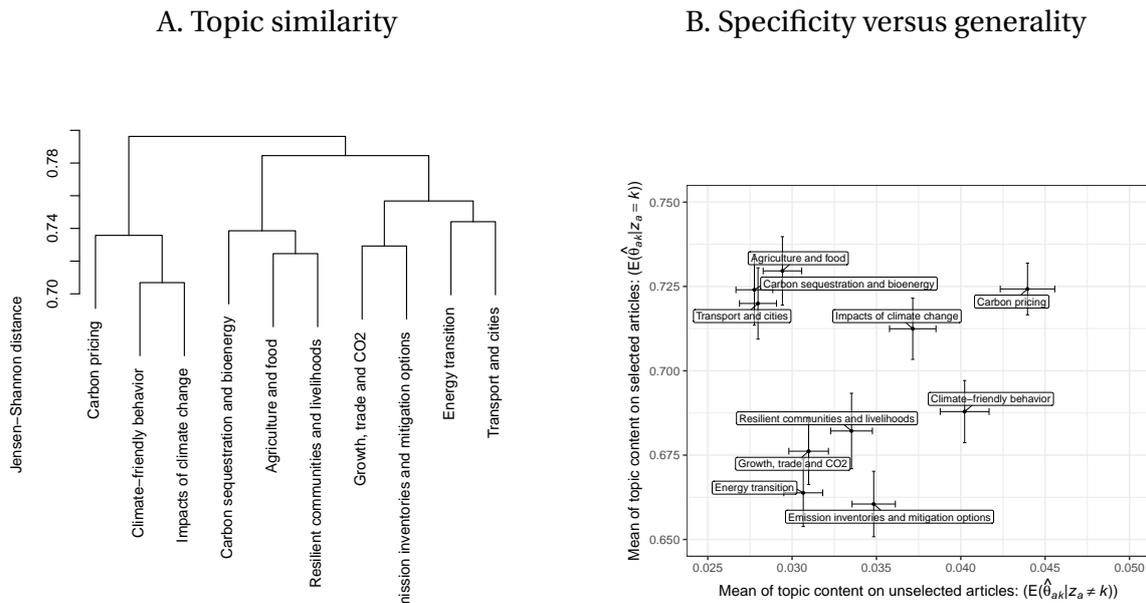
Figure 1.9: Topic prevalence by journals.



Note: Topic proportions by journal groups. Topic share is measured by dividing the quantity of topic published by a journal group, as in Equation (1.3), with the number of articles on climate change published by the journal group N_j . Almost 25% of the articles on climate change published in *top-5* economic journals focus on economic instruments to price GHG emissions, while this share is comprised between 13 and 14% for the whole sample, for the group of economic journals specialized on climate change, and for top AERE-field journals. The top-AERE field journals are determined according to the *CNRS* ranking, and the top 5% of journals publishing the most on climate change account for 70% of all articles in corpus A. They are journals with at least 55 articles over the 1980–2019 time period, and correspond to the “Regularly” publishing group as defined in Table 1.6.

policy instruments and welfare analyses in the presence of very long-term impacts. The remaining topics in the economic literature on climate change could allegedly contain relatively more incremental works that re-use or re-adapt the existing arsenal of tools in economics.

Topic similarity and topic specificity versus generality The distance between topics in terms of semantic is illustrated on Figure 1.10. Lower location of connected topics on the dendrogram indicates that these topics are made of more similar words. This illustrates how some topics share the same language. In addition to highlighting the closest pairs of topics, we can notice three broad groups of topics relatively equidistant and sharing similarities in the words used: further to the left, the group composed of “Carbon pricing”, “Climate-friendly behavior” and “Impacts of climate change”; the group made of “Carbon sequestration and bioenergy”, “Agriculture and food” and “Resilient communities and livelihoods” in

Figure 1.10: **Topic similarity and topic specificity versus generality.**

Note: Similarity between topics (Panel A) using the Jensen-Shannon distance between the topic semantics as presented in Equation (1.6), and then hierarchically clustering topics to group the ones which are closed to each others. Topic generality (x -axis) is measured with the mean value of topic prevalence on articles where the topic is not dominant, and topic specificity (y -axis) is measured with the mean value of topic prevalence on articles where the topic dominates. The “Growth, trade and CO2” topic is respectively closer to the “Energy transition” topic than from the “Agriculture and food”, and it is closer from the latter than from “Carbon pricing”. Relative to the rest of other topics, the “Growth trade and CO2” is moderately general, and weakly specific. The horizontal and vertical segments on panel B. represent the 95% confidence interval of the estimator of the mean.

the middle; and further to the right, the group with “Growth, trade and CO2”, “Emission inventories and mitigation options”, “Energy transition” and “Transport and cities”. The first group brings together topics dealing with global approaches to design climate policy or to understand behavioral barriers to change. The second group mixes topics which are interacting land-based or natural-based economic activities, their distribution in space and the distribution of the impacts of climate change, the determinants of land use change and GHG emissions. The last group focuses on the economic mechanisms behind GHG emissions, the emissions intensity, and options to reduce emissions.

Figure 1.10 confirms that “Carbon pricing” is at the heart of the economic research on climate change. Indeed, a high measure of topic’s specificity (y -axis on panel B of Figure 1.10) indicates that this topic heavily dominates the articles where it is selected and there is no place for other topics. A high measure of topic’s generality (x -axis on panel B of Figure 1.10) shows that this topic occurs evenly in the literature. This topic is simultaneously the most general topic and is among the most specific ones. This suggests that there exists a sub-

literature specifically focusing on market-based instruments to price GHG emissions, while these tools have also permeated in the other research areas in the economics of climate change. This is also consistent with the fact that this topic results from major scientific advances—being published in the most recognized journals in economics—generating its own literature, which also spreads to other topics in the literature.

In addition, Figure 1.10 underlines that topics focusing on economic sectors (transport, agriculture, carbon sequestration, except for energy) are highly specific topics which are not interacting with the rest of the literature.

Intersections of topics and potential research directions Table 1.7 shows the co-presence of topic prevalence by pairs. A relatively low $P_{j,k}$ (in light color) indicates that topic j and k are rarely combined, as opposed to a high $P_{j,k}$ (in dark color) showing that the two topics are regularly associated. In conjunction with the topic trends, potential research gaps can be identified at the intersection of rapidly growing topics, which remain poorly connected.

First, the “Growth, trade and CO₂” topic is increasingly popular over the recent years, and it is not well associated with “Carbon sequestration and bioenergy”, “Agriculture and food”, “Transport and cities”, “Resilient communities and livelihoods” and “Impacts of climate change”. This topic develops empirical approaches identifying the causal role of economic production and trade on GHG emission patterns. By combining this topic with the under-associated ones, potential research directions could focus on the role of trade (or trade agreements) on conservation, on deforestation or on land use change. Other interesting gaps could concern the role of trade in mitigating the impacts of climate change, or the link between trade and transports and the effect of the fragmentation of global value chain in some industries.

Second, combinations of ideas in association with the “Carbon sequestration and bioenergy” topic might be fruitful. This topic is among the most specific one (see Figure 1.10), and with the lowest levels of co-presence with other topics. The topic was more prevalent in the early 2000’s and is now in a slowing phase. There are interesting research questions in conjunction with “Climate-friendly behavior”, which is increasingly popular. These questions could highlight the determinants—such as beliefs, norms, or governance issues related to

Table 1.7: Topic co-presence

	Transport and cities	Resilient communities and livelihoods	Impacts of climate change	Growth, trade and CO2	Energy transition	Emission inventories and mitigation options	Climate-friendly behavior	Carbon sequestration and bioenergy	Carbon pricing
Agriculture and food	42.6	66.1	71.2	60.8	48.4	59.1	69.5	67.3	55.4
Carbon pricing	73.1	62	105.5	78.9	91.6	101.1	97.6	61.1	
Carbon sequestration and bioenergy	40.8	47.9	49.8	47.3	52.5	47.7	55.4		
Climate-friendly behavior	63.7	74.2	97.8	80.2	81.9	77.8			
Emission inventories and mitigation options	60.7	59	68.4	80.3	71.3				
Energy transition	52.7	62.6	63.9	66.7					
Growth, trade and CO2	61	60.8	64.1						
Impacts of climate change	48.7	63.1							
Resilient communities and livelihoods	53.5								

Note: Co-presence by pair of topics, as measured in Equation (1.7). The darker the cell, the more the topics are associated together.

political stability—which can hinder the adoption of sequestration practices or improve the policy design of carbon offset contracts. “Climate change impacts” is also poorly associated with the topic, showing that assessments of climate change impacts face difficulties in incorporated questions related to carbon sequestration and bioenergy.

Third, sectoral studies of climate change on transport and agriculture, which benefit from an ascendent trend according to Figure 1.8, are studied in isolation from the rest of the economics of climate change. Empirical sectoral approaches are often studied independently from topics with more global approaches such as “Carbon pricing” or “Impacts of climate change”. For instance, “Agriculture and food” is the least associated topic with “Carbon pricing”, suggesting that market-based instrument in the agricultural sector are under-investigated. Also, approaches from the “Climate-friendly behavior” topic—those are, voluntary approaches such as nudges or labels, agents’ beliefs and norms, and political stability and governance—are not well connected with research issues on transport, agriculture and

food. There is here potential to interrogate some barriers in these sectors to organize decarbonization.

Finally, Figure 1.7 illustrates the over-representation of economic studies related to the adaptation to climate change in the “Agriculture and food” topic, while it is under-studied in relation with the other topics. Future research agenda may include novel ideas on the effect of trade on the adaptation to climate change or the assessment of climate change effects—at the sectoral or global level—which better characterize adaptation strategies in order to cope with these effects.

1.5 Conclusion

Oswald and Stern’s claim seems to be overstated. Economics has actually produced a vast literature on climate change, whether being global or covering many economic sectors, and including a variety of methods and tools. Moreover, the subject enjoys an increasing visibility, as it is more and more published in general economic journals. It is published by journals with significantly high impact factors on average. Also, articles on climate change are relatively more cited than any other articles in economics.

Oswald and Stern’s call for *top-5* journals to “dramatically increase their works now” may be relevant, if one believes that these journals will influence economic and political change to tackle climate change. As a counterpart, this call also weakens an already substantial scientific production on the subject by qualifying it as non-legitimate. It remains to be understood in more detail why this abundant literature does not enough influence or generate rapid global change. As also underlined by Oswald and Stern (2019), there might be needs for advances favoring the cohesion and coherence of this myriad of works categorized in this overview.

The analysis could include additional tests and safeguards to improve the representativity of the corpus and the robustness of the classification algorithm. For instance, one could check by hand if we effectively include all articles related to climate change for a small subset of journals, to then improve the bibliographic data extraction protocol accordingly. Also,

the bibliometric results could be adjusted by the quality of journals, as is usually done in bibliometric investigations in economics (see e.g. Angrist et al., 2017, for one recent implementation of a weighted scheme). Finally, further checks on the LDA approach regarding the topic selection and identification can be implemented to improve the consistency of the classification.

Further extensions can also directly benefit from the data collection protocol to analyze more deeply the structure of the literature. First, the geography and the network of co-authorship can be one fruitful direction. It can reveal how countries cooperate to tackle this global externality. Is there any geographical segregation or patterns in terms of topic published, or nature of collaboration? Also, what do these international collaborations tell in terms of climate policy? Do we observe some large emitting-countries isolated from the rest of the world in their research effort on climate change? Second, co-citation network can also be investigated. In particular, this networks can be used to cross-validate our topic model. If each topics are shown to be represented by specific network patterns of co-authors or of co-citations, one could argue that our topics are not only a semantical structure, but also a tangible scientific construction given the co-authors and the referenced literature.

To conclude, the mechanisms that encourage economists to publish on climate change in economic journals remain unresolved through this work. Further works are needed to understand the incentives for economists to work on these questions and publish in economic journals. The insularity of the subject, and the place of the economists with their peers regarding climate change can be characterized if we extend the analysis to other disciplines or to other journals with a general audience. For instance, we may question whether economists working on climate change are also producing materials of general scientific value, in journals such that *Nature*, *Science*, or the *Proceedings of the National Academy of Science*. Also, are other disciplines citing articles on economic research on climate change from economics journals or from general journals? This can be done by studying the extramural citations and publications of economists on climate change.

Appendix

1.A Additional information on the corpus construction

See Table 1.A.1 on the next page.

Table 1.A.1: Lists of words used to assign articles in each corpus

Lexicon	List of words
1. Broadly related to climate change	'climate change', 'climatic change', 'global warm', 'greenhouse gas', 'climate policy', 'ghg', 'carbon emission', 'co2 emission', 'co2', 'carbon dioxide', 'greenhouse effect', 'ch4', 'n2o', 'methan', 'nitrous oxide', 'abat', 'adaptive capacity', 'adaptation', 'afforest', 'AFOLU', 'albedo', 'bioenergy', 'biofuel', 'cap and trade', 'ccs', 'carbon footprint', 'carbon price', 'carbon capture sequestration', 'carbon offset', 'carbon sink', 'carbon tax', 'cdm', 'climate damage', 'climate agreement', 'climate change agreement', 'climatic agreement', 'climate club', 'climate event', 'climate extreme', 'climate justice', 'climate impact', 'climate finance', 'climate var', 'cyclon', 'decarbon', 'deforest', 'disaster', 'discount rate', 'double dividend', 'emission standards', 'emissions tax', 'emissions trading', 'energy transition', 'drought', 'environmental hazard', 'extreme event', 'extreme rainfall', 'extreme temperature', 'extreme weather', 'flood', 'forest fire', 'green growth', 'heat wave', 'hurrican', 'kyoto', 'leakage', 'lock-in', 'LULUCF', 'mitigation', 'natural hazard', 'paris agreement', 'permits market', 'pigovian tax', 'rainfall shock', 'rainfall variabilit', 'redd', 'reforest', 'regime shift', 'renewable energ', 'resilien', 'scc', 'social cost of carbon', 'temperature shock', 'temperature var', 'tipping point', 'typhoon', 'UNFCCC', 'vulnerability', 'water sav', 'water scarc', 'water short', 'weather event', 'weather extreme', 'weather shock', 'weather variabilit', 'wildfire'
2. Strictly related to climate change	'climate change', 'climatic change', 'global warm', 'greenhouse gas', 'carbon emission', 'co2 emission', 'carbon dioxide', 'climate policy'
3. Adaptation to climate change	'adaptive capacity', 'adaptation', 'climate damage', 'climate event', 'climate extreme', 'climate justice', 'climate impact', 'climate finance', 'climate variability', 'cyclon', 'disaster', 'drought', 'environmental hazard', 'extreme event', 'extreme rainfall', 'extreme temperature', 'extreme weather', 'flood', 'forest fire', 'heat wave', 'hurrican', 'natural hazard', 'paris agreement', 'rainfall shock', 'rainfall var', 'regime shift', 'resilien', 'temperature shock', 'temperature var', 'tipping point', 'typhoon', 'vulnerability', 'water sav', 'water scarc', 'water short', 'weather event', 'weather extreme', 'weather shock', 'weather variabilit', 'wildfire'
4. Mitigation of climate change	'greenhouse gas', 'ghg', 'carbon emission', 'co2 emission', 'carbon dioxide', 'co2', 'greenhouse effect', 'ch4', 'n2o', 'methan', 'nitrous oxide', 'abat', 'afforest', 'AFOLU', 'albedo', 'bioenergy', 'biofuel', 'cap and trade', 'ccs', 'carbon footprint', 'carbon price', 'carbon capture sequestration', 'carbon offset', 'carbon sink', 'carbon tax', 'cdm', 'climate agreement', 'climatic agreement', 'climate change agreement', 'climate club', 'decarbon', 'deforest', 'discount rate", 'double dividend', 'emission standards', 'emissions tax', 'emissions trading', 'energy transition', 'kyoto', 'leakage', 'lock-in', 'LULUCF', 'mitig', 'permits market', 'pigovian tax', 'redd', 'reforest', 'renewable energ', 'scc', 'social cost of carbon', 'tipping point', 'UNFCCC'

Note: Regular expressions in a singular version or a plural version are accounted. Words from lexicons 2, 3, and 4 are all included in lexicon 1. As a result, the corpora associated with lexicons 2, 3, and 4 are all subsamples of corpus A.

1.B Additional tables

Table 1.B.1: Number of articles and ranking of the 25 journals publishing the most on climate change

Journal	(A)		(B)		(C)		(D)	
	N	r_i	N	r_i	N	r_i	N	r_i
Energy Policy	3875	1	3413	1	293	1	3633	1
Energy Econ.	1121	2	953	2	83	6	1043	2
Ecol. Econ.	1021	3	851	3	283	2	729	3
Environ. Resour. Econ	486	4	435	4	117	4	399	4
J. Environ. Econ. Manag.	297	5	262	6	61	7	224	7
Energy J.	292	6	243	7	18	19	270	5
Intern. J. Energy Econ. Policy	280	7	272	5	20	16	265	6
World Dev.	227	8	160	10	152	3	101	14
Clim. Chang. Econ.	210	9	200	8	96	5	136	10
Resour. Energy Econ.	193	10	161	9	20	16	171	8
Transp. Res. A	172	11	150	11	14	23	138	9
Environ. Dev. Econ.	160	12	144	12	59	8	92	15
Eur. J. Oper. Res.	151	13	139	13	10	38	115	13
Environ. Econ. Policy Stud.	150	14	135	14	19	18	129	11
Intern. J. Prod. Econ.	130	15	120	15	5	77	123	12
Econ. Model.	106	16	93	16	15	21	89	16
Am. J. Agric. Econ.	103	17	81	17	48	9	45	30
Food Policy	100	18	81	17	40	10	54	25
Aust. J. Agric. Resour. Econ.	93	19	75	20	39	11	55	24
Appl. Econ.	88	20	76	19	9	41	75	18
Econ. Syst. Res.	88	20	67	22	5	77	79	17
Rev. Environ. Econ. Policy	88	20	75	20	23	15	66	19
J. Assoc. Environ. Resour. Econ.	76	23	67	22	26	14	56	23
Resour. Policy	74	24	65	25	13	26	59	21
Agric. Econ.	68	25	57	27	37	12	36	40
...
Am. Econ. Rev.	54	33	47	33	13	26	29	43
...
J. Political Econ.	10	152	8	163	2	142	7	134
...
Rev. Econ. Stud.	5	243	4	261	0	361	4	212
...
Econometrica	2	376	2	353	0	361	2	308
...
Q. J. Econ.	1	475	1	443	0	361	1	384

Note: Columns (A), (B), (C) and (D) count articles by journals and rank them according to their number of contributions respectively in corpus A, B, C and D. N_i is the number of articles of journal i in the respective corpus and r_i is the rank of the journal. The total number of *EconLit* journals in corpus A is 709. In **bold font** are represented *top-5* economic journals, and in **green bold font** are represented top-AERE field journals according to the *CNRS* ranking.

Table 1.B.2: Ranking of journals according to the five-year *h-index* for articles related to climate change

Journal	(A)		(B)		(C)		(D)	
	h_i	r_i	h_i	r_i	h_i	r_i	h_i	r_i
Energy Policy	57	1	55	1	18	3	55	1
Energy Econ.	47	2	46	2	10	7	47	2
Intern. J. Prod. Econ.	40	3	38	3	3	36	40	3
Ecol. Econ.	33	4	31	4	23	1	28	4
World Dev.	25	5	21	7	20	2	16	10
Eur. J. Oper. Res.	23	6	22	5	6	14	22	5
Transp. Res. A	22	7	22	5	7	11	19	7
Intern. J. Energy Econ. Policy	20	8	20	8	4	23	20	6
J. Environ. Econ. Manag.	19	9	17	10	12	4	18	8
Transp. Res. E	17	10	16	11	2	48	16	10
Rev. Environ. Econ. Policy	16	11	16	11	11	5	11	18
Transp. Res. B	16	11	16	11	5	16	15	12
Econ. Model.	15	13	16	11	5	16	14	13
Environ. Resour. Econ	15	13	19	9	11	5	18	8
Am. J. Agric. Econ.	14	15	12	18	10	7	9	26
Food Policy	14	15	14	15	7	11	11	18
J. Bus. Ethics	14	15	14	15	2	48	12	16
Research Pol.	14	15	9	27	–	–	11	18
Resour. Pol.	14	15	14	15	3	36	13	14
J. Assoc. Environ. Resour. Econ.	13	20	12	18	8	10	11	18
Econ. Syst. Res.	12	21	10	24	2	48	11	18
Resour. Energy Econ.	12	21	12	18	1	85	12	16
Struct. Change Econ. Dyn.	12	21	12	18	1	85	12	16
Applied Econ.	11	24	11	22	3	36	11	18
Energy J.	11	24	11	22	1	85	11	18
...	
Am. Econ. Rev.	8	33	7	32	2	48	5	47
...	
J. Political Econ.	8	33	6	42	2	48	5	47
...	
Econometrica	1	199	1	181	–	–	1	158
...	
Rev. Econ. Stud.	1	199	1	181	–	–	1	158

Note: Journals *h-index* of their articles on climate change published between 2015 and 2019, and ranking for the 25 first journals and for the *top-5* economic journals and top-AERE field journals. *Ecological Economics* has published 33 articles between 2015 and 2019 which are broadly related to climate change and that have received at least 33 citations. Columns (A), (B), (C) and (D) gives the five-year journal *h-index* by retaining articles which are respectively in corpus A, B, C and D. h_i is the *h-index* of journal i , and r_i is its rank in the corresponding corpus. The character “–” means that the journal has not published any article in this corpus. In **bold font** are represented *top-5* economic journals, and in **green bold font** are represented top-AERE field journals according to the CNRS ranking.

Table 1.B.3: Ranking of journals according to the average cites received for articles related to climate change

Journal	(A)			(B)		(C)		(D)	
	N_i	μ_i	r_i	μ_i	r_i	μ_i	r_i	μ_i	r_i
Am. Econ. J. Macro.	2	206.0	1	10.0	214	402.0	2	10.0	190
Econ. Geogr.	8	204.8	2	204.8	1	406.0	1	136.0	2
Rev. Econ. Stat.	15	158.2	3	179.2	2	207.2	5	130.3	3
J. Labor Econ.	1	153.0	4	153.0	3	153.0	7	–	–
J. Econ. Lit.	13	128.3	5	138.2	4	241.5	3	83.1	11
Q. J. Econ.	1	122.0	6	122.0	5	–	–	122.0	5
Account. Rev.	3	118.0	7	121.5	6	–	–	118.0	6
J. Econ. Growth	2	115.5	8	115.5	7	–	–	216.0	1
J. Econ. Behav. Organ.	1	113.0	9	113.0	8	–	–	–	–
Econometrica	2	104.5	10	104.5	9	–	–	104.5	7
J. Econ. Perspect.	20	92.2	11	91.4	11	58.5	18	59.5	25
Am. Econ. Rev.	54	87.9	12	95.9	10	130.5	10	68.9	14
J. Urban Econ.	11	83.1	13	87.4	12	37.0	29	92.8	8
California Manag. Rev.	11	80.5	14	52.4	32	–	–	128.2	4
Am. Econ. J. Applied Econ.	4	79.0	15	79.0	13	120.5	11	42.0	46
World Bank. Econ. Rev.	7	75.9	16	75.9	14	213.0	4	62.8	21
J. Political Econ.	10	72.5	17	74.1	16	100.0	15	72.7	12
Manag. Sci.	15	70.5	18	58.3	27	178.5	6	49.3	34
World Bank Res. Obs.	11	68.6	19	25.2	98	116.7	13	92.4	9
Judgm. Decis. Mak.	8	66.0	20	66.0	22	–	–	10.7	184
J. Econ. Psychol.	5	65.4	21	75.8	15	24.0	52	17.0	128
Econ. Soc.	12	64.3	22	73.6	17	13.7	101	16.4	136
Financial Manag.	1	64.0	23	–	–	–	–	64.0	18
Manch. Sch.	1	64.0	23	–	–	–	–	64.0	18
Research Policy	34	61.9	25	47.4	37	94.5	16	66.0	16
...		
Ecol. Econ.	974	42.9	45	44.1	41	31.4	37	45.6	39
...		
J. Environ. Econ. Manag.	289	38.6	54	40.2	49	23.5	55	43.0	42
...		
Am. J. Agric. Econ.	94	30.2	80	34.3	63	32.1	36	32.6	62
...		
Energy J.	291	24.1	104	23.9	106	22.5	58	23.7	94
...		
Rev. Econ. Stud.	5	21.0	117	26.2	89	–	–	14.2	153

Note: Average citations received by journal and journal ranking for the 25 first journals and for the *top-5* economic journals and top-AERE field journals. Columns (A), (B), (C) and (D) gives the average cites received by retaining articles which are respectively in corpus A, B, C or D. N_i , μ_i and r_i are respectively the number of articles, the average cites received, and the rank of journal i in the corresponding corpus. The character “–” means that the journal has not published any article in this corpus. In **bold font** are represented *top-5* economic journals, and in **green bold font** are represented top-AERE field journals according to the CNRS ranking.

Table 1.B.4: Most cited articles on the economics of climate change

Period	Authors	Journal	Cites (WoS)
1974–1991	Pearce (1991)	Econ. J.	323
	Nordhaus (1977)	Am. Econ. Rev.	105
	Torvanger (1991)	Energy Econ.	95
	Edmonds and Reilly (1983)	Energy Economics	79
	Nordhaus (1991)	Am. Econ. Rev.	76
	Adams (1989)	Am. J. Agric. Econ.	64
1992–2005	Unruh (2000)	Energy Policy	1166
	Adger (2003)	Econ. Geogr.	1095
	Greening et al. (2000)	Energy Policy	923
	Mendelsohn et al. (1994)	Am. Econ. Rev.	826
	York et al. (2003)	Ecol. Econ.	796
	Shafik (1994)	Oxf. Econ. Pap.	684
2006–2014	Jacobson and Delucchi (2011)	Energy Policy	741
	Halicioglu (2009)	Energy Policy	730
	Zhang and Cheng (2009)	Ecol. Econ.	685
	Weitzman (2009)	Rev. Econ. Stat.	672
	Soytas et al. (2007)	Ecol. Econ.	630
	Ang (2007)	Energy Policy	605
2015–2020	Kasman and Duman (2015)	Econ. Model.	422
	Al-Mulali et al. (2015)	Energy Policy	267
	Kivimaa and Kern (2016)	Res. Policy	256
	Wadud et al. (2016)	Trans. Res. A	252
	Rogge and Reichardt (2016)	Res. Policy	247
	Mattsson and Jenelius (2015)	Trans. Res. A	237

Note: List of the six most cited articles on the economics of climate change in EconLit journals and by time period. This ranking is done for corpus A. Measure of total cites is collected by WoS (and Scopus if not available on WoS) in February 2021. In **bold font** are represented articles published in *top-5* economic journals, and in **green bold font** are represented articles in top-AERE field journals according to the CNRS ranking.

Table 1.B.5: Tests for equality of the means of cites received by year between climate-related articles and all articles

Year	N	(1) μ_{AA}^{All}	(2) s_{AA}^{All}	(3) μ_{AA}^{CC}	(4) s_{AA}^{CC}	(5) t-stat	(6) p-value
1992	15	0.66	0.20	1.97	0.94	-1.358	0.097
1993	17	1.12	0.26	1.16	0.27	-0.106	0.458
1994	16	1.28	0.37	3.28	1.88	-1.039	0.157
1995	21	0.97	0.14	1.51	0.59	-0.907	0.187
1996	19	1.20	0.27	1.75	0.47	-0.996	0.164
1997	18	1.79	0.44	1.95	0.40	-0.262	0.397
1998	23	1.60	0.27	3.13	0.93	-1.585	0.063
1999	23	1.95	0.32	3.56	0.83	-1.824	0.039
2000	28	1.90	0.27	2.45	0.42	-1.098	0.139
2001	25	2.19	0.36	2.21	0.41	-0.048	0.481
2002	23	2.40	0.36	2.64	0.44	-0.405	0.344
2003	33	2.41	0.33	4.03	1.82	-0.875	0.194
2004	23	1.95	0.28	2.84	0.60	-1.348	0.094
2005	33	2.47	0.31	4.32	1.08	-1.639	0.055
2006	37	2.48	0.28	4.08	0.67	-2.211	0.016
2007	43	2.24	0.26	3.40	0.79	-1.399	0.084
2008	66	2.75	0.34	4.66	0.83	-2.147	0.017
2009	81	2.09	0.21	3.86	0.80	-2.130	0.018
2010	100	2.25	0.28	2.98	0.47	-1.341	0.091
2011	103	2.09	0.17	2.82	0.42	-1.622	0.054
2012	119	2.19	0.18	3.38	0.48	-2.313	0.011
2013	109	2.16	0.18	2.44	0.28	-0.819	0.207
2014	138	2.17	0.18	3.67	0.41	-3.316	0.001
2015	134	1.75	0.12	2.36	0.24	-2.257	0.013
2016	142	1.82	0.14	2.79	0.34	-2.616	0.005
2017	155	1.58	0.11	1.91	0.15	-1.724	0.043
2018	159	1.42	0.08	2.18	0.22	-3.287	0.001
2019	170	1.11	0.07	2.15	0.35	-2.904	0.002
2020	171	0.66	0.04	1.45	0.19	-4.043	0.000

Note: Comparison of means and standard deviation of age-adjusted cites received by year at the journal level for any articles (column 1 and 2) and for articles related to climate change (column 3 and 4). Test for equality of the means between groups under the alternative assumption that the means for articles related to climate change is higher (column 5 and 6). In 2010, 100 journals have published at least one article on climate change. These journals received a mean value of 2.98 cites each year for CC-related articles, while for any of their articles published in 2010 they received a mean value of 2.25 cites each year. The null hypothesis of the equality of mean (under the alternative hypothesis that articles relative to climate change received more cites in average) cannot be rejected at the 5% level this year.

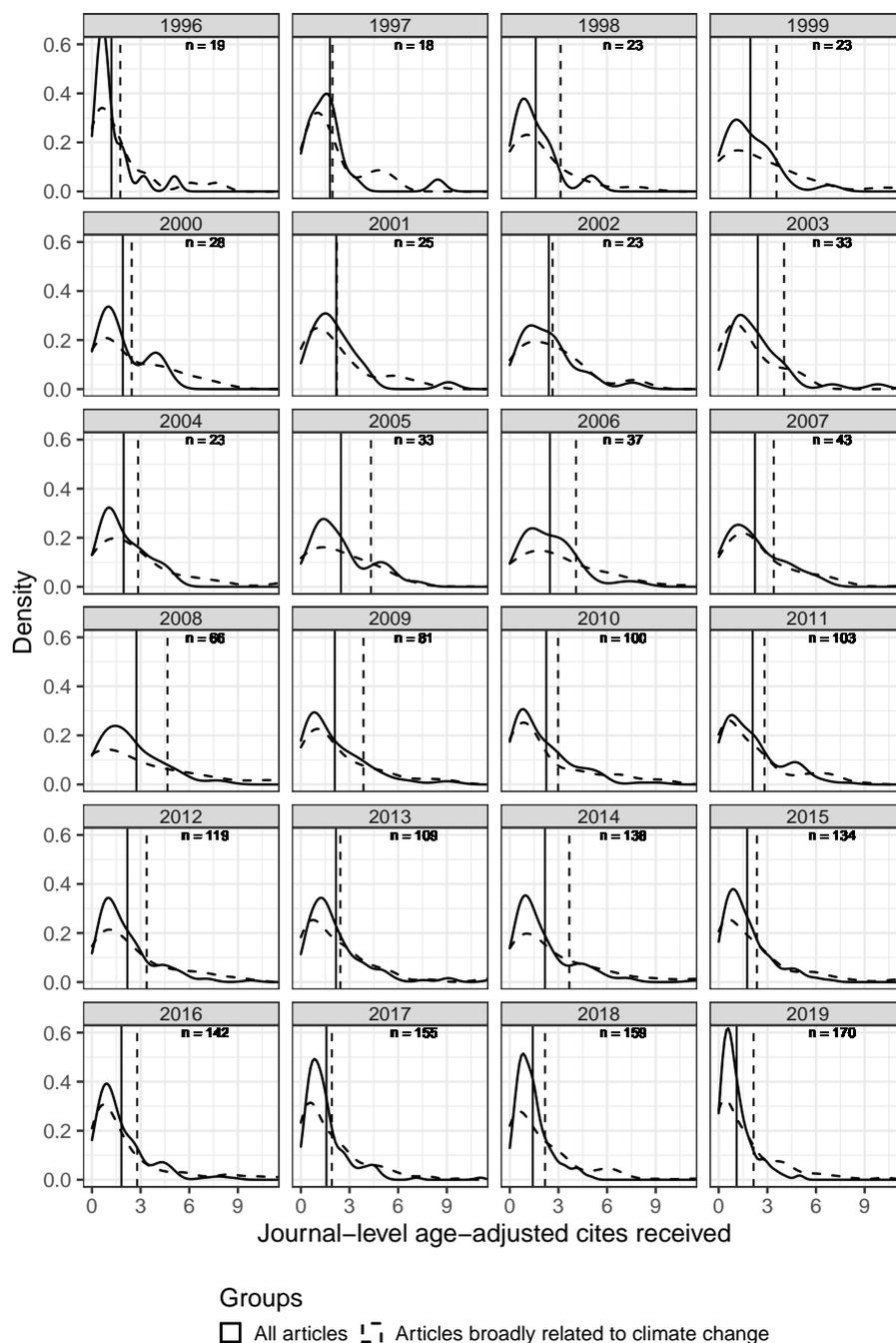
Table 1.B.6: Five most cited articles by topic

Topic	Article	Cites (WoS)	Topic share ($\hat{\theta}_{a,k} z_a = k$)
Carbon pricing	Hoekstra and van den Bergh (2003)	472	0.55
	Menanteau et al. (2003)	415	0.74
	Dell et al. (2012)	402	0.55
	Weber et al. (2008)	388	0.52
	Sinn (2008)	339	0.85
Impacts of climate change	Weitzman (2009)	672	0.89
	Kahn (2005)	487	0.85
	McDonald and Schrattenholzer (2001)	459	0.81
	Nordhaus and Yang (1996)	455	0.83
	Tol (2005)	437	0.89
Emission inventories and mitigation options	Greening et al. (2000)	923	0.85
	Shafik (1994)	684	0.28
	Peters (2008)	599	0.88
	Hua et al. (2011)	447	0.59
	Friedl and Getzner (2003)	403	0.76
Energy transition	Unruh (2000)	1166	0.69
	Jacobson and Delucchi (2011)	741	0.78
	Rubin et al. (2007)	485	0.96
	Gibbins and Chalmers (2008)	442	0.86
	Fischer and Newell (2008)	416	0.57
Carbon sequestration and bioenergy	Holtz-Eakin and Selden (1995)	611	0.68
	Angelsen and Kaimowitz (1999)	503	0.71
	Havlík et al. (2011)	388	0.89
	Pattanayak et al. (2010)	344	0.88
	Faaij (2006)	343	0.70
Resilient communities and livelihoods	Adger (2003)	1095	0.42
	Isaac and van Vuuren (2009)	482	0.79
	Deschênes and Greenstone (2007)	456	0.52
	Martínez et al. (2007)	380	0.56
	Connolly et al. (2014)	375	0.97
Transport and cities	Egbue and Long (2012)	559	0.61
	Lund and Kempton (2008)	547	0.42
	Poumanyong and Kaneko (2010)	499	0.92
	Edwards et al. (2008)	488	0.83
	Bektaş and Laporte (2011)	484	0.92
Agriculture and food	Mendelsohn et al. (1994)	826	0.92
	Hanjra and Qureshi (2010)	469	0.93
	Garnett (2011)	434	0.64
	Tol (2002)	427	0.26
	Beckerman (1992)	399	0.34
Climate-friendly behavior	Norgaard (2010)	551	0.87
	Horbach et al. (2012)	489	0.59
	Bridge et al. (2013)	425	0.85
	Kahan (2012)	423	0.96
	Unruh (2002)	421	0.93
Growth, trade and CO2	York et al. (2003)	796	0.61
	Halicioglu (2009)	730	0.85
	Zhang and Cheng (2009)	685	0.68
	Soytas et al. (2007)	630	0.55
	Ang (2007)	605	0.85

Note: List of the five most cited articles assigned to each topic. Citations measured by WoS in February 2021.

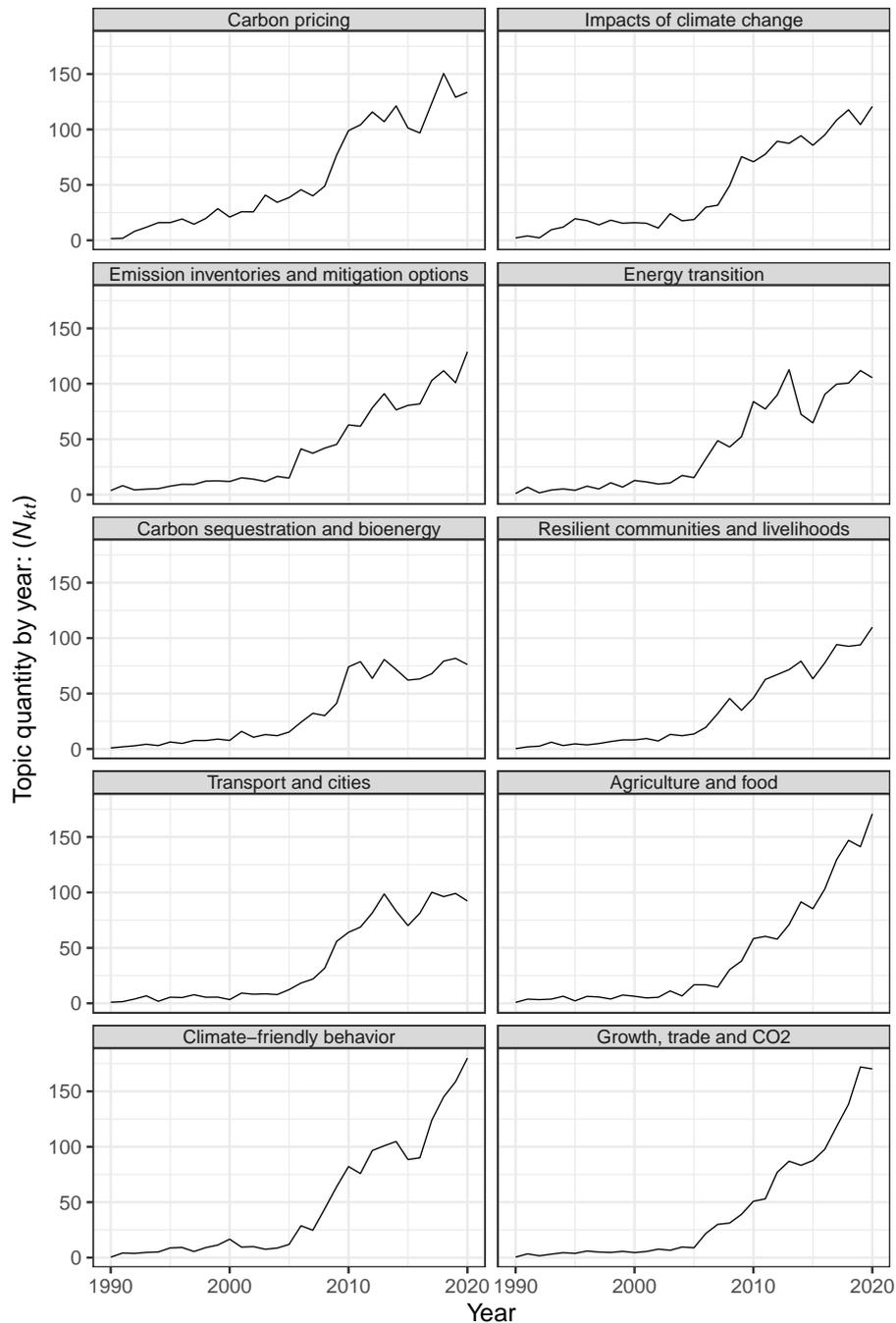
1.C Additional figures

Figure 1.C.1: Journal-level distribution of age-adjusted cites by year for CC-related articles and any articles.



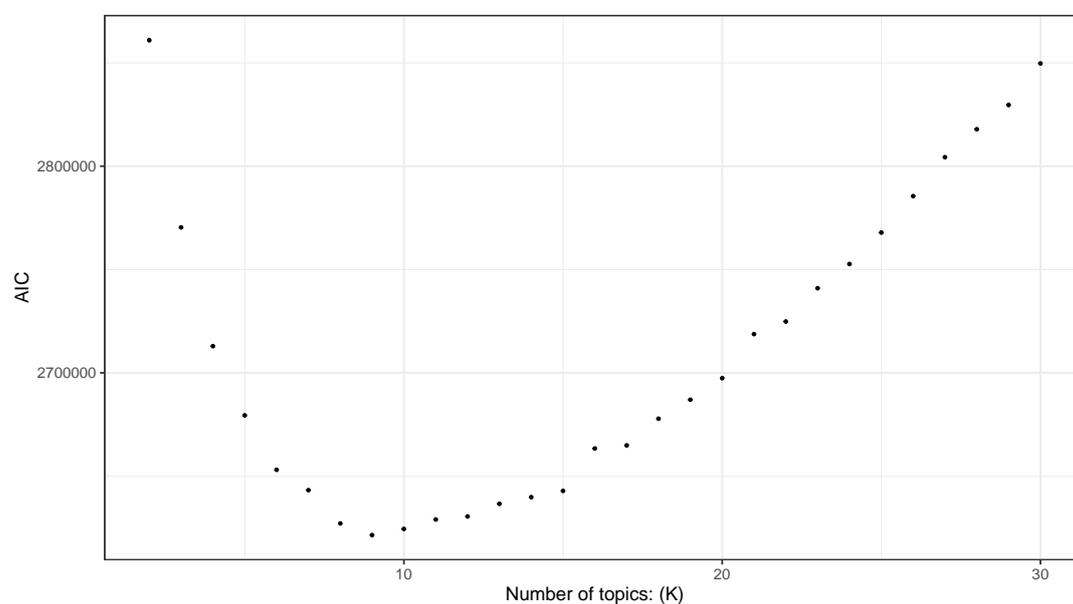
Note: Distributions of age-adjusted cites (average value at the journal-level) by year, for any articles published by the journal that year (solid line) and for articles broadly related to climate change (dashed line). The vertical lines represent the mean of age-adjusted cites for each group of articles and correspond to the means represented in Table 1.B.5. n is the number of journals in both distributions, that is, the number of journals having published at least one article on climate change a given year and with available bibliometric data on JCR.

Figure 1.C.2: Dynamics of the absolute quantity of topics.



Note: Evolution of the absolute quantity of topics by year, $N_{k,t}$ as in Equation (1.2).

Figure 1.C.3: Quality of LDA estimation with the number of topics using AIC.



Note: Values of the AIC associated to the estimation of the Latent Dirichlet Allocation when varying the number of topics. The AIC is minimized with 9 topics.

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Chapter 2

Optimal coverage of an emission tax in the presence of monitoring, reporting, and verification costs

Abstract

Environmental policies often include exemptions for some firms, e.g. the small emitters. This chapter explores the implications of such exemptions in the case of an emission tax, and in the presence of monitoring, reporting, and verification (MRV) costs. We develop an analytical framework capturing the trade-off between the cost-effectiveness of a broader tax base, and the savings on MRV costs enabled by a partial coverage. Second-best partial coverage is defined by a threshold value of some characteristic of the firms below which firms are exempted. We characterize the optimal threshold and discuss its welfare implications. Since determining this threshold is demanding in terms of information regarding firm-level MRV and abatement costs, we show how limited knowledge about these costs at the aggregate level can be used in practice to approximate the optimal threshold. We apply this framework to assess the welfare implications of such an instrument in the case of greenhouse gas emissions from European agriculture. The findings indicate that exempting the small emitters may provide significant savings on MRV costs compared to the full coverage, while still incentivizing cost-effective reductions in emissions.

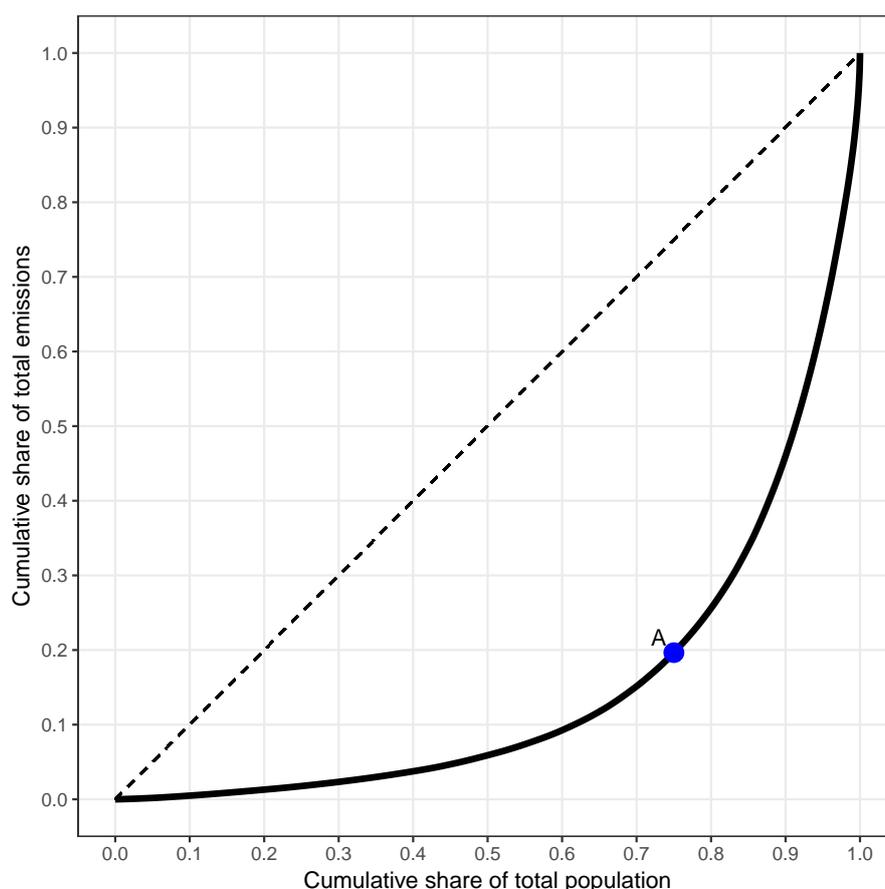
2.1 Introduction

Many policy instruments include provisions that leave some agents out of the scope of regulation. These provisions may involve exclusion of firms in specific sectors, or a threshold value of some characteristic above or below which agents are granted exemption. A typical example is income tax, which in many countries includes exemption provisions for households in the lowest income bracket. Examples can also be found in the field of environmental policy (Becker et al., 2013). The European Union Emissions Trading Scheme (EU-ETS)—currently the main instrument in EU climate policy—explicitly excludes emissions from the residential, agricultural, transport, and waste sectors. Within the sectors included in the EU-ETS, only the installations emitting more than a given amount are subject to cap-and-trade. The EU-ETS covers almost 45% of total European emissions, but only some 11,200 installations (Vlachou, 2014; European Commission, 2015), a small number compared to the millions of car and home owners and farmers in Europe who account for most of the remaining 55% of emissions.

The justification for adopting partial coverage is often based on considerations of inequality, as e.g. in the case of income-tax exemptions for lowest-income households. It may be based also on cost-effectiveness considerations, in particular when the implementation of the policy requires the regulator and/or the agents to engage in costly monitoring, reporting, and verification (MRV) procedures.¹ If the related costs increase with the number of agents subject to the policy, the regulator faces a trade-off between the larger benefits that may be expected from broader coverage, and the cost savings associated with the monitoring of fewer agents.

In this chapter, we examine this trade-off in the context of an emission tax. The regulator must determine *ex ante* which firms should be subject to the emission tax, taking into account the fact that the broader the coverage, the larger the overall reduction in emissions but also the larger the MRV costs. Grosjean et al. (2018) suggest a relationship between the

¹The term MRV is commonly used in the context of climate policy (Bellassen et al., 2015). The related costs correspond to the costs associated with (i) the collection of the relevant data (monitoring), (ii) their communication to the administration or the environmental agency (reporting), and (iii) the certification of the reliability of reports (verification) that ensures the compliance with the regulatory requirements defined in the policy objective.

Figure 2.1: Lorenz curve of initial emissions

Note: Point A corresponds to the third quartile of emissions. Emissions from firms emitting more than this value total approximately 80% of total emissions.

social interest of partial coverage and the distribution of emissions among firms. The intuition is that the more concentrated the emissions among agents, the larger the social interest of targeting only the larger emitters. As an illustration, consider that firms' initial emissions are distributed as depicted by the Lorenz curve in Figure 2.1.

In this situation, targeting only the top 25% emitters (i.e. those to the right of point A in Figure 2.1) saves the MRV costs associated with the remaining 75% of agents, while still covering almost 80% of total initial emissions. Of course, it may be that (some of) the smaller emitters are very efficient at reducing their emissions, while abatement and MRV are very costly for (some of) the larger emitters. Therefore, how such a partial coverage would perform in terms of social welfare depends on the distribution of abatement and MRV costs among agents, not just the distribution of emissions. Determining the optimal coverage thus requires detailed information about individual abatement and MRV costs. This is a

strong requirement, especially if a large number of heterogeneous firms are involved, as is the case for many environmental issues.

Informational issues have given rise to a large body of literature in environmental economics. Most of this literature has focused on the design of truthful direct revelation mechanisms to tackle adverse selection and/or moral hazard (see e.g. Spulber, 1988; Macho-Stadler and Pérez-Castrillo, 2006; Montero, 2008). A recent example can be found in Mason and Plantinga (2013). The authors address the additionality issue in carbon offset programs under asymmetric information about the agents' opportunity costs. They propose a two-part menu of contracts that combines an amount of land included in the program and a differentiated payment. The mechanism enables the regulator to identify to what extent emission reductions are truly additional. It thus avoids paying for reductions in emissions that would have been undertaken anyway. Note that such a mechanism involves the transfer of information rents to induce the agents to reveal their true type. It also requires *ex ante* knowledge of the distribution of agents' types. In addition, even if the mechanism can overcome adverse selection, the issue of costly monitoring and enforcement would remain (Bontems and Bourgeon, 2005; Stranlund et al., 2009).

In this chapter, we explore a simpler design whereby firms below a given threshold are exempted, and emissions from firms above the threshold are all taxed at the same marginal rate. We circumvent the adverse selection problem by using a threshold based on some known and non-manipulable characteristic of the firms. Unlike Mason and Plantinga (2013), we explicitly account for the presence of administrative, transaction and other MRV costs involved by the implementation of the policy instrument.

The optimal coverage of a policy instrument in the presence of administrative costs has been examined in optimal commodity taxation theory (e.g. Yitzhaki, 1979; Wilson, 1989; Dharmapala et al., 2011). Those works determine the tax base (i.e. taxed and untaxed goods) that maximizes welfare given the government's revenue requirement. A slightly different but related idea is developed in Keen and Mintz (2004), who study the turnover threshold above which firms are obliged to register for value-added tax. Although developed in a different context, the simple rule proposed by Keen and Mintz results from a similar trade-off to that

discussed in the present chapter.

In the field of environmental economics, the nature of transaction costs² and their implications for the design of environmental policy have resulted in a large body of theoretical and empirical work (see e.g. Krutilla and Krause, 2011). Two questions addressed in the recent empirical literature on this topic are of particular interest for the present chapter. The first is how transaction costs vary with firm size. Evidence from this literature suggests a less-than-linear increasing relationship, which can be explained by the presence of size-independent setup costs (Betz et al., 2010; Becker et al., 2013; Bellassen et al., 2015). The second question is how the choice of policy instrument influences the level of transaction costs. Joas and Flachsland (2016) and Coria and Jaraité (2019) provide empirical evidence showing that transaction costs are lower under an emission tax than under a cap-and-trade system.

How transaction costs affect the design and efficiency of an environmental policy instrument was studied by Polinsky and Shavell (1982) in the case of an emission tax, and by Stavins (1995) in the case of an emissions trading scheme. Since we focus on an emission tax, the present research is related to Polinsky and Shavell (1982). An important difference between this early research and the present study is that in our study the emission tax coverage is determined endogenously.

The present chapter makes three contributions to this literature. First, it characterizes the optimal threshold in the context of an emission tax when pollution is caused by a set of heterogeneous firms in the presence of MRV costs. This characterization allows us to discuss its performance in terms of social welfare in relation to the first-best, *laissez-faire*, and full-coverage situations. Second, the chapter demonstrates how aggregate (rather than individual) information obtained from sectoral models can be used in practice to approximate the optimal threshold. The third contribution is empirical and consists of a quantitative assessment of the welfare implications of implementing the proposed threshold in the context of greenhouse gas (GHG) emissions from agriculture in the European Union. The empirical

²The term ‘transaction costs’ is somewhat vague in the literature as it may refer to a wide variety of costs. In this chapter, we focus on ‘*ex post* transaction costs’ in the categorization proposed in the review by Krutilla and Krause (2011), i.e. the costs of a policy’s implementation, administration, and enforcement, which we group under ‘MRV costs’.

application covers a large and diverse agricultural sector. This contrasts with previous studies of GHG mitigation in agriculture that have focused on narrower areas and/or a limited set of activities and mitigation options (Dakpo et al., 2017; Garnache et al., 2017; Pellerin et al., 2017).

GHG emissions from European agriculture provide an interesting application case for the analytical framework developed in this chapter. First, despite their weight in total European GHG emissions (about 10% of total net EU emissions according to the European Environment Agency, 2017a), non-CO₂ emissions from agriculture are excluded from the scope of the main climate policy instruments currently in place. This is the case for the EU-ETS, but also for the carbon tax policies implemented in an increasing number of European countries (World Bank, 2017).³ The resulting limitation of inter-sectoral flexibility raises concerns about the possibility of meeting the ambitious EU mitigation targets in a cost-effective manner (Tol, 2009; De Cara and Vermont, 2011; European Environment Agency, 2017b). Second, agricultural GHG emissions result from a large number of heterogeneous farms, which makes monitoring costly (Garnache et al., 2017), a fact that has been used as a justification for excluding agricultural GHG emissions from the scope of climate policy in Europe (Ancev, 2011). Third, many provisions in the Common Agricultural Policy (CAP) are already based on a differentiated treatment of small and large farms. For instance, the requirements that farmers have to fulfill in order to be eligible for green direct payments are more stringent for farms above a certain size. The existence of such thresholds in current CAP provisions may ease the implementation of the optimal threshold proposed in this chapter.

The empirical application relies on a supply-side model of the European agricultural sector. This model has two main advantages. First, it provides sectoral level aggregate results, such as the abatement that can be achieved at a given emission price, and the corresponding total abatement costs to the farmers. Second, the model provides insights into farm-level marginal abatement costs for a large number of representative farms operating

³A carbon tax is currently implemented in ten EU countries: Denmark, Estonia, Finland, France, Ireland, Latvia, Poland, Portugal, Sweden, and the United Kingdom (World Bank, 2017). In none of these countries does the carbon tax apply to non-CO₂ GHG emissions from agriculture.

in a wide variety of contexts across Europe. This information can be used to determine the optimal threshold, and assess the cost-effectiveness implications of the approximation of the optimal threshold proposed in the chapter in various configurations with regard to the marginal damage from GHG emissions, the overall magnitude of MRV costs, and how MRV costs vary with farm size.

The remainder of the chapter is structured as follows. The framework is presented in Section 2.2 and the optimal threshold is characterized analytically in Section 2.3. The sectoral model of EU agriculture and its results in terms of abatement supply of GHG emissions are presented in Section 2.4. The assumptions about MRV costs are presented in Section 2.5. The simulation results with regard to the optimal threshold in the case EU GHG agricultural emissions are presented in Section 2.6. Section 2.7 concludes.

2.2 Analytical framework

Consider a continuum of firms characterized by a parameter θ distributed according to a cumulative distribution function $F(\theta)$ defined for all θ in $\Theta = [\theta_l, \theta_h]$ with $0 \leq \theta_l < \theta_h$. The associated probability distribution function, denoted $f(\theta)$, is such that $f(\theta) > 0$ for all θ in Θ and is equal to 0 everywhere else. The parameter θ can represent any characteristic of the firm observable by the regulator, such as the level of output, use of inputs, or initial emissions. Without loss of generality, the total population of firms is normalized to unity. Therefore, aggregate values over the entire support can be interpreted alternatively as total (denoted by uppercase letters) or per-firm averaged (denoted with a bar) values.

In the unregulated situation, the activity of each firm causes emissions which are denoted e_0 in $[e_{0l}, e_{0h}]$. For any given value of the characteristic θ , reducing emissions below this level entails for the corresponding firm an abatement cost $c(a, \theta)$, where a denotes abatement. There are no fixed costs of abatement.⁴ The function $c(.,.)$ is assumed to be twice differentiable with respect to both arguments. Abatement costs are assumed to be increasing and strictly convex with respect to a . Thus, the following standard assumptions are

⁴Fixed costs (in the form of MRV costs) are introduced later on in the chapter. Accounting for fixed abatement costs would be possible at the expense of additional notations. The insights gained from the analytical model do not depend on this assumption.

made for individual firm values of θ in Θ : $c(0, \theta) = 0$, $c_a(0, \theta) = 0$, $c_a(a, \theta) > 0$ for all $a > 0$, $c_{aa}(a, \theta) > 0$ where the subscripts indicate partial derivatives.

Each unit of emissions causes an environmental damage $\delta > 0$, which is assumed to be constant.⁵ The regulator considers an emission tax where each unit of emissions is taxed at rate τ . Implementing the emission tax involves MRV costs. Some of these costs are borne by the firm (e.g. those related to compliance and reporting), and some by the regulator (e.g. those related to enforcement and verification). For simplicity and unlike e.g. Keen and Mintz (2004), the opportunity cost of public funds is assumed to be zero. Therefore, we do not distinguish between the costs borne by the firm and the regulator. Moreover, MRV costs are assumed to be firm-specific and do not depend on the level of abatement. They are thus akin to fixed (sunk) costs on a per-firm basis. Per-firm MRV costs are denoted by $m(\theta)$, which is assumed to be twice differentiable with respect to θ . Total MRV costs are denoted by $M \equiv \int_{\Theta} m(\theta) dF(\theta)$.

Note that the assumption that MRV costs $m(\theta)$ do not depend on the firm's level of abatement contrasts with the assumption made by Stavins (1995). However, it is supported by (i) the choice of studying an emission tax rather than a cap-and-trade scheme (no trading costs), and (ii) empirical evidence which suggests that MRV requirements and the related costs depend primarily on the size of the regulated entity rather than on how much is abated (Bellassen et al., 2015). In addition, total (abatement and MRV) costs are assumed to remain sufficiently small relative to the firms' profit, so that all firms subject to the emission tax continue to produce.⁶ These two assumptions ensure that MRV costs do not interfere with the firms' optimal abatement choice. Under these assumptions, the level of abatement that maximizes any firm's profit is such that the marginal abatement cost is equal to the level of

⁵The damage function is therefore assumed to be linear. This simplifying assumption may be interpreted as a first-order approximation of the damage function, which is satisfactory when the total level of abatement remains small relative to global concentrations. In the case of a stock pollutant, such as GHG emissions, and in particular when addressing emissions from only one among many emitting sectors (as is the case in the empirical application presented in Section 2.4), this approximation appears to be satisfactory. Relaxing this assumption is possible and does not fundamentally change the nature of the results.

⁶This assumption is different to that made by Polinsky and Shavell (1982), where some firms may exit the market upon implementation of the environmental policy. Relaxing this assumption is possible at the expense of some additional complexity.

the emission tax, i.e.:

$$c_a(a, \theta) = \tau \text{ for all } \theta \text{ in } \Theta. \quad (2.1)$$

Equation (2.1) implicitly defines the individual abatement supply $a(\tau, \theta)$ for any value of the characteristic θ . As a direct consequence of the assumptions regarding abatement costs, the abatement supply for any firm is monotone increasing with respect to the emission tax and is equal to zero if the emission tax is zero. Thus, for all θ in Θ , $a(0, \theta) = 0$ and $a_\tau(\tau, \theta) > 0$ for all $\tau > 0$. For a given level of the emission tax τ , the industry-wide aggregated abatement is denoted by $A(\tau) \equiv \int_{\Theta} a(\tau, \theta) dF(\theta)$, and the corresponding total abatement cost is given by $C(\tau) \equiv \int_{\Theta} c(a(\tau, \theta), \theta) dF(\theta)$.

The regulator's objective is to minimize the total social loss, given by the sum of total environmental damage (total emissions—i.e. initial emissions minus abatement—valued at the marginal damage δ) and abatement and MRV costs. Since initial emissions are fixed, this is equivalent to maximizing the social benefit of implementing the tax defined as:

$$B(\tau) \equiv \int_{\Theta} b(\tau, \theta) dF(\theta), \quad (2.2)$$

$$\text{where } b(\tau, \theta) \equiv \delta a(\tau, \theta) - c(a(\tau, \theta), \theta) - m(\theta) \text{ for all } \theta \in \Theta. \quad (2.3)$$

Consider first that all firms are subject to the emission tax ('full coverage'). The regulator chooses the tax rate that maximizes $B(\tau)$. Under our assumptions regarding MRV costs, it is straightforward to see that the standard Pigouvian result is not affected by the presence of MRV costs. Thus, emissions should be taxed at the marginal damage, i.e. $\tau = \delta$. In this case, using Eq. (2.1) and a standard change of variable, the social value of any firm's abatement net of the corresponding abatement costs ($n(\delta, \theta)$) can be expressed as:

$$n(\delta, \theta) \equiv \delta a(\delta, \theta) - c(a(\delta, \theta), \theta) = \int_0^{\delta} a(v, \theta) dv, \quad (2.4)$$

which is positive for all $\theta \in \Theta$. The aggregate net social value of abatement is defined as $N(\delta) \equiv \int_{\Theta} n(\delta, \theta) dF(\theta)$ and can be computed either as $N(\delta) = \delta A(\delta) - C(\delta)$, or as $N(\delta) = \int_0^{\delta} A(v) dv$.

Note that, under full coverage, total MRV costs may outweigh the aggregate net social value of abatement, thereby deteriorating social welfare compared to the initial situation ($B(\delta) < 0$). This occurs if and only if the ratio of aggregate MRV costs over the total net social value of abatement:

$$k(\delta) \equiv \frac{M}{N(\delta)} > 1 \quad (2.5)$$

Provided that M and $N(\delta)$ are known, $k(\delta)$ provides a synthetic indicator of whether *laissez-faire* should be preferred to full coverage.

If total MRV costs exceed the total net social value of abatement (i.e. if $k(\delta) > 1$), it may be tempting to stop any further cost-benefit investigation and rule out any regulation of emissions in the sector. The main point made in this chapter is that, even if $k(\delta) > 1$, it may be possible to achieve a higher level of welfare than that associated with *laissez-faire* by taxing emissions only from a fraction of the firms.

This requires that the regulator is able to exempt some firms from the emission tax. Because exempted firms have no incentive to reduce their emissions, their abatement is zero. At the same time, no MRV costs are incurred by those firms. Firms characterized by individual MRV costs greater than the net social value of their abatement should be exempt, and only firms such that $b(\tau, \theta) \geq 0$ (if any) should be liable for the emission tax. The regulator's objective function thus becomes:

$$B^*(\tau) = \int_{\Theta} \mathbb{1}_{b(\tau, \theta) \geq 0} b(\tau, \theta) dF(\theta) \quad (2.6)$$

where $\mathbb{1}_{b(\tau, \theta) \geq 0}$ denotes an indicator function equal to 1 when $b(\tau, \theta) \geq 0$, and 0 otherwise.

Under the MRV and abatement costs assumptions underlying Eq. (2.1), the standard Pigouvian result still holds in this context, i.e. $\tau^* \equiv \operatorname{argmax}_{\tau} B^*(\tau) = \delta$ (as long as at least some firms are such that $b(\delta, \theta) > 0$). Emissions from firms subject to the emission tax should thus be taxed at the marginal damage. By construction, when $\tau = \delta$, the social benefit given by Eq. (2.6) corresponds to the first-best situation. It is therefore greater than or equal to the social benefit under both full coverage ($B^*(\delta) \geq B(\delta)$) and *laissez-faire* ($B^*(\delta) \geq 0$).

Implementing the first-best situation requires that the regulator is able to 'cherry-pick'

firms subject to the emission tax. In practice, this may be both unrealistic and at odds with the basic principles of taxation law. Therefore, although useful as a benchmark, this situation does not appear to be a realistic policy option.

2.3 Optimal threshold

2.3.1 Characterization of the optimal threshold

We turn now to a more realistic—and more common in practice—exemption scheme based on a single threshold value θ_s . Only firms characterized by sufficiently large θ , i.e. $\theta \geq \theta_s$, are subject to the emission tax. Firms characterized by θ lower than the threshold are granted exemption, and thus have no incentive to mitigate their emissions. Note that this requires that θ is non-manipulable (based on some historic level for instance) and that it can be observed by the regulator. As abatement and MRV costs are zero for exempt firms, the regulator's objective function becomes:

$$B^s(\tau, \theta_s) = \int_{\theta_s}^{\theta_h} b(\tau, \theta) dF(\theta) \quad (2.7)$$

A minimal cost-benefit test that any partial coverage should pass is that it yields at least a higher social benefit than both the *laissez-faire* and the full-coverage situations, that is:

$$B^s(\tau, \theta_s) \geq \max\{B(\tau); 0\}. \quad (2.8)$$

The following proposition characterizes the interior optimal threshold (if it exists).

Proposition 2.1 (Interior optimal threshold). *Consider that the regulator chooses the level of the emission tax ($\tilde{\tau}$) and the threshold value ($\tilde{\theta}$) so as to maximize $B^s(\tau, \theta_s)$. The pair $(\tilde{\tau}, \tilde{\theta})$ such that $\theta_l < \tilde{\theta} < \theta_h$ (if it exists) must satisfy: (i) $\tilde{\tau} = \delta$, (ii) $b(\tilde{\tau}, \tilde{\theta}) = 0$, and (iii) $b_\theta(\tilde{\tau}, \tilde{\theta}) > 0$.*

Proof. See 2.A.1. □

Again, the standard Pigouvian result holds for firms subject to the emission tax (condi-

tion (i)). Under the optimal level of the tax $\tilde{\tau} = \delta$, condition (ii) is equivalent to:

$$\delta a(\delta, \tilde{\theta}) - c(a(\delta, \tilde{\theta}), \tilde{\theta}) = m(\tilde{\theta}). \quad (2.9)$$

The ‘pivotal’ firm should be such that the social value of the abatement of this firm net of abatement costs (left-hand side) compensates the MRV cost associated with this firm (right-hand side). Although slightly different in its presentation, this condition is similar to that obtained by Keen and Mintz (2004) in the context of the turnover threshold above which a firm must register for value-added tax, or by Betz et al. (2010) in the context of a cap-and-trade scheme. It illustrates the trade-off faced by the regulator when setting the exemption threshold: including one additional firm in the scheme—i.e. marginally lowering θ_s —achieves a higher environmental benefit net of abatement costs but comes with additional MRV costs. Condition (iii) ensures that the second-order conditions are satisfied. Differentiating Eq. (2.3) with respect to θ and using Eq. (2.1) with $\tau = \delta$, this condition is equivalent to:

$$c_\theta(a(\delta, \tilde{\theta}), \tilde{\theta}) + m'(\tilde{\theta}) < 0. \quad (2.10)$$

Therefore, individual costs (abatement plus MRV) must be decreasing with respect to θ in the neighborhood of an interior optimum.

By totally differentiating Eq. (2.9) and using the second-order condition in Eq. (2.10), it can be shown that the interior optimal threshold $\tilde{\theta}$ (if it exists) is decreasing with respect to δ . Therefore, the greater the marginal damage, the larger the proportion of firms that should be subject to the emission tax.

Note that corner solutions are possible. There may exist no interior value of θ_s satisfying Eqs. (2.9) and (2.10). Even if such a solution exists, it may not satisfy the condition in inequality (2.8). Full coverage ($\tilde{\theta} = \theta_l$) may be optimal if the overall magnitude of MRV costs is sufficiently small. Conversely, the *laissez-faire* situation ($\tilde{\theta} = \theta_h$) may be optimal if MRV costs outweigh the environmental benefits of covering (even a fraction of the) firms.⁷ The following proposition provides sufficient conditions that ensure that the optimal threshold

⁷Note that, in that case, the tax rate is irrelevant as no firm is subject to the tax, and the social benefit is by construction equal to zero.

corresponds to an interior solution.

Proposition 2.2. *If $b(\delta, \theta_l) < 0$ and $b(\delta, \theta_h) > 0$, then the optimal threshold is interior ($\theta_l < \tilde{\theta} < \theta_h$).*

Proof. See 2.A.2 □

Without any further assumptions about how abatement and MRV costs vary with respect to θ , there may also be several interior solutions satisfying Eqs. (2.9) and (2.10). As a consequence, the use of a single threshold may lead to tax emissions from firms such that $b(\delta, \theta) < 0$ and grant exemption to firms such that $b(\delta, \theta) > 0$. Therefore, the optimal threshold $\tilde{\theta}$ characterized in Proposition 2.1 is only a second-best instrument. Proposition 2.3 provides a sufficient condition under which the optimal threshold corresponds to a first-best instrument.

Proposition 2.3. *If $b_\theta(\delta, \theta) > 0$ for all θ in Θ , then an emission tax δ affecting only the firms characterized by $\theta \geq \tilde{\theta}$ yields the first-best social benefit, i.e. $B^s(\delta, \tilde{\theta}) = B^*(\delta)$.*

Proof. See 2.A.3 □

The condition that $b(\delta, \theta)$ is monotone increasing with respect to θ over the entire support is equivalent to monotone decreasing individual costs (abatement plus MRV, see Eq. (2.10)). It ensures that the use of a (well-chosen) single threshold is sufficient to perfectly discriminate between the less and the more efficient firms. If this condition is satisfied, implementing the threshold $\tilde{\theta}$ leads to the first-best partition of the population as in Eq. (2.6).

2.3.2 Optimal threshold under constant-elasticity MRV costs and net social value of abatement

The findings presented in Propositions 2.1, 2.2, and 2.3 underscore the importance of two factors for the existence of an optimal interior threshold and its performances in terms of social benefit: (i) the overall magnitude of the net social value of abatement and MRV costs, and (ii) how firm-level net social value of abatement and MRV costs vary with respect to θ .

To illustrate this, further assumptions regarding the distribution of the net social value of abatement and MRV costs are useful. Assume that, for all θ in Θ , $n(\delta, \theta)$ and $m(\theta)$ are specified as follows:

$$n(\delta, \theta) = \alpha_1(\delta)\theta^{\alpha_2} \qquad m(\theta) = \beta_1\theta^{\beta_2}, \qquad (2.11)$$

with $\alpha_1(\delta) > 0$ as soon as $\delta > 0$, and $\beta_1 > 0$. For clarity, we shall also assume that both the net social value of abatement and MRV costs are increasing with respect to θ (i.e. $\alpha_2 \geq 0$ and $\beta_2 \geq 0$).⁸

The specifications in Eqs. (2.11) allow the effects related to the overall magnitude of abatement and MRV costs and those related to their distribution among firms to be disentangled. $\alpha_1(\delta)$ and β_1 are scaling factors independent of θ . The greater $\beta_1/\alpha_1(\delta)$, the larger the ratio of aggregate MRV costs over the total net social value of abatement ($k(\delta)$). α_2 and β_2 represent the (constant) elasticity of the net social value of abatement and MRV costs with respect to θ , respectively. Under specifications (2.11), α_2 is also the elasticity of the firm-level abatement supply with respect to θ (see Eq. (2.4)). Note also that $b(\delta, \theta)$ may not be monotone increasing over the entire support Θ .

The following proposition gives the optimal threshold when the net social value of abatement increases faster than MRV costs with respect to θ .⁹

Proposition 2.4. *If the firm-level net social value of abatement and MRV costs are specified*

⁸These two assumptions are simply meant to simplify the discussion. They are not required to establish the results presented in Proposition 2.4.

⁹When the abatement supply increases slower than MRV costs with respect to θ (i.e. when $\alpha_2 < \beta_2$), the optimal coverage consists of taxing only emissions from the smaller firms (in terms of θ). The results of Proposition 2.4 can easily be extended to this case by considering $\hat{\theta}$ as an upper (rather than lower) threshold. In the limit case $\alpha_2 = \beta_2$, it is straightforward to see that $b(\delta, \theta)$ is of the same sign as $(1 - k(\delta))$ for all θ in Θ , and therefore that the optimal coverage corresponds to either the full coverage (if $k(\delta) < 1$) or the *laissez-faire* (if $k(\delta) > 1$). Lastly, in the degenerate case where $\alpha_2 = \beta_2$ and $k(\delta) = 1$, the full coverage, *laissez-faire*, and any partial coverage all yield zero social benefit.

as in Eqs. (2.11) with $\alpha_2 > \beta_2$, then the optimal threshold is given by:

$$\tilde{\theta} = \begin{cases} \theta_l & \text{if } \theta_i \leq \theta_l \text{ (full coverage)} \\ \theta_i & \text{if } \theta_l < \theta_i < \theta_h \text{ (interior optimal threshold)} \\ \theta_h & \text{if } \theta_i \geq \theta_h \text{ (laissez faire)} \end{cases} \quad (2.12)$$

where

$$\theta_i = \left(k(\delta) \frac{\int_{\Theta} \theta^{\alpha_2} dF(\theta)}{\int_{\Theta} \theta^{\beta_2} dF(\theta)} \right)^{\frac{1}{\alpha_2 - \beta_2}}. \quad (2.13)$$

An emission tax δ affecting only the firms characterized by $\theta \geq \tilde{\theta}$ yields the first-best social benefit, i.e. $B^s(\delta, \tilde{\theta}) = B^*(\delta)$.

Proof. See 2.A.4. □

It is apparent from Eq. (2.13) that, holding everything else constant, the larger the ratio of aggregate MRV costs over the total social value of abatement net of abatement costs ($k(\delta)$), the larger the value of the (interior) optimal threshold, and therefore the smaller the fraction of firms that should be subject to the emission tax. It also appears clearly from Proposition 2.4 that, even in cases where *laissez-faire* is preferable to full coverage (i.e. if $k(\delta) > 1$), taxing emissions from only a fraction of the firms may be socially optimal. This requires that the abatement supply increases sufficiently faster than MRV costs with respect to θ , so that the net social value of abatement for the larger firms (in terms of θ) exceeds their MRV costs. Note also that, despite the possible non-monotonicity of $b(\delta, \theta)$ with respect to θ under specifications (2.11), the use of the threshold defined in Eq. (2.13) is able to perfectly discriminate between firms such that $b(\delta, \theta) < 0$ and those such that $b(\delta, \theta) \geq 0$, and therefore achieves the first-best solution.

The particular case where the firm-level net social value of abatement increases linearly with respect to θ ($\alpha_2 = 1$)¹⁰ and MRV costs are constant across agents ($\beta_2 = 0$) illustrates the

¹⁰Recall that α_2 is also the elasticity of the firm-level abatement supply with respect to θ (see Eq. (2.4)). Therefore, the assumption $\alpha_2 = 1$ is equivalent to assuming that the abatement supply *per unit* of θ ($a(\tau, \theta)/\theta$) is identical across all firms for any given marginal emission tax rate τ . When θ is taken as initial emissions ($\theta \equiv e_0$), $a(\tau, e_0)/e_0$ simply represents the abatement rate, i.e. the relative change in emissions for a given value of τ .

intuition discussed in the Introduction regarding the relationship between a partial coverage and the concentration of θ among firms. Denote by $L(\cdot)$ the Lorenz curve defined as: $L(F(\theta)) \equiv \left(\int_{\theta_i}^{\theta} t \, dF(t) \right) / \bar{\theta}$, where $\bar{\theta} \equiv \int_{\Theta} \theta \, dF(\theta)$ denotes the average value of θ over the entire population. Plugging specifications (2.11) with $\alpha_2 = 1$ and $\beta_2 = 0$ into Eqs. (2.2), (2.3), and (2.7), the inequality (2.8) reduces to:

$$\frac{L(F(\theta_s))}{F(\theta_s)} \leq k(\delta) \leq \frac{1 - L(F(\theta_s))}{1 - F(\theta_s)} \quad (2.14)$$

The inequalities in (2.14) provide, for any given value θ_s of the threshold, a range for the ratio $k(\delta)$ within which taxing the emissions only from firms such that $\theta \geq \theta_s$ passes the minimal cost-benefit test in inequality (2.8). This is depicted in Figure 2.2 (point A). In this case, the lower and upper limits of $k(\delta)$ are given by the slopes of the two blue lines passing through point A. Moreover, the Lorenz curve depicted in Figure 2.2 can be used to determine the optimal proportion of exempted firms for a given value of $k(\delta)$. If $\alpha_2 = 1$ and $\beta_2 = 0$, Eq. (2.13) reduces to:

$$\theta_i = k(\delta)\bar{\theta}. \quad (2.15)$$

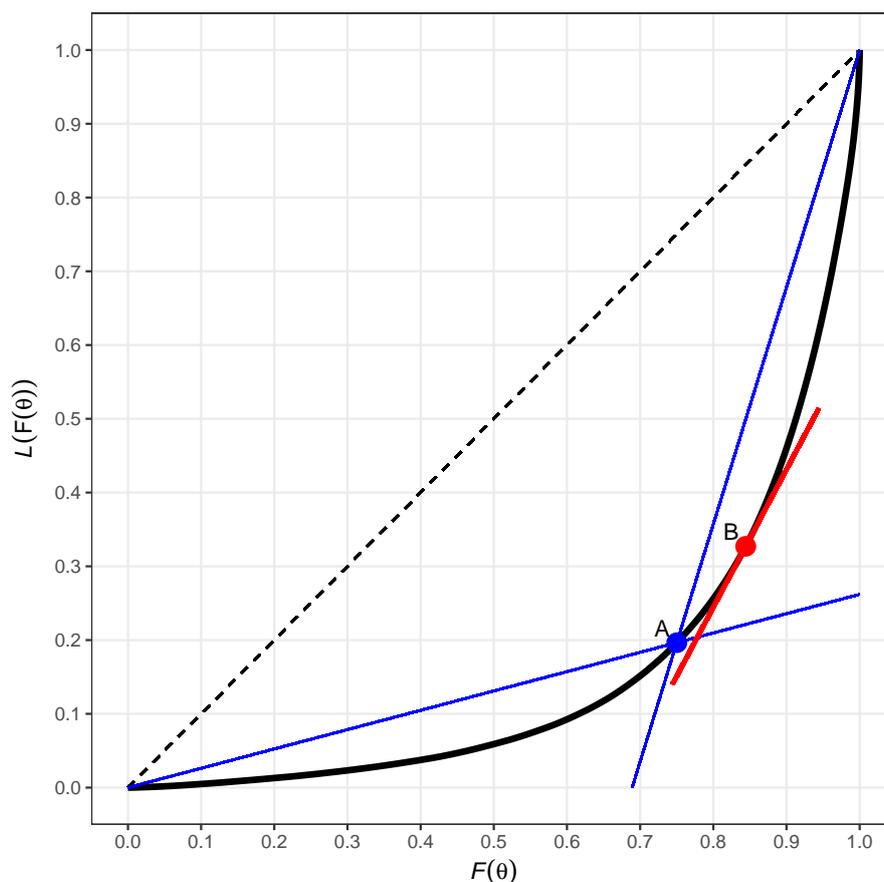
Using Eq. (2.15) and the property of the Lorenz curve that $L'(F(\theta)) = \theta/\bar{\theta}$, this proportion is obtained at the point where the slope of the Lorenz curve is equal to $k(\delta)$. This is illustrated in Figure 2.2 for the case where total MRV costs are almost twice as large as the total net social value of abatement under full coverage (point B).

2.3.3 Discussion: Informational requirements and incentives

How can the findings presented in this section inform the regulator about the optimal coverage in practice? The answer to this question very much depends upon the information that the regulator has access to prior to setting the threshold. It is therefore worth examining the informational requirement involved by the various formulas proposed in this section.

In order to implement the optimal coverage, the regulator must be able to determine whether each firm falls below or above the threshold. This requires that θ is known to the regulator, and that it is non-manipulable by firms. Moreover, *ex post* emissions of the firms

Figure 2.2: Graphical interpretation of the results of Proposition 2.4 in the case $\alpha_2 = 1$ and $\beta_2 = 0$.



Note: The slopes of the two blue lines passing through point A give the lower and upper limits of $k(\delta)$ within which a partial coverage covering only the top 25% emitters performs better than both laissez-faire and full coverage (i.e. satisfies inequality 2.8). Point B corresponds to the optimal threshold when $k(\delta) = 1.87$ (slope of the red line).

above the threshold must also be known in order to determine the applicable tax base. The costs of collecting this information are included in MRV costs.

If the regulator has perfect *ex ante* knowledge about all individual abatement supply curves $a(\tau, \theta)$ and MRV costs $m(\theta)$, the conditions provided in Proposition 2.1 can be used to determine the optimal coverage. However, assuming full and perfect information is admittedly a strong requirement, especially when a large number of heterogeneous emitters are involved.

It may be the case that the regulator has access only to aggregate evaluations of the costs and benefits of implementing an emission tax under full coverage. For instance, $N(\delta)$ may be derived from simulations of aggregate models of the sector-level response to an emission tax, either based on the full curve $A(\tau)$ or on point-estimates of $A(\delta)$ and the corresponding

total abatement costs $C(\delta)$.¹¹ The overall magnitude of MRV costs (M) may be evaluated based on similar regulations in the sector, or on observations on a representative sample of the population. If M and $N(\delta)$ are known, Eq. (2.15) provides a rule-of-thumb approximation of the optimal threshold, which is valid if both the firm-level abatement supply *per unit of* θ and MRV costs can be reasonably assumed to be constant across firms. In more general cases where $\alpha_2 \neq 1$ and/or $\beta_2 \neq 0$, Eq. (2.13) of Proposition 2.4 may be used to determine the optimal threshold provided that (i) the regulator has prior knowledge of the elasticities of the firm-level abatement supply and MRV costs with respect to θ , and (ii) those elasticities can reasonably be assumed to be constant with respect to θ .

In practice, it is possible that specifications such as those proposed in (2.11) reflect only imperfectly the specificities of each individual firm. To illustrate this, consider the modified versions of Eqs. (2.11):

$$n(\delta, \theta, \varepsilon) = \alpha_1(\delta)\theta^{\alpha_2}\varepsilon \qquad m(\theta, \eta) = \beta_1\theta^{\beta_2}\eta, \qquad (2.16)$$

where ε and η are two independent random error terms such that $\mathbb{E}[\varepsilon] = \mathbb{E}[\eta] = 1$, where \mathbb{E} represents the expectation operator over the joint distribution of ε and η . In this case, the objective of a (risk-neutral) regulator is to maximize $\mathbb{E}[B^s(\delta, \theta_s)]$. Under these assumptions, the linearity of the expectation operator then implies that $\mathbb{E}[B^s(\delta, \theta_s)] = \int_{\theta_s}^{\theta_h} [\alpha_1(\delta)\theta^{\alpha_2} - \beta_1\theta^{\beta_2}] dF(\theta)$.¹² Therefore, the formula given in Eq. (2.13) can still be used, provided that unbiased estimates of the elasticities α_2 and β_2 have been obtained, for instance from an econometric estimation of Eqs. (2.16) over a representative sample of the total population. Replacing α_2 and β_2 by their respective (unbiased) estimates in Eq. (2.13) gives the threshold value that maximizes $\mathbb{E}[B^s(\delta, \theta)]$. Note however that because of the local non-monotonicity due to the error terms ε and η , the *ex post* social benefit may not correspond to the first-best.

¹¹Some studies provide a functional specification for $A(\tau)$ (e.g. De Cara and Vermont, 2011; Vermont and De Cara, 2010). Other studies report only point estimates for some emission prices (e.g. Pérez Domínguez et al., 2016).

¹²Note that the same argument would apply under a specification with independent, zero-mean additive error terms. The choice of multiplicative error terms in Eqs. (2.16) is motivated by the estimation on the log-transformed specification conducted in the empirical application (see Section 2.4 and 2.B.3).

Lastly, imposing a differentiated treatment of small and large firms may raise issues regarding the incentives to escape taxation. It may be argued that, under a partial coverage, firms above the threshold face incentives either to pretend to be below the threshold, or to set their output at a sub-optimal level. In the context of the model presented above, this difficulty is circumvented by the assumption that the threshold hinges on an observable and non-manipulable characteristic. This is nevertheless a valid concern if, for instance, firms expect the threshold to be revised over time. The policy design may mitigate this concern, e.g. by taxing only the emissions that are above that of the pivotal firm. Such a design would be equivalent to a lump-sum transfer to all firms above the threshold, and it would not affect their abatement levels (see Eq. (2.1)) compared to the situation where all their emissions are taxed.

2.4 Abatement costs of greenhouse gas emissions in the EU agricultural sector

The empirical application is based on the results from a supply-side sectoral model of the European agricultural sector (AROPAJ). This model has been used in several empirical assessments of agricultural and/or climate policies in Europe (e.g. De Cara et al., 2005; De Cara and Vermont, 2011; Leclère et al., 2013; Lungarska and Jayet, 2016). For a general presentation of (a previous version of) the model, see e.g. De Cara and Vermont (2011).¹³

The model is an annual supply-side model which describes the optimal economic decisions of a set of representative farms regarding land allocations and livestock management. An important data source is the European Union Farm Accountancy Data Network (EU-FADN) data set, which provides economic and structural information on approximately 80,000 professional farms in the EU-27 for the year 2009. Based on this information, representative farms are constructed as clusters of the real farms surveyed by the EU-FADN. The

¹³The main changes compared to this previous version include a wider geographic coverage (27 EU member states in 2017, i.e. all EU member states in 2017 except Croatia), the use of more recent farm-level data (pertaining to the year 2009), inclusion of the EU Common Agricultural Policy instruments prevailing in 2009, and updated relationships for the computation of GHG emissions based on the information reported by all member states in their GHG inventory reports. A full technical presentation of the model is available at https://www6.versailles-grignon.inra.fr/economie_publique/Media/fichiers/ArticleAROPAJ.

typology relies on automatic classification techniques that combine the information provided by the EU-FADN on farm location (134 regions and three altitude classes within the EU-27), economic size, and main types of farming. The model covers crop- and livestock-oriented farming systems as well as mixed-farming systems. Farms specialized in perennial crops (orchards, vineyards) are excluded from the analysis. The typology results in 1,802 representative farms, representing approximately 3.7 million existing farms.

Each representative farm is associated with a micro-economic gross-margin maximization model subject to resource availability (e.g. land, size of cattle operation facilities), agronomy (e.g. crop rotations, animal feeding requirements, livestock demography), and policy constraints. These constraints depend on the conditions of production and type of farming, and thus vary from one representative farm to the other. The main decision variables for each farmer are the areas allocated to different crops (the model accounts for the 24 main annual crops grown in Europe, and for temporary and permanent grassland), livestock numbers in each animal category (dairy and non-dairy cattle broken down by age and sex, sheep, goats, swine, poultry), and animal feed (e.g. on-farm produced vs. purchased feed, forage vs. concentrates) given animal-specific protein and energy minimum requirements and maximal ingested matter constraints. Most input parameters (input and output prices, yields, variable costs) are farm-specific and estimated using EU-FADN data. A restricted set of technical parameters, for which farm-level observations are lacking, are calibrated so that the model reproduces FADN observations at the representative farm level for the year 2009.

The model covers the major non-CO₂ GHG sources caused by farming activities: N₂O emissions from agricultural soil and manure management, and CH₄ emissions from manure management, enteric fermentation, and rice cultivation. It excludes CO₂ emissions from agriculture,¹⁴ as well as carbon sources and sinks related to agricultural soils.¹⁵ The

¹⁴Non-energy related sources of CO₂ in agriculture are much smaller than that of methane and nitrous oxide emissions. They are mainly caused by the use of carbon-containing fertilizers (lime, urea) for a EU total of about 9 MtCO₂eq in 2009. The European Environment Agency (2017a) reports the emissions due to fossil fuel use in agriculture together with those of fisheries and forestry. These emissions represent slightly less than 77 MtCO₂eq, a figure to be compared to a total of non-energy related agricultural emissions of about 431 MtCO₂eq.

¹⁵Accounting for soil carbon sinks and sources would introduce additional complexity because of the dynamic nature of natural processes involved and because of the importance of land-use changes from and to agricultural uses (forestry, urban, etc.).

emissions accounting method uses country-specific emission factors taken from national GHG inventory reports. The emission factors are linked to each farm's relevant activity variables, so that emissions for all categories are computed endogenously. CH₄ and N₂O emissions are converted into CO₂ equivalent using the respective Global Warming Potential (25 for CH₄, 298 for N₂O). Total initial emissions amount to about 407 MtCO₂eq, or about 94% of agricultural emissions reported by the European Environment Agency (2017a) for the year 2009.

Initial emissions vary markedly among farms.¹⁶ Computed per-farm emissions at the representative farm level range from 0.3 tCO₂eq to about 7,700 tCO₂eq per year, with an average of approximately 109.8 tCO₂eq (see Table 2.B.1 in Appendix). The corresponding Lorenz curve of initial emissions is depicted in Figures 2.1 and 2.2, with 25% of the farms responsible for about 80% of total emissions.¹⁷

When faced with an emission tax τ , each representative farmer endogenously adjusts the land allocation among crops, animal feed, and/or animal numbers until the marginal abatement cost is equal to τ . Note that these adjustments depend on the set of active capacity constraints at the representative farm level, and therefore vary from one representative farm to the other. Plotting the resulting individual reductions in emissions against the emission tax (from 0 to 200 €/tCO₂eq in steps of 1 €/tCO₂eq) provides the abatement supply curve for each representative farm. The corresponding EU-wide aggregated abatement supply curve is provided in the Appendix (Figure 2.B.1).

For simplicity, the analysis focuses on four emission tax rates: 5, 30, 50, and 100 €/tCO₂eq. The lowest value corresponds approximately to the average price of CO₂ emissions allowances in the EU ETS in 2016-2017.¹⁸ A price of 30 €/tCO₂eq is the 2017 level of the carbon tax in France, the largest emitting country of agricultural emissions in Europe (World Bank, 2017).

¹⁶Complete model results at the representative farm level (initial emissions, abatement, abatement costs, etc.), along with the R code necessary to reproduce all graphs and calculations reported in the chapter can be retrieved from the on-line supplemental material available at: <https://doi.org/10.17632/w4ygt38p86.1>.

¹⁷Note that, as (i) the EU-FADN data does not provide information about non-professional farms, (ii) some farming activities (vineyards, orchards) are excluded from the analysis, (iii) emissions are computed for representative farms that result from the grouping of real farms, the Lorenz curve presented in Figure 2.2 may not fully reflect the actual concentration of emissions among farms.

¹⁸See <https://www.eex.com/en/market-data/environmental-markets/auction-market>, (checked on November 21, 2017). Note that this price has significantly increased and have currently reached 50 €/tCO₂eq in spring 2021.

50 and 100 €/tCO₂eq correspond to the lower and upper values of the carbon price range recommended by the Stern-Stiglitz Commission for 2030 in the aftermath of the Paris Agreement (High-Level Commission on Carbon Prices, 2017). At these prices, aggregate abatement represents approximately 2%, 7.5%, 11%, and 20% of total initial EU agricultural emissions, respectively.¹⁹ The corresponding EU-wide abatement costs range from 18 million to almost 3.6 billion euros, while the social value of abatement net of abatement costs ranges from 22 million to 4.5 billion euros (see Table 2.1).

Table 2.1: Aggregate results under full coverage

Emission price δ [€/tCO ₂ eq]	Emissions $E(\delta)$ [10 ⁶ tCO ₂ eq]	Abatement $A(\delta)$ [10 ⁶ tCO ₂ eq]	Abatement cost $C(\delta)$ [10 ⁶ €]	Net social value of abatement $N(\delta)$ [10 ⁶ €]
0	406.8	-	-	-
5	398.8	8.0	18.0	22.0
30	376.2	30.6	375.6	543.5
50	361.0	45.8	979.4	1310.3
100	326.0	80.8	3557.4	4524.0

Note: Total farm population: $F = 3.7 \times 10^6$ farms.

The model results at the representative farm level are used to compute the individual net social value of abatement $n(\delta, \theta)$ over the full explored range of emission prices and for each representative farm. These values are then regressed on the corresponding emission price (in the form of a smooth non-parametric term), and on a measure of farm size using a Generalized Additive Model (Wood, 2006) on the log-transformed model presented in Eq. (2.16). Three alternative measures of farm size are used: initial emissions (e_0), initial area (s_0), and initial number of livestock (ℓ_0). The estimated results are reported in Appendix (Table 2.B.2). For all three measures, the estimated elasticity α_2 is larger than 1, suggesting that the abatement supply increases more than proportionally with respect to size. The estimated elasticity ranges from 1.11 (for $\theta \equiv e_0$) to 1.48 (for $\theta \equiv \ell_0$). The quality of the fit is the highest using initial emissions as the measure of farm size.

¹⁹As a comparison, Pérez Domínguez et al. (2016, see table 35, p. 117) report abatement rates in EU agriculture of 3.5%, 5%, 10%, and 16% for carbon prices of 10, 20, 50, and 100 €/tCO₂eq, respectively.

2.5 MRV costs data and assumptions

MRV costs correspond to the costs of (public and private) resources needed to (i) determine whether each farm is above or below the threshold, (ii) measure *ex post* emissions for farms above the threshold, and (iii) implement and collect the emission tax.

The magnitude of the costs associated with each of the above items depends on how MRV activities are deployed in practice. The costs of determining which farms are above the threshold depends on the characteristic upon which exemption is based. In the context of the present study, we assume that this characteristic can be readily observed by the regulator, and we therefore assume that the related costs are negligible.²⁰ Emissions may be computed using standardized emission factors and equations linking the level of emissions with activity data retrieved from farm-level book-keeping information; or they may be directly measured, through e.g. sensors, monitoring devices, or satellite observations. MRV costs are also likely to depend on the type of mitigation technologies adopted by farmers. Some of these methodologies may be easier to monitor and verify than others. Another important determinant of the magnitude of MRV costs is the extent to which the implementation of the emission tax can build on existing policy instruments. The European agricultural sector has a long history of regulation, most notably through the Common Agricultural Policy (CAP). Many CAP provisions require that farmers collect and report data about their farm operations on a regular basis to be eligible for CAP payments. They also include standardized control and verification procedures of the reported data. Arguably, relying on already-collected data and existing information systems to process and verify it may significantly reduce MRV costs.

The calibration of MRV costs is all the more challenging in that MRV costs data pertaining to the mitigation of GHG emissions in European agriculture are scant. The vast majority of the estimates available in the literature pertain to firms in energy-intensive sectors (see e.g. Bellassen et al., 2015), or to carbon projects in the forestry sector (see e.g. Phan et al.,

²⁰Note that the model can be generalized to incorporate the cost of determining whether each firm is above or below the threshold. As this would require to collect information for the entire population, which size is given, the related cost can be considered as fixed (i.e., independent of θ_s). Incorporating such a fixed cost in the regulator's objective function would not change the results presented in Proposition 2.1. This would however affect the conditions under which an interior solution prevails (inequality (2.8)).

2017). Some estimates in the agricultural sector are available, but they often pertain to policy instruments not directly related to GHG emissions (e.g. OECD, 2007), and/or have been obtained in non-European contexts (e.g. Cacho et al., 2013).

Based on a compilation of available estimates and taking into account the specificities of the EU agricultural sector, Ancev (2011) proposes a figure of 2.5 € per ton of CO₂eq initially emitted. Extrapolating this figure to the entire European sector using the total emissions reported in Table 2.1 leads to total MRV costs (M) slightly above 1 billion € and to a per-farm average of 275 €. Based on the average hourly labor cost in the EU,²¹ the corresponding workload is about 11 hours per farm, which is in line with the assumptions made by Cacho et al. (2013) in the context of the Australian carbon farming program.

To our knowledge, Foucherot (2015) is the only reference that provides an in-depth analysis of MRV costs in an actual agricultural GHG mitigation project in the European context. The Joint Implementation project analyzed in this work aims at reducing N₂O emissions from nitrogen fertilizer use through the introduction of legume crops in 316 farms in France.²² The author reports a total of 40,000 € in MRV costs for the project as a whole, or an average of approximately 127 € per farm. Extrapolated to the entire farm population represented in the model, this corresponds to total MRV costs of about 470 million €.

Given the scarcity of empirical information about MRV costs, a range of calibrations for MRV costs will be explored. As underscored in Section 2.3, two features are important: (i) the overall magnitude of MRV costs (M), and (ii) how these costs are distributed among farms.

As for the magnitude of MRV costs, three scenarios will be explored. The “low” and “medium” scenarios are based on the figures reported by Foucherot (2015) and Ancev (2011), respectively. The “high” scenario draws from a compilation of the estimated implementation costs of agri-environmental programs in the EU by (OECD, 2007, Table I.1.4), which reports an average per-farm implementation costs of 1,522 € in France. When upscaled to the entire population, this figure corresponds to total MRV costs of about 5.6 billion €.

These three scenarios are combined with three contrasted assumptions regarding the

²¹This information is extracted from Eurostat, see: http://ec.europa.eu/eurostat/statistics-explained/index.php/Hourly_labour_costs

²²A detailed description of the project is available from the UNFCCC website: <http://ji.unfccc.int/JIITLProject/DB/B62UQB13Z82B384RU4SBK14JR7P9RS/details>.

distribution of per-farm MRV costs: (A) constant across farms, (B) increasing and concave with respect to initial emissions, and (C) increasing and linear with respect to initial emissions. Assumption (B) builds on the results reported by Bellassen et al. (2015). In this recent review, the authors compile the available information on MRV costs within energy-intensive sectors related to various climate policy instruments (ETS, clean development mechanism projects, inventories), and at various scales (jurisdiction, entity, project). Their estimation results indicate a constant elasticity of per-entity MRV costs with respect to initial emissions equal to about 0.34.

The implications of these various assumptions for total, per-farm, and per-ton MRV costs are presented in Table 2.2.

Table 2.2: Assumptions regarding MRV costs: $m(e_0) = \beta_1 e_0^{\beta_2}$

Specification and magnitude	Total	Per farm			Per ton			
	M [10 ⁶ €]	$m(e_0)$ [€/farm]			$\mu(e_0) = m(e_0)/e_0$ [€/tCO ₂ eq]			
	β_1	\bar{m}	min	max	$\bar{\mu}$	min	max	
(A) Constant per-farm MRV costs ($\beta_2 = 0$)								
Low	126.58	469	127	127	127	1.15	0.02	494.80
Medium	274.52	1017	275	275	275	2.50	0.04	1073.09
High	1522.00	5639	1522	1522	1522	13.86	0.20	5949.37
(B) Increasing, concave per-farm MRV costs ($\beta_2 = 0.34$)								
Low	32.81	469	127	28	916	1.15	0.09	80.87
Medium	71.15	1017	275	56	1831	2.50	0.19	175.39
High	394.47	5639	1522	271	8850	13.86	1.06	972.40
(C) Increasing, linear per-farm MRV costs ($\beta_2 = 1$)								
Low	1.15	469	127	0	8860	1.15	1.15	1.15
Medium	2.50	1017	275	1	19215	2.50	2.50	2.50
High	13.86	5639	1522	4	106528	13.86	13.86	13.86

2.6 Optimal threshold in the case of GHG emissions from the European agricultural sector

In this section, we start by considering that the threshold is defined as a minimum level of initial emissions above which farms are subject to the emission tax (i.e. $\theta \equiv e_0$). Note that

this requires that farm-level initial emissions be observed by the regulator.²³

It is possible also to base exemption on alternative criteria that require no prior computations by the regulator. Two additional criteria are investigated in this section: the farm's total agricultural area, and number of animals (expressed in livestock units –LU). Information regarding these variables is reported routinely by farmers for fiscal or agricultural policy purposes. Note that determining the tax base still requires farms' emissions to be computed but only for the farms liable for the emission tax, not necessarily the entire farm population. All three criteria are based on historic levels of the respective characteristic—i.e. prior to the implementation of the emission tax—to ensure that they are not manipulable by farmers. The summary statistics for all three criteria are reported in Appendix (Table 2.B.1).

For clarity, the results are presented first for a benchmark configuration characterized by a marginal damage equal to 30 €/tCO₂eq, total MRV costs under full coverage equal to 1,017 M€ (medium MRV costs), increasing and concave per farm MRV costs with respect to initial emissions ($\beta_2 = 0.34$), and an exemption criterion based on initial emissions ($\theta \equiv e_0$).

In this configuration, all the information needed to approximate the optimal emission threshold using the simple formula from Eq. (2.15) can be retrieved from Tables 2.1 and 2.2. Total MRV costs under full coverage are about 1.87 times higher than the net social value of abatement. Thus, the corresponding threshold is given simply by $k(30) \times \bar{\theta} = 1.87 \times 109.8 \approx 205$ tCO₂eq. Setting the threshold at this level implies that only the emissions from the top 15.6% of emitting farms are taxed, for an emission coverage of about 67.3% (point B in Figure 2.2). The use of the formula in Eq. (2.13) requires additional information, in particular with regard to elasticities α_2 and β_2 . Plugging the values of $N(30)$, M , α_2 and β_2 reported in Tables 2.B.2 and 2.2 into Eq. (2.13) yields a threshold value of about 391 tCO₂eq. Only 7.7% of the farms emit more than this value initially.

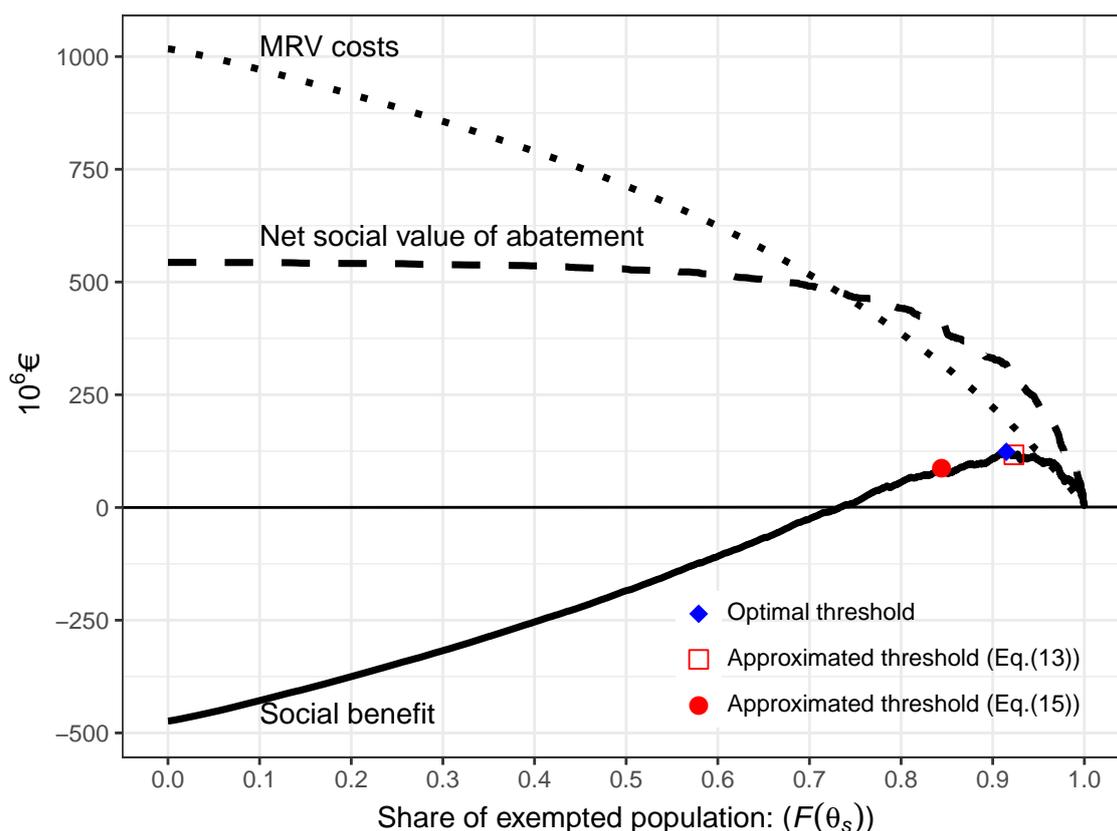
How accurate are these approximations of the optimal emission threshold? And what are their welfare implications? To answer these questions, we make full use of the model

²³In the context of GHG emissions from European agriculture, this appears to be a reasonable assumption insofar as individual emissions can be approximated quite well using standardized computation rules—such as those used in national GHG inventories—based on farm-level data (area, yields, animal numbers, and synthetic and organic nitrogen management). As argued by De Cara and Vermont (2011), existing CAP provisions demand that farmers—as soon as they benefit from CAP payments—collect and/or report this information.

results, which provide marginal abatement costs at both the EU level and the (representative) farm level. This information can be used to compute total social benefit in the first-best situation (as in Eq. (2.6)), and in the optimal emission threshold case (characterized by Proposition 2.1).

Figure 2.3 depicts how MRV costs, the net social value of abatement, and the resulting total social benefit vary with respect to the emission threshold in the benchmark configuration. To make it easier to compare Figures 2.2 and 2.3, these variables are plotted against the cumulative share of the total farm population, with farms sorted by increasing initial emissions. The x -axis in Figure 2.3 thus gives the share of exempted farms in the total population for all values of the threshold. Therefore, the full-coverage situation is obtained when $F(\theta_s) = 0$, and the *laissez-faire* situation when $F(\theta_s) = 1$.

Figure 2.3: Total social benefit in the benchmark situation.



Note: Total social benefit is the solid curve and its components are the dashed curves. $\delta = 30 \text{ €/tCO}_2\text{eq}$, $m(e_0) = 71.15(e_0)^{0.34}$ (medium, increasing and concave per-farm MRV costs), and only the largest emitting farms are subject to the emission tax ($\theta \equiv e_0$).

In the benchmark configuration, taxing emissions from all farms (full coverage) leads to a net social loss of about 474 M€. This configuration corresponds to the situation de-

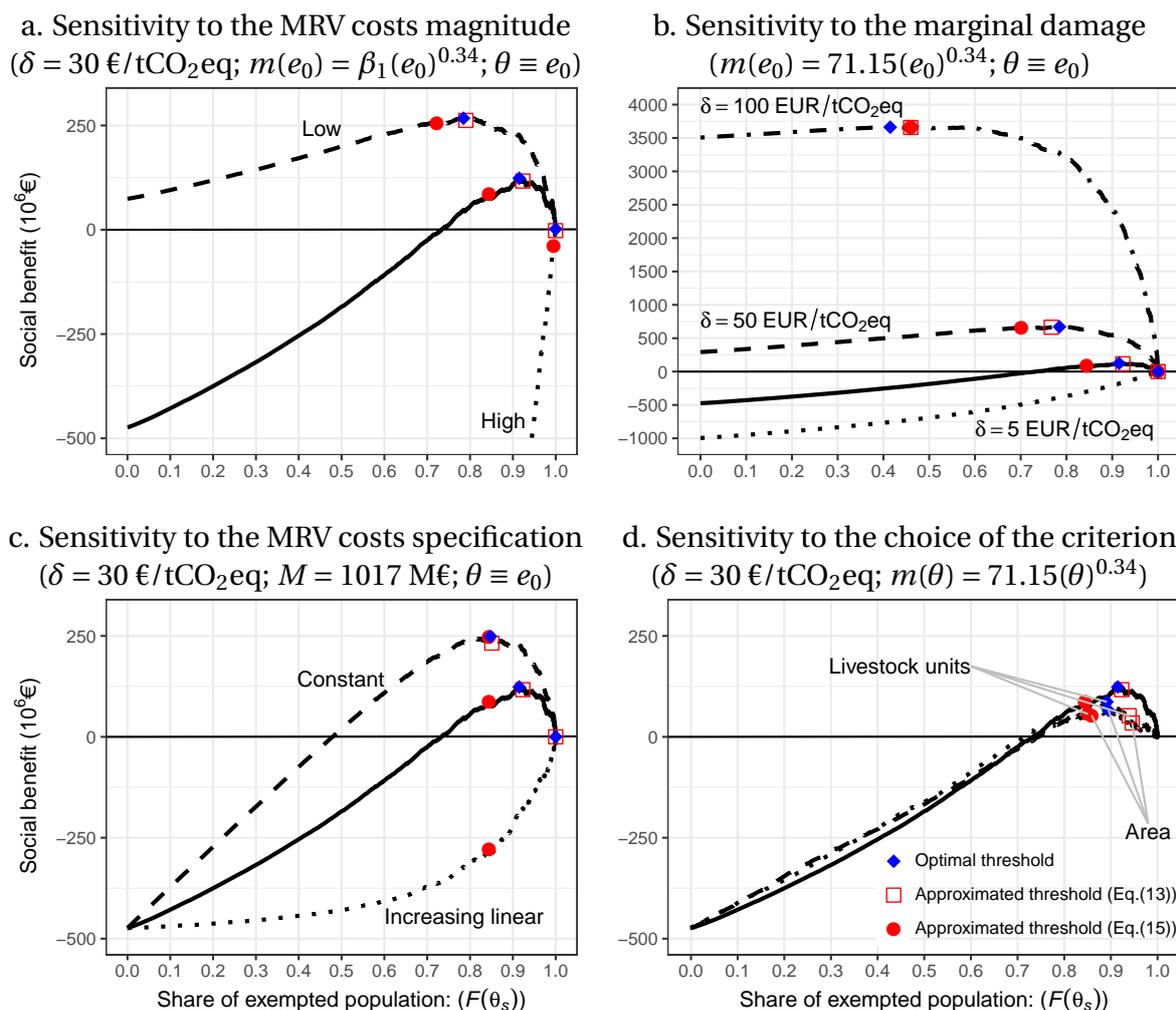
scribed by Ancev (2011): under full coverage, MRV costs are markedly higher than the net social value of abatement. Figure 2.3 shows also that the *laissez-faire* situation is preferable to a partial coverage for any emission threshold below the 73rd percentile. The optimal emission threshold is equal approximately to 370 tCO₂eq. This would entail exemption of around 91.5% of farms (but only 50.7% of emissions) for a corresponding abatement of approximately 16.7 MtCO₂eq and abatement costs of about 184 M€s. The latter figure is to be compared with a sector-wide gross margin of about 140 billion €s initially. The resulting total social benefit in the benchmark configuration is approximately equal to 124 M€ (blue diamond in Figure 2.3). In this configuration, the social benefit associated with the implementation of the threshold approximated by Eq. (2.13) (red square) is about 7 M€ smaller than under the optimal threshold. The use of the simple approximation given in Eq. (2.15) would yield a social benefit about 37 M€ smaller than under the optimal threshold.

Figure 2.4 depicts how the total social benefit in the benchmark configuration is affected by alternative assumptions regarding the magnitude of MRV costs, the level of marginal damage, the MRV cost specification, and the choice of the exemption criterion. The full results for the first-best, optimal emission threshold, and approximated emission threshold configurations are reported in Tables 2.B.3 to 2.B.6 in the Appendix.

As underscored in Section 2.3, the overall magnitude of the MRV costs is an important determinant of both the optimal and the approximated thresholds. This is illustrated by Figure 2.4.a which depicts the social benefit associated with three values of total MRV costs under full coverage, holding constant the value of the marginal damage ($\delta = 30 \text{ €/tCO}_2\text{eq}$) and the elasticity of per-farm MRV costs with respect to initial emissions ($\beta_2 = 0.34$). The optimal emission threshold under high MRV costs (5250 tCO₂eq) would lead to the exemption of about 99.99% of the farms. Under low MRV costs, the optimal threshold is only 138 tCO₂eq, leading to 78.5% of the farms being exempted. In all three configurations, the social loss when the emission threshold is approximated based on Eq. (2.13) does not exceed 7 M€; while the social loss using the approximation based on Eq. (2.15) amounts at most to 40 M€ (see Appendix, Tables 2.B.4 to 2.B.6).

Figure 2.4.b illustrates the role of the marginal damage. The magnitude and distribution

Figure 2.4: Total social benefit under alternative assumptions.



Note: The solid curve is the same as in Figure 2.3 and corresponds to the social benefit in the benchmark configuration: $\delta = 30 \text{ €/tCO}_2\text{eq}$, $m(e_0) = 71.15(e_0)^{0.34}$ (medium, increasing and concave per-farm MRV costs), and $\theta \equiv e_0$ (only the largest emitting farms are subject to the emission tax).

of MRV costs ($m(e_0) = 71.15(e_0)^{0.34}$, i.e. medium, increasing and concave per-farm MRV costs) are held constant. The optimal emission threshold involves farm exemption rates ranging from about 41% (if $\delta = 100 \text{ €/tCO}_2\text{eq}$) to 100% (if $\delta = 5 \text{ €/tCO}_2\text{eq}$). For all the values of δ explored in Figure 2.4.b, the social loss from approximating the emission threshold using Eq. (2.13) does not exceed 7 M€, see Tables 2.B.4 and 2.B.5). The use of the simpler approximation given in Eq. (2.15) would yield to a social loss up to 37 M€.

Figure 2.4.c highlights the effect of the specification of per-farm MRV costs. For the same value of total MRV costs under full coverage (medium, $M = 1017 \text{ M€}$) and the same value of the marginal damage ($\delta = 30 \text{ €/tCO}_2\text{eq}$), the optimal emission threshold leads to 84.7% of the farms being exempted in the constant per-farm MRV costs case, and to all farms (i.e.

laissez-faire) being exempted in the linear increasing case. By construction, the formula in Eq. (2.15) only depends on aggregate results under full coverage. Therefore, for any given values of M and δ , the associated threshold (205 tCO₂eq) is the same regardless of the actual distribution of MRV costs among farms. This approximation performs fairly well when per-farm MRV costs are constant, but deteriorates social welfare by 279 M€ compared to *laissez-faire* in the increasing linear case. By contrast, the approximation from Eq. (2.13) yields a non-negative social benefit in all three configurations.

Figure 2.4.d depicts how the total social benefit is affected if exemption is based on initial area or livestock numbers rather than on emissions in the benchmark configuration. The respective values of the total social benefit under the three criteria are fairly close. This is true in particular, for thresholds below the third quartile. This can be explained by the fact that the smaller farms, be they measured in terms of area or the number of animals, are also the smaller emitters. Nevertheless, for any given value of the threshold θ_s , the social benefit is larger if exemption is based on the farm's initial emissions rather than on area or the number of animals. This suggests that the level of individual initial emissions is a better predictor of the sign of the respective social value of abatement net of abatement and MRV costs ($b(\delta, \theta_s)$) than farm area or number of animals. The optimal area threshold is about 82 ha/farm, while the optimal animal number threshold is about 68 LU/farm. The respective corresponding social benefit is 58 M€ and 37 M€ lower than under the optimal emission threshold.

Figure 2.5 summarizes the implications of the optimal threshold for social welfare for the 36 scenarios explored in the chapter (4 values of the marginal damage, 3 levels of per-farm average MRV costs, and 3 specifications of per-farm MRV costs). For clarity, we focus only on the case of an emission threshold (i.e. $\theta \equiv e_0$).²⁴ The upper set of graph in Figure 2.5 compares the total social benefit if only firms above the optimal emission threshold are subject to the emission tax (x -axis) with the first-best social benefit (y -axis) under the three assumptions regarding the specification of per-farm MRV costs. In all situations except those where the first-best situation leads to a 100% exemption rate, the differences between the first- and

²⁴All other things being equal, the use of area or number of animals as the exemption criterion (not shown here) yields a social benefit very close to that under the emission threshold.

second-best social benefit are strictly positive. The approximation using Eq. (2.13) appears to offer a satisfactory approximation of the second-best emission threshold under the three assumptions regarding the distribution of MRV costs (middle row). The simple formula provided in Eq. (2.15) performs satisfactorily if per-farm MRV costs are constant (specification (A), bottom row). However, this simple formula may lead to a substantial social loss, and even deteriorate welfare compared to the *laissez-faire* situation, when per-farm MRV costs are increasing with respect to initial emissions.

2.7 Concluding remarks

When pollution is caused by a large number of heterogeneous firms and firms' actions are costly to monitor and verify, the question that naturally arises is whether MRV costs more than offset the social benefit that can be expected from environmental policy, and therefore, whether implementing a policy instrument makes economic sense. Our findings emphasize that the choice faced by the regulator is not necessarily restricted to choosing between *laissez-faire* and full coverage. Targeting only a fraction of the firms may limit MRV costs, while simultaneously incentivizing cost-effective reductions in emissions. A partial coverage may thus be welfare-improving, even in situations where total MRV costs outweigh the social benefit of including all firms into the environmental policy.

Designing a partial coverage regulation requires determining which agents will be subject to the environmental instrument, and which should be outside of its scope. The policy design examined in this chapter is simple insofar as it relies on a single threshold value of some known firm characteristic such as size. This corresponds to a second-best approach. Partial coverage may also involve informational issues with regard to firm-level abatement and MRV costs. To circumvent this issue, a simple rule-of-thumb formula is proposed. This formula only requires knowledge of the aggregate (rather than individual) magnitude of abatement and MRV costs. Note that this information is also needed for the *ex ante* cost-benefit analysis under full coverage. This simple formula is however valid only under rather restrictive assumptions (constant per-firm MRV costs and abatement supply proportional

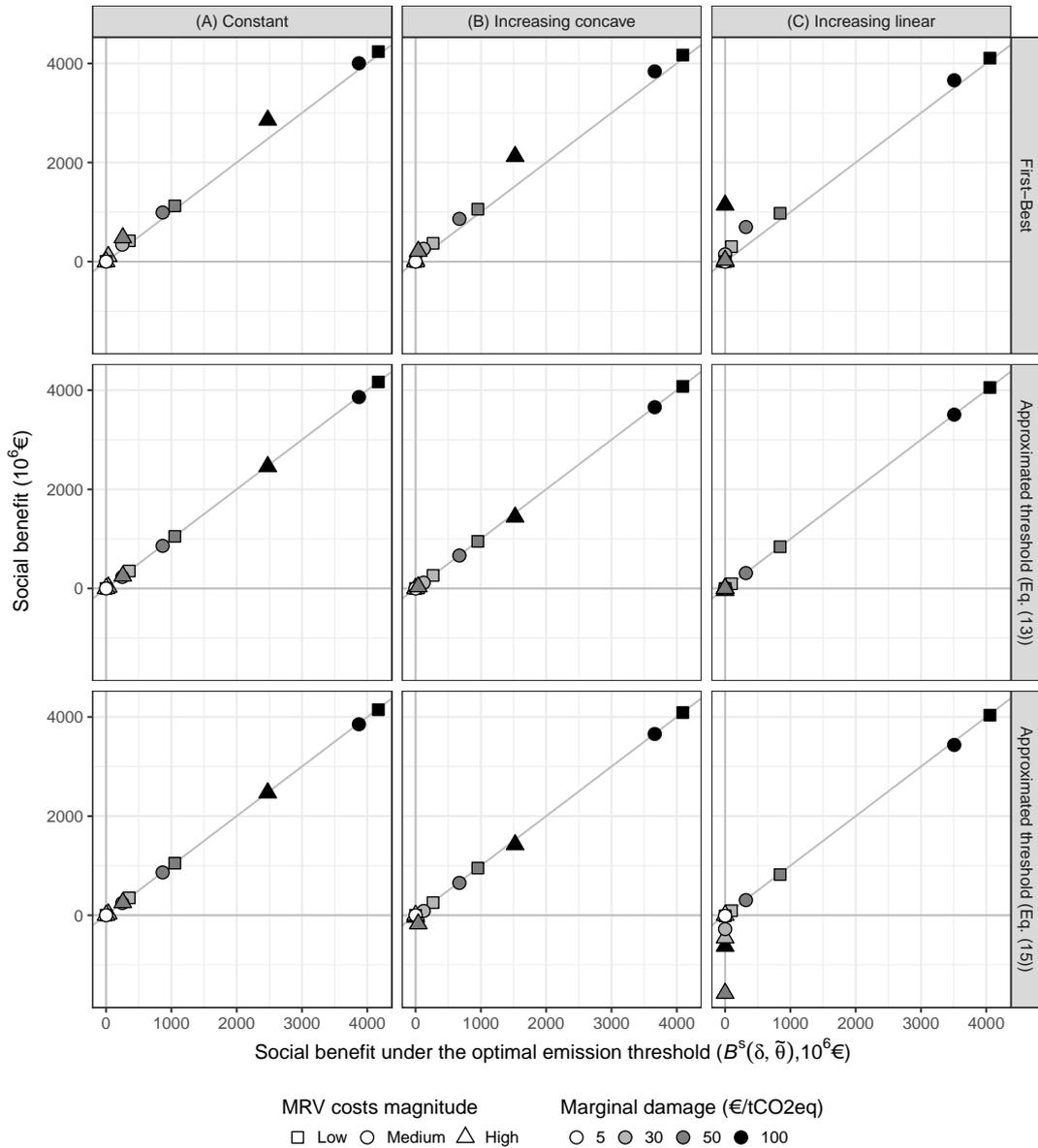
to initial emissions), and may perform poorly if these assumptions are not satisfied. We also propose a more general formula, which performs better under a wider range of cases, but requires some additional information with regard to the structure of MRV and abatement costs. Our findings show how in practice the results from applied aggregate models could inform policymakers about the design of a second-best exemption scheme, even in the absence of detailed firm-level information.

The empirical application to the issue of GHG emissions from European agriculture sheds new light on whether emissions from the agricultural sector should be included within the scope of climate policy instruments. Our results indicate that the social interest of taxing emissions from *all* farms very much depends on the value of the marginal damage. For low emission prices, such as those that have prevailed in the EU-ETS in past years (around 5 €/tCO₂eq between 2016–2017), a full coverage deteriorates welfare relative to *laissez-faire* as soon as the average value of MRV costs is greater than 6 € per farm. By contrast, if the marginal damage reaches 100 €/tCO₂eq, a full coverage can be welfare-improving as long as average per-farm MRV costs stay below 1220 €. Furthermore, even if total MRV costs exceed the net social value of abatement under full coverage, our findings indicate that targeting only the large emitting farms may increase welfare relative to *laissez-faire* under a wide range of assumptions regarding the marginal damage and the overall magnitude of MRV costs. These findings depend on how per-farm MRV cost and farm-level abatement supply vary with respect to size, e.g. measured as initial emissions. Our empirical findings suggest that, in the EU agricultural sector, farm-level abatement increases slightly more than proportionally with initial emissions. Therefore, if per-farm MRV costs increase less than proportionally with initial emissions, this leaves room from implementing an emission tax that targets only large emitting farms, while still improving social welfare.

This work could be extended in several directions. First, the analysis of an emission tax could be adapted to examine a cap-and-trade mechanism. Although the fundamental mechanisms at work would remain, this would require to take into account the costs related to the trading of allowances. Since these costs depend on the level of abatement, this would introduce a wedge between marginal abatement cost and the emission price. Second, the

simple second-best approach developed here could be compared to a more complex mechanism design aimed at revealing individual information. The empirical model used in this chapter could serve as a basis for quantifying the associated information rent. Third, the introduction of a partial coverage might cause leakage effects, and/or induce strategic behavior from firms in response to implementation of partial coverage.

Figure 2.5: Summary results of the 36 scenarios.



Note: Comparison of the total social benefit under the optimal emission threshold (x axis) with the first-best (upper row), the approximated optimal threshold based on Eq. (2.13) (middle row), and approximated optimal threshold based on Eq. (2.15) (bottom row), under three specifications of per-farm MRV costs (columns), and various assumptions regarding the magnitude of MRV costs and marginal damage.

Appendix

2.A Proofs

2.A.1 Proof of Proposition 2.1

The Lagrangian of the regulator's maximization problem is:

$$\mathcal{L} = B^s(\tau, \theta_s) - \rho_l(\theta_l - \theta_s) - \rho_h(\theta_s - \theta_h), \quad (2.17)$$

where ρ_l and ρ_h are the (non-negative) multipliers associated with the constraints $\theta_s \geq \theta_l$ and $\theta_s \leq \theta_h$, respectively. The corresponding first-order conditions with respect to τ and θ_s are:

$$B_\tau^s(\tau, \theta_s) = \int_{\theta_s}^{\theta_h} b_\tau(\tau, \theta) dF(\theta) = 0 \quad (2.18)$$

$$B_{\theta_s}^s(\tau, \theta_s) + \rho_l - \rho_h = -b(\tau, \theta_s)f(\theta_s) + \rho_l - \rho_h = 0 \quad (2.19)$$

(i) Differentiating Eq. (2.3) with respect to τ and using Eq. (2.1), we have that for all $\theta \in \Theta$:

$$b_\tau(\tau, \theta) = \delta a_\tau(\tau, \theta) - c_a(a(\tau, \theta), \theta) a_\tau(\tau, \theta) = (\delta - \tau) a_\tau(\tau, \theta). \quad (2.20)$$

As $a_\tau(\tau, \theta) > 0$ for all θ and all $\tau > 0$, Eq. (2.18) is therefore equivalent to $\tilde{\tau} = \delta$ as soon as $\tilde{\theta} < \theta_h$.

(ii) The complementarity slackness conditions imply that if $\theta_l < \tilde{\theta} < \theta_h$ then $\rho_l = \rho_h = 0$.

Condition (ii) thus directly results from Eq. (2.19) in the case of an interior solution.

(iii) For an interior solution ($\theta_l < \tilde{\theta} < \theta_h$), the second-order conditions are verified when the Hessian matrix of $B^s(\tau, \theta_s)$ evaluated in $(\tilde{\tau}, \tilde{\theta})$ is negative definite. Differentiating B^s twice with respect to τ and θ_s and using Eq. (2.1), it comes:

$$B_{\tau\tau}^s(\tau, \theta_s) = \int_{\theta_s}^{\theta_h} b_{\tau\tau}(\tau, \theta) dF(\theta) = \int_{\theta_s}^{\theta_h} [(\delta - \tau)a_{\tau\tau}(\tau, \theta) - a_{\tau}(\tau, \theta)] dF(\theta) \quad (2.21)$$

$$B_{\theta_s\tau}^s(\tau, \theta_s) = -b_{\tau}(\tau, \theta_s)f(\theta_s) = -(\delta - \tau)a_{\tau}(\tau, \theta_s)f(\theta_s) \quad (2.22)$$

$$B_{\theta_s\theta_s}^s(\tau, \theta_s) = -b_{\theta}(\tau, \theta_s)f(\theta_s) - b(\tau, \theta_s)f'(\theta_s) \quad (2.23)$$

Evaluating Eqs. (2.21) to (2.23) in $\tau = \tilde{\tau} = \delta$ and $\theta_s = \tilde{\theta}$, and using that $a_{\tau}(\tau, \theta) > 0$ for all θ and all $\tau > 0$, we thus have that $B_{\tau\tau}^s(\delta, \tilde{\theta}) < 0$ and that $B_{\tau\tau}^s(\delta, \tilde{\theta})B_{\theta_s\theta_s}^s(\delta, \tilde{\theta}) - (B_{\theta_s\tau}^s(\delta, \tilde{\theta}))^2 > 0$ if and only if $b_{\theta}(\delta, \tilde{\theta}) > 0$.

2.A.2 Proof of Proposition 2.2

As $m(\theta)$, $c(a, \theta)$, and $a(\tau, \theta)$ are all differentiable with respect to θ , we have that $b(\tau, \theta)$ is continuous with respect to θ . Therefore, if $b(\delta, \theta_l) < 0$ and $b(\delta, \theta_h) > 0$, there is at least one interior value of θ_s satisfying conditions (ii) and (iii) of Proposition 2.1.

Moreover, if $\tilde{\theta} = \theta_l$ (full coverage) then $\tilde{\theta} < \theta_h$, which implies that $\rho_h = 0$ (complementarity slackness condition relative to the constraint $\theta_s \leq \theta_h$). Eq. (2.19) thus reduces to $b(\delta, \theta_l)f(\theta_l) = \rho_l$. As $\rho_l \geq 0$ in the optimum, a full coverage cannot maximize social benefit if $b(\delta, \theta_l) < 0$. Using the same line of reasoning for $\tilde{\theta} = \theta_h$ (*laissez-faire*), the condition $b(\delta, \theta_h) > 0$ implies that the *laissez-faire* situation cannot maximize social benefit. Therefore, the optimal threshold necessarily corresponds to an interior solution.

2.A.3 Proof of Proposition 2.3

If $b(\delta, \theta)$ is strictly monotone increasing with respect to θ for all $\theta \in \Theta$, there is at most one value of θ satisfying conditions (ii) and (iii) of Proposition 2.1. In the case of an interior solution, all exempted firms (i.e. $\theta < \tilde{\theta}$) are such that $b(\delta, \theta) < b(\delta, \tilde{\theta}) = 0$, and all firms subject to the emission tax (i.e. $\theta \geq \tilde{\theta}$) are such that $b(\delta, \theta) \geq 0$. If the optimal threshold is equal to θ_l (full coverage), then necessarily $b(\delta, \theta_l) \geq 0$ (see Eq. (2.19)), and therefore $b(\delta, \theta) \geq 0$ for all

$\theta \in \Theta$. Symmetrically, if the optimal threshold is equal to θ_h (*laissez-faire*), then necessarily $b(\delta, \theta_h) \leq 0$, and therefore $b(\delta, \theta) \leq 0$ for all $\theta \in \Theta$. In all cases, the partition of the firms is the same as in the first-best situation presented in Section 2.2.

2.A.4 Proof of Proposition 2.4

Denote by θ_i the value of θ that solves $b(\delta, \theta_i) = n(\delta, \theta_i) - m(\theta_i) = 0$ (conditions (i) and (ii) of Proposition 2.1). Under specification in Eq (2.11) with $\alpha_2 > \beta_2$, this value is:

$$\theta_i = \left(\frac{\beta_1}{\alpha_1(\delta)} \right)^{\frac{1}{\alpha_2 - \beta_2}} \quad (2.24)$$

It is straightforward to verify that $b_\theta(\delta, \theta_i) > 0$ (condition (iii) of Proposition 2.1) as soon as $\alpha_2 > \beta_2$. Moreover, combining Eqs (2.3), (2.11), and (2.24) and rearranging, we have:

$$b(\delta, \theta) = \beta_1 \theta^{\beta_2} \left[\left(\frac{\theta}{\theta_i} \right)^{\alpha_2 - \beta_2} - 1 \right]. \quad (2.25)$$

From Eq. (2.25), it appears clearly that $b(\delta, \theta) < 0$ for all $\theta < \theta_i$ and $b(\delta, \theta) > 0$ for all $\theta > \theta_i$. If $\theta_l < \theta_i < \theta_h$, then $b(\delta, \theta_l) < 0$ and $b(\delta, \theta_h) > 0$, and therefore the optimal threshold corresponds to the interior solution $\tilde{\theta} = \theta_i$. In addition, using the definition of M and $N(\delta)$ under specifications (2.11):

$$N(\delta) = \alpha_1(\delta) \int_{\Theta} \theta^{\alpha_2} dF(\theta) \quad M = \beta_1 \int_{\Theta} \theta^{\beta_2} dF(\theta). \quad (2.26)$$

The expression given in Proposition 2.4 is obtained by combining Eqs. (2.24) and (2.26).

If $\theta_i < \theta_l$, then $b(\delta, \theta) < 0$ for all $\theta \in \Theta$, which implies that $\rho_h > 0$ (see Eq. (2.19)), and therefore that the optimal solution is the *laissez-faire* ($\tilde{\theta} = \theta_h$). Conversely, if $\theta_i > \theta_h$, then $b(\delta, \theta) > 0$ for all $\theta \in \Theta$, $\rho_l > 0$, and the optimal solution is the full coverage ($\tilde{\theta} = \theta_l$).

2.B Empirical application results

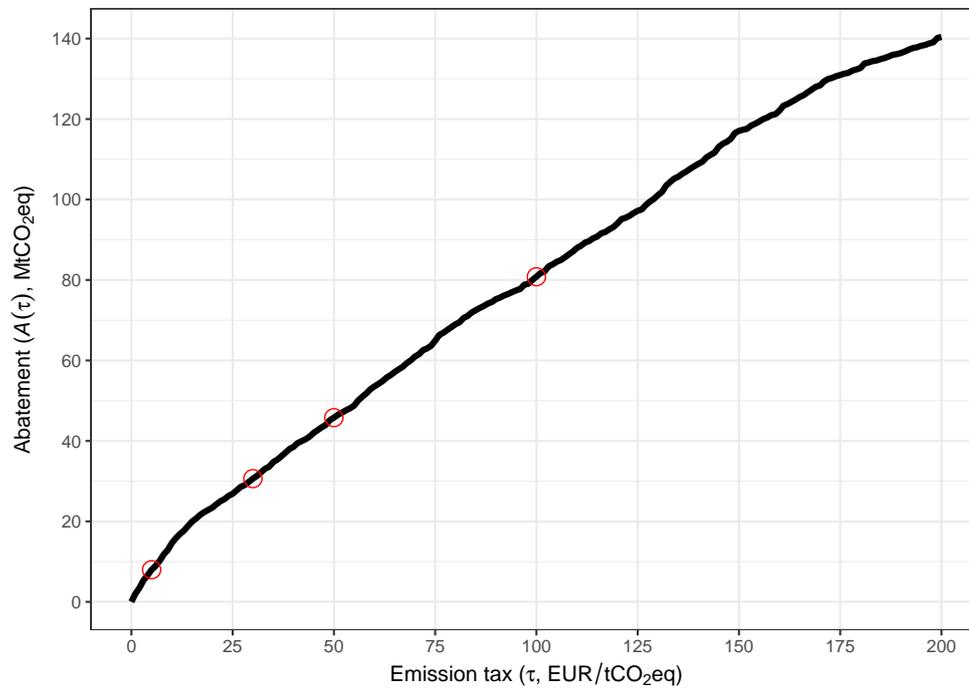
2.B.1 Descriptive statistics

Table 2.B.1: Per-farm characteristics in the absence of emission tax

	Emissions e_0 [tCO ₂ eq]	Agricultural area s_0 [ha]	Livestock numbers ℓ_0 [Livestock units]
Mean	109.81	35.10	27.54
Standard deviation	259.53	94.50	90.27
Min	0.26	0.05	0.00
Q1	11.25	6.09	1.82
Median	29.14	13.34	4.82
Q3	113.83	37.53	24.19
Max	7685.83	2696.22	5928.86

2.B.2 Aggregate abatement supply

Figure 2.B.1: Aggregate abatement supply for the EU-27 agriculture under full coverage.



2.B.3 Farm-level net social value of abatement: Estimation results

The net social value of abatement is computed for each representative farm k (representing f_k real farms) and each value of δ (from 1 to 200 €/tCO₂eq by steps of 1 €/tCO₂eq) as:

$$n_k(\delta) = \delta a_k(\delta) - c(a_k(\delta)) \quad (2.27)$$

The following discrete version of the log-transformed version of Eq (2.16) is estimated:

$$\log(n_k(\delta)) = \log(\alpha_1(\delta)) + \alpha_2 \log(\theta_k) + \epsilon_k \quad (2.28)$$

where $\log(\alpha_1(\delta))$ is introduced as a smooth non-parametric term, α_2 is the elasticity with respect to θ , and θ_k alternatively represents initial emissions (e_{0k}), area (s_{0k}), or livestock numbers (ℓ_{0k}). Equation (2.28) (weighted by f_k) is estimated using a Generalized Additive Model (GAM) model as implemented in the package `mgcv` (version 1.8) under R 3.2.

Table 2.B.2: Net social value of abatement as a function of farm size: Estimation results

	Initial emissions $\theta \equiv e_0$ [tCO ₂ eq/farm]	Initial area $\theta \equiv s_0$ [ha/farm]	Initial livestock numbers $\theta \equiv \ell_0$ [LU/farm]
Parametric coefficient (α_2)			
$\log(\theta)$	1.11*** (0.00)	1.39*** (0.00)	1.48*** (0.00)
Approximate significance of smooth term ($\log(\alpha_1(\delta))$)			
EDF:	8.99*** (9.00)	8.99*** (9.00)	8.99*** (9.00)
Predicted value of smooth term for specific values of δ			
$\alpha_1(5)$	$5.44 \cdot 10^{-4}$	$5.73 \cdot 10^{-4}$	$4.84 \cdot 10^{-4}$
$\alpha_1(30)$	0.09	0.09	0.09
$\alpha_1(50)$	0.29	0.30	0.29
$\alpha_1(100)$	1.73	1.72	1.77
Log Likelihood	-971486.50	-996536.91	-968460.82
Deviance	6233.51	7233.25	7700.32
Deviance explained	0.73	0.69	0.65
Adj. R ²	0.52	0.44	0.35
Num. obs.	336816	336816	320697

*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

2.B.4 Results under various assumptions

Table 2.B.3: First-best results

MRV costs specification and magnitude	Emission tax δ [€/tCO ₂ eq]	Share of exempted		Abatement $A^*(\delta)$ [10 ⁶ tCO ₂ eq]	MRV costs $M^*(\delta)$ [10 ⁶ €]	Social benefit $B^*(\delta)$ [10 ⁶ €]
		Farms	Emissions			
		[1]	[1]			
(A) Constant per-farm MRV costs						
Low	5	0.989	0.928	3.6	5.3	5.4
	30	0.819	0.480	27.3	84.6	420.7
	50	0.716	0.317	43.1	133.0	1124.6
	100	0.501	0.146	79.6	234.1	4237.1
Medium	5	0.996	0.965	2.2	4.1	2.4
	30	0.886	0.588	23.9	115.7	342.8
	50	0.787	0.394	40.9	216.3	992.7
	100	0.618	0.205	77.9	389.0	4002.7
High	5	1.000	0.998	0.1	0.2	0.2
	30	0.978	0.860	11.2	122.5	105.3
	50	0.937	0.688	26.6	356.5	482.5
	100	0.815	0.385	68.1	1043.3	2855.8
(B) Increasing, concave per-farm MRV costs						
Low	5	0.997	0.973	1.8	3.8	1.8
	30	0.841	0.556	25.9	120.7	369.7
	50	0.712	0.357	42.8	197.5	1057.8
	100	0.478	0.164	79.6	307.9	4168.7
Medium	5	1.000	0.994	0.3	1.0	0.4
	30	0.915	0.692	21.2	157.0	260.3
	50	0.811	0.477	38.9	310.8	863.3
	100	0.591	0.224	78.0	567.6	3839.2
High	5	1.000	1.000	-	-	-
	30	0.995	0.952	4.5	70.7	25.2
	50	0.975	0.855	14.9	302.5	209.9
	100	0.851	0.489	62.3	1495.9	2123.7
(C) Increasing, linear per-farm MRV costs						
Low	5	0.999	0.999	0.1	0.4	0.1
	30	0.790	0.638	24.6	169.6	303.4
	50	0.565	0.401	42.2	280.7	975.6
	100	0.263	0.155	80.2	396.2	4107.4
Medium	5	1.000	1.000	0.0	0.0	0.0
	30	0.893	0.798	17.8	205.6	148.1
	50	0.721	0.562	37.1	445.4	698.0
	100	0.353	0.210	79.1	803.2	3659.6
High	5	1.000	1.000	-	-	-
	30	1.000	1.000	0.1	1.4	0.1
	50	0.984	0.977	4.6	127.9	28.9
	100	0.798	0.654	49.8	1948.3	1141.9

Table 2.B.4: Optimal emission threshold

MRV costs specification and magnitude	Emission tax δ [€/tCO ₂ eq]	Threshold \tilde{e}_0 [tCO ₂ eq]	Share of exempted		Abatement $A^s(\delta, \tilde{e}_0)$ [10 ⁶ tCO ₂ eq]	MRV costs $M^s(\delta, \tilde{e}_0)$ [10 ⁶ €]	Social benefit $B^s(\delta, \tilde{e}_0)$ [10 ⁶ €]
			Farms $F(\tilde{e}_0)$ [1]	Emissions $L(F(\tilde{e}_0))$ [1]			
(A) Constant per-farm MRV costs							
Low	5	1675	0.998	0.944	0.5	1.0	0.8
	30	128	0.774	0.222	25.2	106.2	354.8
	50	50	0.607	0.096	43.0	184.3	1052.8
	100	17	0.386	0.035	79.6	287.9	4169.6
Medium	5	5250	1.000	0.992	0.1	0.1	0.3
	30	212	0.847	0.333	21.8	155.2	248.6
	50	93	0.714	0.163	39.9	290.6	866.8
	100	39	0.570	0.081	76.8	437.7	3872.6
High	5	7686	1.000	1.000	-	-	-
	30	952	0.992	0.880	3.9	46.5	33.4
	50	409	0.927	0.550	22.3	410.0	256.4
	100	138	0.785	0.236	66.1	1213.9	2475.4
(B) Increasing, concave per-farm MRV costs							
Low	5	5250	1.000	0.992	0.1	0.3	0.1
	30	138	0.785	0.236	24.9	187.8	267.4
	50	42	0.579	0.084	43.5	297.0	952.8
	100	16	0.350	0.030	79.8	379.9	4091.8
Medium	5	7686	1.000	1.000	-	-	-
	30	370	0.915	0.507	16.7	194.1	123.6
	50	138	0.785	0.236	36.9	407.4	670.7
	100	19	0.415	0.040	79.3	779.2	3662.0
High	5	7686	1.000	1.000	-	-	-
	30	5250	1.000	0.992	0.3	3.9	1.8
	50	1295	0.996	0.924	3.8	72.9	41.0
	100	211	0.847	0.332	59.3	1744.4	1523.8
(C) Increasing, linear per-farm MRV costs							
Low	5	7686	1.000	1.000	-	-	-
	30	138	0.785	0.236	24.9	358.3	96.9
	50	9	0.128	0.007	45.7	465.7	842.7
	100	5	0.047	0.002	80.8	468.2	4055.5
Medium	5	7686	1.000	1.000	-	-	-
	30	7686	1.000	1.000	-	-	-
	50	42	0.579	0.084	43.5	931.6	318.1
	100	6	0.052	0.002	80.8	1015.1	3508.4
High	5	7686	1.000	1.000	-	-	-
	30	7686	1.000	1.000	-	-	-
	50	7686	1.000	1.000	-	-	-
	100	7686	1.000	1.000	-	-	-

Table 2.B.5: Approximated emission threshold (Eq. (2.13))

MRV costs specification and magnitude	Emission tax δ [€/tCO ₂ eq]	Threshold \hat{e}_0 [tCO ₂ eq]	Share of exempted		Abatement $A^s(\delta, \hat{e}_0)$ [10 ⁶ tCO ₂ eq]	MRV costs $M^s(\delta, \hat{e}_0)$ [10 ⁶ €]	Social benefit $B^s(\delta, \hat{e}_0)$ [10 ⁶ €]
			Farms $F(\hat{e}_0)$ [1]	Emissions $L(F(\hat{e}_0))$ [1]			
(A) Constant per-farm MRV costs							
Low	5	1928	0.998	0.952	0.3	0.8	0.3
	30	106	0.738	0.184	26.1	122.8	351.5
	50	48	0.599	0.092	43.2	188.0	1050.5
	100	16	0.352	0.030	79.8	304.0	4165.9
Medium	5	3881	1.000	0.979	0.1	0.5	0.0
	30	214	0.851	0.340	20.9	151.8	232.2
	50	97	0.725	0.172	39.1	279.8	859.4
	100	32	0.522	0.065	77.6	486.4	3861.1
High	5	7686	1.000	1.000	-	-	-
	30	1006	0.993	0.890	3.5	40.0	27.7
	50	454	0.940	0.599	19.7	338.8	250.5
	100	148	0.798	0.253	64.8	1139.3	2458.7
(B) Increasing, concave per-farm MRV costs							
Low	5	7686	1.000	1.000	-	-	-
	30	143	0.790	0.243	24.5	184.3	262.1
	50	45	0.591	0.089	43.3	291.8	950.1
	100	9	0.163	0.010	80.5	432.0	4077.2
Medium	5	7686	1.000	1.000	-	-	-
	30	391	0.923	0.535	15.7	177.8	116.8
	50	124	0.767	0.215	37.4	432.0	664.4
	100	25	0.460	0.049	78.7	745.6	3657.7
High	5	7686	1.000	1.000	-	-	-
	30	3638	1.000	0.979	0.5	12.0	-2.2
	50	1157	0.995	0.911	4.4	92.1	35.2
	100	231	0.858	0.353	56.2	1647.0	1440.7
(C) Increasing, linear per-farm MRV costs							
Low	5	7686	1.000	1.000	-	-	-
	30	78	0.680	0.137	27.7	404.7	93.6
	50	0	-	-	45.8	469.0	841.3
	100	0	-	-	80.8	469.0	4055.0
Medium	5	7686	1.000	1.000	-	-	-
	30	7686	1.000	1.000	-	-	-
	50	29	0.498	0.058	44.2	957.7	310.5
	100	0	-	-	80.8	1017.0	3506.9
High	5	7686	1.000	1.000	-	-	-
	30	7686	1.000	1.000	-	-	-
	50	7686	1.000	1.000	-	-	-
	100	2470	0.999	0.972	2.1	160.0	-40.4

Table 2.B.6: Approximated emission threshold (Eq. (2.15))

MRV costs specification and magnitude	Emission tax δ [€/tCO ₂ eq]	Threshold \hat{e}_0 [tCO ₂ eq]	Share of exempted		Abatement $A^s(\delta, \hat{e}_0)$ [10 ⁶ tCO ₂ eq]	MRV costs $M^s(\delta, \hat{e}_0)$ [10 ⁶ €]	Social benefit $B^s(\delta, \hat{e}_0)$ [10 ⁶ €]
			Farms $F(\hat{e}_0)$ [1]	Emissions $L(F(\hat{e}_0))$ [1]			
(A) Constant per-farm MRV costs							
Low	5	2340	0.999	0.971	0.2	0.3	0.4
	30	95	0.722	0.170	26.5	130.4	350.2
	50	39	0.570	0.081	43.6	201.5	1050.4
	100	11	0.252	0.018	80.3	350.8	4146.7
Medium	5	5075	1.000	0.989	0.1	0.2	0.2
	30	205	0.844	0.327	21.9	158.4	246.6
	50	85	0.701	0.152	40.3	303.8	863.9
	100	25	0.460	0.049	78.7	549.5	3853.7
High	5	7686	1.000	1.000	-	-	-
	30	1139	0.995	0.909	2.9	29.0	27.3
	50	473	0.945	0.620	18.8	310.4	255.5
	100	137	0.784	0.235	66.1	1219.1	2470.8
(B) Increasing, concave per-farm MRV costs							
Low	5	2340	0.999	0.971	0.2	1.5	-0.8
	30	95	0.722	0.170	26.5	225.9	254.7
	50	39	0.570	0.081	43.6	300.7	951.3
	100	11	0.252	0.018	80.3	408.5	4089.0
Medium	5	5075	1.000	0.989	0.1	1.0	-0.6
	30	205	0.844	0.327	21.9	318.7	86.3
	50	85	0.701	0.152	40.3	514.9	652.8
	100	25	0.460	0.049	78.7	745.6	3657.7
High	5	7686	1.000	1.000	-	-	-
	30	1139	0.995	0.909	2.9	94.8	-38.5
	50	473	0.945	0.620	18.8	738.3	-172.4
	100	137	0.784	0.235	66.1	2265.8	1424.1
(C) Increasing, linear per-farm MRV costs							
Low	5	2340	0.999	0.971	0.2	13.4	-12.7
	30	95	0.722	0.170	26.5	389.4	91.1
	50	39	0.570	0.081	43.6	431.1	820.9
	100	11	0.252	0.018	80.3	460.6	4036.9
Medium	5	5075	1.000	0.989	0.1	11.3	-10.9
	30	205	0.844	0.327	21.9	684.3	-279.3
	50	85	0.701	0.152	40.3	862.0	305.7
	100	25	0.460	0.049	78.7	967.2	3436.0
High	5	7686	1.000	1.000	-	-	-
	30	1139	0.995	0.909	2.9	511.8	-455.6
	50	473	0.945	0.620	18.8	2139.9	-1574.0
	100	137	0.784	0.235	66.1	4315.0	-625.2

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Chapter 3

Adapting Geographical Indication to climate change

Abstract

This chapter examines the relocation of the agricultural supply of products under Geographical Indication (GI) labels as an option to adapt to climate change. I develop a stylized framework that endogenously relates the delineation of the area of production of the GI product to the distribution of specific geographical characteristics, and to their influence on the quality of the product and the corresponding comparative advantages. The model is used to study how the GI area of production responds to climate-related changes in the conditions of production. The model shows that the GI area of production can marginally expand as climate change deteriorates the conditions of production, but that it then progressively disappears under more severe deteriorations. I analyze the conflicting incentives between historical producers and potential entrants which can maintain the GI in its historical configuration.

3.1 Introduction

One of the most pressing issues regarding climate change lies in its impacts on agricultural production (IPCC, 2019). As these impacts are likely to vary across space, reallocating crops to areas better suited to new climate conditions offers a promising adaptation margin (Costinot et al., 2016; Baldos et al., 2019; Gouel and Laborde, 2021). However, this type of adaptation may not be readily available for products that are defined precisely by where they are produced, as is the case for products with a geographical indication (GI hereafter) label.¹

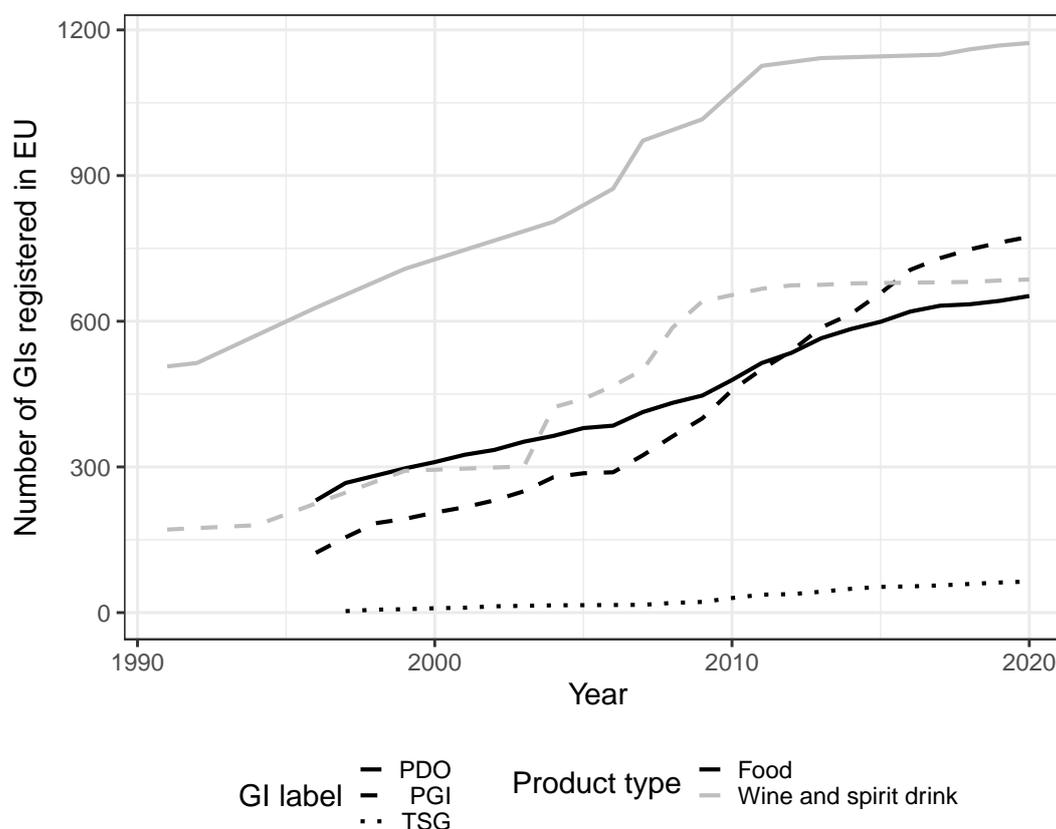
The quality of GI products is deemed to originate from a combination of climate, topography, geology, and soil characteristics that is specific to a given region of production, as in the case for example of wine, whose type and quality is related to biophysical attributes of land that are very specific not only to some regions but more specifically to some land parcels (Ay, 2021). This particular combination, also known as *terroir*, justifies restricting the production of a given GI product to a precisely delineated and exclusive area of production. Only the producers located in this area have the right to use the GI label to signal the quality of their product, provided that they also meet certain production standards. Well-known examples of GI products include Champagne, Napa Valley wines, and Parmigiano Reggiano cheese. A recent study of the EU commission reports a 7% share—and a corresponding amount of EUR 77 billion—for GI labeled products in the total sales value of the food and drink sector in the EU-28 in 2017. This share reaches 15% in France and 12% in Italy (European Commission, 2020).²

Despite the rent they provide to those who own the land in the GI region (Josling, 2006),

¹Geographical indications are labels that certify the geographical origin of a product so that it can be identified by consumers. The GI label grants property rights to the name of a location, to protect the producers from the misuse of their regional name. GI labels are internationally recognized in the WTO agreement on Trade-Related Aspects of Intellectual Property Rights (1994) as a legal tool comparable with trademark laws in that it enhances informational efficiency and restricts fraudulent behaviors (Menapace and Moschini, 2014). For details on these legal provisions, see Articles 22 and 23: https://www.wto.org/english/docs_e/legal_e/27-trips_04b_e.htm.

²In the EU, a homogeneous GI protection scheme was created in 1992 with the Regulation No 2081/92. This protection uses three labels: the (i) Protected Designation of Origin (PDO), (ii) Protected Geographical Indication (PGI) and (iii) Traditional Specialty Guaranteed (TSG) schemes. Since the regulation was passed, the number of registered GI designations has more than doubled, and now exceeds 3500 designations of food and drink products (see Figure 3.1).

Figure 3.1: Number of GI labels in the EU quality labeling scheme since Regulation No 2081/92 in 1992.



Note: PDO designates *Protected Designation of Origin*, PGI corresponds to *Protected Geographical Indication*, and TSG is *Traditional Speciality Guaranteed*. The PDO label is more binding, as the whole production process has to occur in the defined geographical area, while only one stage of the production process within the defined area is needed for the PGI and TSG labels. Source: DOOR database and eAmbrosia.

GI labels may also have welfare-enhancing effects. In particular, they alleviate the classical “lemons problem” (Akerlof, 1970). That is, if the information conveyed by the GI label credibly ensures that the product meets a certain quality level, it can secure incentives for the producers to supply high-quality goods (Mérel et al., 2021). Whether the welfare-enhancing effect of GIs remains in the face of climate change depends on the scope for maintaining supply, which is ultimately tied to the flexibility of the exclusive area of production. This in turn is determined by the institutional context that frames the attribution of GI labels and by its governance structure. There are a variety of GI protection systems around the world, which lead to different decisions regarding the delineation of the production area (Gangjee, 2017). By globally preventing the use of a GI label in a different area, GI protection systems only allow consideration of marginal modifications at the border of the existing area. If the

area is carved in stone, little margin is left for adaptation through land reallocation, and new adverse climate conditions may result in a significant drop in output. Adapting the exclusive area of production—for example, by extending it to nearby parcels—may mitigate these impacts, but at the expense of a change in the (real or perceived) quality of the product as well as a redistribution of the rents associated with the exclusivity of production.

In this chapter, I investigate the conditions under which the relocation of the supply of agricultural products under GI labels takes place. The relocation considered is contiguous to an exclusive GI area of production whose delineation process reflects the GI institutional setting in a stylized way. To this end, I develop an original framework to model the location of the production of an agricultural good under a GI label, as well as its associated market. This model borrows from the industrial organization literature that assesses the welfare effects of GI labels (see Bonroy and Constantatos, 2015, for a recent review). These works examine the setting of quality in GIs, and show that the level of differentiation depends on the shape of the variable costs of producing quality and on consumers' preferences regarding quality (Zago, 1999; Mérel and Sexton, 2012). This strand of the literature also studies the welfare effects of supply control instruments, such as minimum standard and specifications or controls on inputs and outputs (Marette et al., 1999; Lence et al., 2007; Moschini et al., 2008), to see how the associated collusive effect compares with the mitigation of information asymmetries. However, these works do not explicitly model the link between quality provision and the place of production.

To account for heterogeneous and climate-sensitive potential in supplying the quality of the GI product, I incorporate features related to both the agricultural economics literature on land use (Lichtenberg, 1989; Feng and Babcock, 2010) and to modern general equilibrium models which have recently been introduced to assess the mitigation of climate change impacts allowed by the relocation of agricultural production (Costinot et al., 2016; Gouel and Laborde, 2021). These models represent the land allocation decision between parcels of heterogeneous productivity and across multiple agricultural commodities. I integrate this heterogeneity in land allocation decisions into a vertical differentiation model by considering that producers have heterogeneous comparative advantages in supplying GI quality. This

approach provides consistent modeling of land allocation from the distribution of comparative advantages of the GI product relative to an agricultural commodity across land parcels. Also, it allows us to explicitly model the adaptation of land allocation following climate-induced changes in opportunity costs, and, ultimately, the determinants of the benefits of relocating GI agricultural production.

I then analyze how the GI area of production may be changed at the GI industry level. To this end, the model includes the following features and assumptions. First, changes in the exclusive area of production can only occur at the border of the existing GI area. Second, the model combines adaptation options (i) at the individual level, through modification of land allocation according to the evolution of comparative advantage, and (ii) at the sectoral level, through redefinition of the eligible parcels. Third, the parcels located at the margins of the exclusive area of production are assumed to be of lower suitability; thus, their integration reduces the quality of the GI product (Deconinck and Swinnen, 2021). Fourth, the definition of the land parcels eligible to the GI is made according to one of these either two polar cases: (i) one where entry in the GI industry is open to any producers having a comparative advantage, and (ii) another where the area of production is delineated to maximize aggregate profits of the GI industry so that it excludes some producers (Moschini et al., 2008; Mérel and Sexton, 2012). The model summarizes GI structures into these two situations, while in practice, GIs across the world are various and can fall in between or be close to one of the two extremes. For instance, the *Comté* cheese has a more restricted area than that of the French *Gruyère* cheese, which is producible on the same area plus other locations representing approximately twice the *Comté* area. As a result, *Gruyère* specifications bring this GI closer to an open GI industry setting, while *Comté* specifications are more likely to exclude producers from the industry, and thus delineate area to maximize industry's profits. Fifth, the relocation operates as climate change affects the opportunity costs of producing the GI uniformly across all producers.

First, the model shows that the direction of the relocation, when the GI industry is exclusionary, depends on the variation of quantity and that of (actual or perceived) quality with changes in the exclusive area of production. Specifically, if a marginal modification of the

exclusive area of production leads to a large GI quality variation relative to the quantity variation, a climate-induced decrease in comparative advantage in GI leads to a further restriction in the exclusive area of production. In this configuration, the optimum profits under climate change are maintained by shrinking the exclusive area of production, because the supply becomes concentrated on the most suitable producers and leads to a further increase in price that compensates for the quantity losses from the area restriction.

Then, when the GI industry is exclusionary but if quality varies moderately with changes in the area of production, and also when the GI industry is open, the GI area of production can expand and include parcels at the border that are less suitable for the production of GI. The climate-induced supply shortage generates an increase in the GI price which makes including more producers highly valuable, despite the resulting deterioration in quality. This extension of the exclusive area of GI production occurs for a moderate range of climate change effects and is more likely to happen if consumers have high preferences for the GI and also if the opportunity cost in GI specialization is low. Finally, as climate change effects become more extreme, the supply of GI declines and disappears as can be expected in the absence of technological adaptation.

Marginal production border movements due to climate change have already occurred in existing GI industries. In 2013, the *Cítricos Valencianos* GI enlarged its production area in reaction to climate change, as neighboring ecosystems have become suitable to produce the required citrus quality (Marescotti et al., 2020).³ Note that this expansion has been motivated by the equivalent quality of the citrus production on the neighboring parcels.⁴ Thus, this example in the EU labeling context shows how changes in quality at the border are critical in determining potential expansion as a strategy to adapt to climate change.

³Although not in the farming context, the EU PGI label for Cornish sardines also extended its geographical area in 2017. The temperature of water in the catching area increases with climate change, which shifts the shoals of sardines and which is required to include Plymouth port to land fresh sardines. See <https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1511421882537&uri=CELEX:32017R0910>

⁴To be more precise, “Climate change in the production area has led to the development of ecosystems which are suitable for citrus production using the same growing methods and producing fruit of the same organoleptic quality. [...] although the production areas were traditionally on the coast and in the river valleys because of the risk of frost inland, now, because climatic conditions have changed, the inland areas have also become suitable for citrus growing, with mild winters, summers that are not too hot, a well-defined temperature difference between day and night and winds that are neither hot nor dry.” See [https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52013XC0614\(02\)](https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52013XC0614(02))

Finally, any expansions (or shrinkages) in GI area of production to adapt to climate change affects differently new entrants (or excluded producers) and inside producers. The model illustrates that these conflicting effects constitute barriers to adaptation, which can impede any relocation. For the open GI industry, historical GI producers could use the rent accrued from the climate-induced rarefaction of their GI supply to exclude potential entrants. For the exclusionary GI industry, an agreement between producers upon expansion (or shrinkage) of GI area can only occur if compensation payments are implemented between new entrants (or excluded producers) and inside producers. This questions whether governance of GI agencies is adequately equipped to challenge these barriers. To the extent that the adaptation of existing GIs is mainly organized by historical GI producers, existing GI labels barely plan to expand their production area. Policy actions promoting the involvement of producers bordering the historical area in the governance of GI labels can be undertaken to maintain a vertically differentiated supply in the face of climate change.

3.2 Modeling the market of the GI product

In this section, I present the modeling framework. First, I present the assumptions made regarding the heterogeneous geographic characteristics that influence quality and confer a comparative advantage in the production of a vertically differentiated product. Then, I define the demand for the GI product. Finally, I model the GI legal protection system that defines the GI area of production.

Assumption on land characteristics and comparative advantage Consider a continuum of producers, with a mass normalized to 1. Each producer is endowed with a land parcel of identical surface area. Producers are heterogeneous with respect to the characteristics of their land. Assume that the heterogeneity can be summarized into a one-dimensional measure denoted by y ; in this analysis, y is assumed to be non-manipulable by the producers and is distributed according to a CDF $F(y)$, defined for all y in $\mathcal{Y} = [\underline{y}, \bar{y}]$ with $\underline{y} \geq 0$. The associated PDF, denoted $f(y)$, is such that $f(y) > 0$ for all $y \in \mathcal{Y}$ and is equal to 0 everywhere else. \mathcal{Y} can be thought as the range of land characteristics in the *a priori* denominated GI

region where one can reasonably claim the GI name. $f(y)$ reflects the variety of conditions of production existing within the GI region and forms what we call the *terroir*, that is pedo-climatic properties specific to a place contributing to the comparative advantage in the GI product *and* to the actual (or perceived) quality of the GI product.

The producers can allocate their land to the production of two goods: the GI product and the commodity, respectively indexed with subscript $k = \{G, C\}$. The GI product is produced according to production standards that are assumed as given and are mandatory to be granted the GI label. Each producer can alternatively produce a commodity, which is an undifferentiated product as in Lence et al. (2007); $\alpha_G(y)$ ($\alpha_C(y)$) denotes the quantity of the GI product (commodity) that a producer with land characteristics y produces. Functions α_G and α_C are assumed to be continuous, but no further assumption on their monotonicity or shape is made. The comparative advantage provided by the land characteristics in the production of the GI product is stated precisely in the following assumption:

Assumption 1. *The greater y , the larger is the comparative advantage of the GI product over the commodity. Denote with $\alpha(y)$ the quantity of GI produced for one unit of commodity by the producer with land characteristics y , that is:*

$$\alpha(y) \equiv \frac{\alpha_G(y)}{\alpha_C(y)}, \quad (3.1)$$

and $\alpha(\cdot)$ is increasing in y , that is, $\alpha'(y) > 0$.

Thus, producers with high y enjoy beneficial natural conditions that make them relatively more efficient in the production of a high quality product (Menapace and Moschini, 2012). Note that we do not impose any restriction on the effect of land characteristics on the quantity of GI produced. That is, producers enjoying greater *terroir* attributes might be able to produce more or less quantities of GI products than those with lower attributes, but they produce more GI for one quantity of commodity produced. This assumption is motivated by the fact that existing GI areas for wine and cheese are located in mountainous areas or on hillsides, where the production of other commodities is made difficult. Under Assumption 1, land uses are ordered by land characteristics, and land share is a function of the land

characteristics distribution, in a similar approach to the Ricardian models (Dornbusch et al., 1977).

Assumption on the technology The producer decides to allocate his land to the production of the GI or the commodity by comparing the net revenues associated with each alternative. The following assumption specifies the technology, in order to derive and compare net revenues according to the land characteristics:

Assumption 2 (GI and commodity technology). *When combining a fraction l_k of land for the production of good $k = \{G, C\}$, with a quantity n_k of labor, the producer with land characteristics y can produce q_k quantity with the following relationship:*

$$q_k(y) = \min \left\{ \alpha_k(y) l_k, \frac{n_k}{v_k} \right\} \quad (3.2)$$

where v_k measures the unit labor requirement with $v_C = 1$ and $v_G > 1$.

Assumption 2 implies that labor and land are perfect complements in the production of both products. First, the perfect complementarity assumption is the one used in modern Ricardian models (Costinot et al., 2016; Gouel and Laborde, 2021), as it has the advantages of simplifying the expression of revenue and keeping the model tractable. Second, even if returns to scale of land are constant at the individual level, they are determined by the shape of $\alpha_k(y)$ at the aggregate level. Third, the labor unit requirement for the GI is greater than that for the commodity ($v_G > 1$). This captures the labor requirements constraining the implementation of the production practices and the certification efforts required when producing the GI, as underlined in the literature (Lence et al., 2007; Moschini et al., 2008).

I can now describe the individual land allocation decision as a function of the land characteristics y . The producers are assumed to be price takers. In addition, land is bought and sold in a competitive market, and thus its price, that is, the land rent, corresponds to the net revenue, that is, the difference between the revenue and the labor cost. Perfect competition in the land market ensures that producers choose the use of land that maximizes their net revenue. Given Assumption 2, the net revenue for product k that a producer with land

characteristics y would earn is

$$r_k(y) = \alpha_k(y) (p_k - v_k w). \quad (3.3)$$

This net revenue is the land rent. The producers compare their land rent between the GI and the commodity and they exit the GI market when $r_G(y) < r_C(y)$, that is, when the net land rent for the GI is non-positive. Note that the GI land rent depends on the GI price, which in turn depends on the preferences for the GI and on the supply conditions induced by the protection of the GI label.

Assumptions on the demand for the GI I assume that consumers' preferences for the GI product are valued in a vertical differentiation framework similar to the one of Mussa and Rosen (1978), specified in the following assumption:

Assumption 3 (Inverse demand function for the GI). *There is a mass of N consumers heterogeneous in their preferences for quality θ who are uniformly distributed along $\Theta \equiv [\underline{\theta}, \bar{\theta}]$ and each buy at most one unit of the GI good. The inverse demand for the GI good denoted with $p_G(Q_G, s_G)$, where Q_G and s_G denote respectively the quantity and the actual (or perceived) quality of the GI product, is the following:*

$$p_G(Q_G, s_G) = s_G \left[\bar{\theta} - \frac{Q_G}{N} (\bar{\theta} - \underline{\theta}) \right] \quad (3.4)$$

for given Q_G in $\left[0, N \frac{\bar{\theta}}{\bar{\theta} - \underline{\theta}} \right]$.

First, the construction of the inverse demand function relies on consumers with heterogeneous preferences for quality and buying one or zero units of the GI.⁵ Second, the uniform distribution assumption for the preferences parameter θ is commonly made to conveniently model the demand for a differentiated product (see among others Roe and Sheldon, 2007; Moschini et al., 2008). Third, I assume that the GI product has no substitute at other levels of quality.⁶ Finally, under Assumption 3 the GI consumers' surplus, denoted with CS , reduces

⁵Appendix 3.C.1.1 presents in more details the construction of Equation (3.4).

⁶I consider an alternative situation in Appendix 3.C.1.2 where the commodity is the lower quality substitute of the GI product in a standard two possible qualities demand structure (Moschini et al., 2008).

to:

$$CS(Q_G, s_G) = s_G \frac{Q_G^2}{2N} (\bar{\theta} - \theta). \quad (3.5)$$

The commodity's price, denoted p , is fixed on a world market and is not affected by changes in the GI market.⁷

Assumptions on the quality signaled by the GI label and the allocation of exclusive production rights The GI label informs the consumers of the place of production, to indicate quality and protect producers from the misuse of their region name. I consider two sets of assumptions, respectively regarding (i) the dependence of the quality of the GI product on land characteristics and (ii) the definition of the GI production area. First, GIs across the world are characterized by distinct perceptions of the ties between their quality and the characteristics of their place of production (Josling, 2006). The two assumptions below represent polar cases as regards whether the GI product's quality is determined by the land characteristics.

Assumption 4.A (Independent GI quality). *The quality of the GI product is said to be independent of the characteristics of the area of production when s_G is a given exogenous parameter.*

Assumption 4.B (GI quality dependent on the characteristics of GI producers). *The quality of the GI product is said to be dependent on the characteristics of GI suppliers, when s_G depends on the producers' land characteristics and corresponds to the mean of the land characteristics of the producers who effectively produce the GI, that is:*

$$s_G = \mathbb{E}(y_G \mid q_G(y) > 0) \quad (3.6)$$

First, Assumption 4.A models GI labels akin to brands, where the product's quality is more related to the marketing success than to geographical characteristics (Moschini et al.,

⁷This simplifying assumption amounts to say that the potential commodity supply of producers in the GI region is relatively small relative to the world supply of commodity, so that they face a perfectly elastic demand for commodity at price p .

2008). We have in mind here the certification mark system, implemented in the US, which is based on this principle (Josling, 2006). Under Assumption 4.A, the quality of the GI product remains at its historical level when climate-induced changes in the composition of the GI producers occur. Second, Assumption 4.B represents GI labels, which consider that the level of quality of the GI product cannot be reached everywhere, as it is linked to land characteristics. This is a principle at the heart of the *sui generis* protection scheme, which is implemented in the EU, for instance (Josling, 2006). In this perspective, the heterogeneity in land characteristics reflects the variety of conditions existing across landscapes and forms what we call the *terroir*, that is, pedoclimatic properties specific to a place and contributing to the actual (or perceived) quality of the product. As a result, the product's quality reacts to a climate-induced change in the location of the area of production. Third, both assumptions are supported empirically, as the literature shows mixed results regarding the attributability of quality to land characteristics.⁸ Last, both assumptions suggest that quality is non-manipulable by the individual producers, albeit producers may in practice modify quality by changing their production practices (Mérel and Sexton, 2012).

Moreover, how GI labels are attributed and how the exclusive areas of production are delineated vary widely from one jurisdiction to another (Gangjee, 2017). Note that the TRIPS agreement does not include provisions regarding the implementation and enforcement of labels. The following assumptions introduce two polar systems of delineation of the GI area of production:

Assumption 5.A (Open delineation). *The open delineation gives the right to produce the GI to any producers having a comparative advantage.*

Assumption 5.B (Exclusionary delineation). *The exclusionary delineation corresponds to the*

⁸Bonnet (2001) have shown weaker effects on the willingness to pay for the *Camembert* PDO label than for the *Camembert* cheese brand. The wine economics literature has also widely debated the causes of wine quality. Some results underline the potential for replicating wine quality independently of land characteristics, since the production technologies (Gergaud and Ginsburgh, 2008) and the reputation building of specific brand names (Costanigro et al., 2010) influence quality more than regional land characteristics. On the other hand, Ay (2021) shows that the heterogeneous soil and climate combinations between wine GI areas in Burgundy allow one to recover the historical ranking of wine quality, meaning that the combination of some physical attributes directly affects GI quality. Finally, the nested structures observed for many GIs may also be the result of some places being more suitable than others to produce a high-quality good (Yu et al., 2018; Costanigro et al., 2019).

allocation of the production rights that maximizes the aggregate GI producers' net land rents.

According to Assumption 5.A, the GI area of production results from distribution of the comparative advantage in the production of the GI. Under Assumption 5.B, the parcels entitled to the production of the GI product are the ones that maximize aggregate net land rent. By associating these two hypotheses with the set of assumptions 4.A and 4.B on GI quality, the model fits into the literature on whether to constrain the GI production area so as to control the quality of the product. Similar GI industry structures have been studied in the literature, alternating from perfect competition (see e.g. Moschini et al., 2008; Menapace and Moschini, 2014) to monopoly (see e.g. Marette et al., 1999; Marette and Crespi, 2003; Mérel and Sexton, 2012) and also including mixed situations with limited supply control (Lence et al., 2007). The GI label is assumed to be credible, with producers effectively complying with the specifications and consumers effectively observing the quality.⁹

If for the open GI industry the area results from the aggregation of private decisions, exclusionary allocation requires that the producers coordinate to maximize their surplus and manage to exclude some producers from the area of production. In practice, parcel selection is made by an organization representative of the producers, (i.e. the producers' organization (PO)), which manages to impose its decision. Under Assumption 5.B, we implicitly assume that the decision emanates from a unified collective of producers who share the same interests and benefits from their label. If this assumption simplifies the understanding by reasoning at the industry level, it omits the need for a binding and stable agreement between the producers to effectively implement the allocation in a cartel fashion (Marette and Crespi, 2003). This assumption is discussed later, in order to reveal the importance of the democratic decision process and the coordination tools required for the GI area to adapt.

Assumptions 5.A and 5.B close the model, as they determine the producers who are allowed to supply the GI. Under Assumption 5.A, the supply structure corresponds to the standard competitive structure in the Ricardo-Roy models of sectoral allocation of hetero-

⁹As underlined by Moschini et al. (2008), the credibility of the GI label rests on the presence of a control and deterrence system that annihilates opportunistic behaviors of producers. This requires us to account for a monitoring policy which sets a fine and a probability of inspection to deter GI producers from failing to comply with specifications. Also, the certification costs must be shared among members, so as to verify coalition stability constraints.

geneous inputs. According to Assumption 1, high- y producers are relatively more able to produce units of GI quality and allocate their land to the GI. Denote with y^* an arbitrary producer who is indifferent between producing the GI and the commodity. This yields:

$$\alpha(y^*) = \frac{p - w}{p_G - v_G w}, \quad (3.7)$$

where y^* is an implicit function of the GI price and the commodity price. By individual optimization and monotonicity of the $\alpha(\cdot)$ -function, all producers with $y > y^*$ allocate their land to the GI, and conversely for the commodity. For this arbitrary producer, the aggregate supply of GI $Q_G(y^*)$ is:

$$Q_G(y^*) = \int_{y^*}^{\bar{y}} \alpha_G(u) f(u) du. \quad (3.8)$$

In addition, GI quality is the left-truncated mean of the land attributes distribution:

$$s_G(y^*) = \frac{\int_{y^*}^{\bar{y}} u f(u) du}{1 - F(y^*)}. \quad (3.9)$$

Under Assumption 5.B, the selection of eligible parcels is made using a threshold \tilde{y} for land characteristics. Only producers with land characteristics y above \tilde{y} are entitled to produce the GI, while producers with y below \tilde{y} are excluded from the GI area of production. The GI aggregate supply and quality correspond to the expressions in Equations (3.8) and (3.9), now expressed, however, as a function of \tilde{y} . The GI industry objective function is expressed as follows:

$$\max_{\tilde{y}} \Pi_G(\tilde{y}) = \int_{\tilde{y}}^{\bar{y}} \{ \alpha_G(u) [p_G(Q_G(\tilde{y}), s_G(\tilde{y})) - v_G w] - \alpha_C(u) (p - w) \} f(u) du \quad (3.10)$$

Since the GI industry maximizes *net* land rents, or the difference between the GI and the commodity land rent, it internalizes the costs and benefits of excluding some producers (Deconinck and Swinnen, 2021). The exclusionary delineation of the GI area is thus similar to the one resulting under the maximization of the sum of commodity and GI producers'

absolute land rents.

3.3 The historical allocation of GI production rights

Under Assumption 5.A, the GI area is determined by the producers at the margin, which are indifferent between producing the GI and the commodity under market-clearing conditions in the GI market. Denote with y_O^* the characteristics of land of the marginal producer when the GI market is at equilibrium; y_O^* is defined as follows:

$$\alpha_G(y_O^*) [p_G(Q_G(y_O^*), s_G y_O^{*H}) - v_G w] = \alpha_C(y_O^*) (p - w) \quad (3.11)$$

Equation (3.11) specifies the producers at the margin under the open allocation of production rights and under Assumption 4.B. Under Assumption 4.A, the price of the GI does not depend on the producers' land characteristics at the border, as quality is exogeneous.

Under Assumption 5.B, the optimal allocation is directly determined from the first order condition of the program in Equation (3.12). The land characteristics at the border that maximize $\Pi_G(\tilde{y})$, denoted \tilde{y}_E , is defined as follows:

$$\underbrace{Q_G(\tilde{y}_E) \left[\frac{\partial p_G}{\partial Q_G} Q_G'(\tilde{y}_E) + \frac{\partial p_G}{\partial s_G} s_G'(\tilde{y}_E) \right]}_{\text{Marginal benefits from exclusion}} = \underbrace{f(\tilde{y}_E) \{ \alpha_G(\tilde{y}_E) [p_G(Q_G(\tilde{y}_E), s_G(\tilde{y}_E)) - v_G w] - \alpha_C(\tilde{y}_E) (p - w) \}}_{\text{Marginal costs of exclusion}} \quad (3.12)$$

From Equation (3.12), the exclusionary area of GI production is optimally delineated when the marginal benefits correspond to the marginal costs induced by the exclusion of the producers at the border. When marginally increasing \tilde{y} , the GI supply decreases, which in turn increases the price and increases the revenue of the included producers. Under Assumption 4.B, the GI price further increases, because the marginal exclusions concentrate the GI supply on producers with high- γ and increase quality. In contrast, the marginal costs of exclusion correspond to the foregone profits for the GI industry as measured by the net land rent of the excluded producers at the border.

In practice, the regulator delegates the design of GIs specifications to the producers, given the heavy administrative burden of collecting information regarding consumers' preferences and comparative advantage. But consider now, as a first-best outcome, the situation where the regulator has perfect knowledge regarding consumers' preferences and producers' comparative advantage. This delineates the GI area of production to maximize total surplus, that is, the sum of consumers' surplus and producers' land rent:

$$\max_{\tilde{y}} W(\tilde{y}) = \int_0^{Q_G(\tilde{y})} p_G(v, s_G(\tilde{y})) dv - v_G w \int_{\tilde{y}}^{\tilde{y}} \alpha_G(u) f(u) du + (p - w) \int_{\underline{y}}^{\tilde{y}} \alpha_C(u) f(u) du \quad (3.13)$$

The solution of the regulator's program in (3.13), denoted with \tilde{y}_B , is characterized as follows:

$$\underbrace{s'_G(\tilde{y}_B) \int_0^{Q_G(\tilde{y}_B)} \frac{\partial p_G(v, s_G(\tilde{y}_B))}{\partial s_G} dv}_{\text{Total marginal valuation of a quality increase}} = \underbrace{f(\tilde{y}_B) \{ \alpha_G(\tilde{y}_B) [p_G(Q_G(\tilde{y}_B), s_G(\tilde{y}_B)) - v_G w] - \alpha_C(\tilde{y}_B) (p - w) \}}_{\text{Marginal costs of exclusion}} \quad (3.14)$$

The following proposition compares the size of the GI area of production under free entry and under monopoly with first-best allocation, for any given climatic conditions:

Proposition 3.1. • *Under Assumption 4.A, the GI area of production under open delineation corresponds to that under first-best, and that under exclusionary delineation is smaller:*

$$y_O^* = \tilde{y}_B < \tilde{y}_E. \quad (3.15)$$

- *Under Assumption 4.B, the GI area of production under open delineation is always larger than that under first-best, and the GI area of production under exclusionary delineation is smaller or larger than that under first-best depending on how quality and*

quantity vary at the border of the exclusive area, that is to say:

$$y_O^* < \tilde{y}_B < \tilde{y}_E \quad \text{when at } \tilde{y}_E, \quad \varepsilon_{s_G/\tilde{y}} < -2\varepsilon_{Q_G/\tilde{y}} \quad (3.16)$$

$$y_O^* < \tilde{y}_E \leq \tilde{y}_B \quad \text{when at } \tilde{y}_E, \quad \varepsilon_{s_G/\tilde{y}} \geq -2\varepsilon_{Q_G/\tilde{y}}, \quad (3.17)$$

where

$$\varepsilon_{Q_G/\tilde{y}} = Q'_G(\tilde{y}) \frac{\tilde{y}}{Q_G(\tilde{y})} \quad \varepsilon_{s_G/\tilde{y}} = s'_G(\tilde{y}) \frac{\tilde{y}}{s_G(\tilde{y})}. \quad (3.18)$$

Proof. See 3.A.1. □

Proposition 3.1 partly recovers well-known results from the industrial organization literature on GI labels (Marette et al., 1999; Lence et al., 2007; Moschini et al., 2008). The two polar perceptions regarding the influence of *terroir* on quality give rise to justifications regarding whether or not to control the entry into the GI industry (Josling, 2006). If quality is independent of land characteristics (Assumption 4.A), there is no need to restrict the area of production, and the open delineation corresponds to the first-best outcome.¹⁰ Indeed, there would be a social loss in circumscribing the GI area to some locations, as it would unnecessarily keep out competitors—for instance, who could reproduce GI quality elsewhere—without providing supplemental information. On the other hand, when quality depends on land characteristics (Assumption 4.B), Proposition 3.1 underlines the collective interest in controlling the area of production. In a similar fashion to Menapace and Moschini (2014), the design of the GI area here results from a trade-off between enabling more competition and enhancing the quality of the GI product. Under open delineation, producers enter the GI market and do not internalize the quality decrease, which pushes down the GI price at the expense of producers with high land characteristics. By controlling the area of production, it is possible to increase quality and consumers' willingness to pay for quality, to the profit of producers with high- y .

In addition, Proposition 3.1 sheds new insights on how the provision of a differentiated

¹⁰By contrast with Moschini et al. (2008), where the open GI industry falls short of delivering the socially optimal outcome, they are reconciled here. The GI product is not under-provided under open delineation, as producers bear no fixed costs in the model that can deter entry or limit the supply of GI.

product under supply control is shaped by the heterogeneity of the quantity and quality supplied between producers. The socially optimal area of production is smaller than the one of the exclusionary industry, when quality increases at least twice more rapidly than the decrease of quantity when marginally changing the border of the exclusive area. In this situation, the marginal revenue is lower than the average valuation of the demand for a marginal increase in quality at the exclusionary outcome. Said differently, it is socially optimal in these conditions to further restrict the supply, so that the increase in quality will substantially compensate the quantity decrease, and in turn increase total consumer surplus. The industrial organization literature on quality provision under monopoly and its application to GI labels has already underlined conditions of over-(under)provision of quality relative to the social optimum (Spence, 1975; Mérel and Sexton, 2012). Proposition 3.1 complements these results by adding conditions on the flexibility of quality and quantity at the borders of the GI area of production.

3.4 Relocating the GI area of production under climate change

Given the historical GI area of production depicted in Proposition 3.1, I now analyze the effects of climate change. I first introduce the modeling of the effects of climate change on GI production and then study their implications for GI supply.

Introducing the effect of climate change on the supply of GI Climate change will likely diminish the supply of currently grown crops in given areas (Schlenker and Roberts, 2009; Zhao et al., 2017). Climate change is here understood as a deterioration of GI production conditions. This yields a decrease of potential GI quantity for all producers. To do so, the given potential quantity produced, $q_G(y)$, is multiplied by a scalar $1 - \delta$, with $0 \leq \delta < 1$. δ is a climate-induced parameter which measures the quantity of the GI product that is lost under climate change relative to the historical conditions. As in the modern Ricardian framework, climate change corresponds to a shift in potential productivities for each producer (Costinot et al., 2016; Gouel and Laborde, 2021), which is here homogeneous. The potential quantity of GI supplied by a producer with land characteristics y is now given by $q_G(y) = (1 - \delta) \alpha_G(y)$,

and the aggregate supply is $Q_G = (1 - \delta) \int \alpha_G(u) f(u) du$. For now, we assume that the potential quantity of the commodity produced is not affected by climate change. Producers are relatively less able to execute GI production, and as a result the comparative advantage in the GI is affected.

Adaptation of the allocation of GI production rights The outcome for the GI market can be expressed as a function of the climate-induced parameter δ ; that is y_O^* and \tilde{y}_E in Equations (3.11) and (3.12) depend on δ . The historical areas of production under free entry and under monopoly, denoted by y_O^{*H} and \tilde{y}_E^H respectively, are defined by $y_O^{*H} \equiv y_O^*(\delta | \delta = 0)$ and $\tilde{y}_E^H \equiv \tilde{y}_E^H(\delta | \delta = 0)$. Climate change decreases the potential supply of GI homogeneously, and δ progressively increases starting from $\delta = 0$. The comparative statics on y_O^* and \tilde{y}_E for marginal increase in δ give the adaptation of the GI area of production. This marginal increase in δ is here understood as a stylized modelling of the gradual effects of climate change on the potential production of GI.

The following proposition depicts the adaptation of the GI area of production when it is defined under free entry (Assumption 5.A):

Proposition 3.2 (Adaptation of the GI area of production under open delineation). *If the effects of climate change imply $\left(\alpha_C(y_O^{*H})(p - w) < -\alpha_G(y_O^{*H}) \frac{\partial p_G}{\partial Q_G} Q_G \right)$ then there exists a $0 < \hat{\delta}_O < \bar{\delta}$ such that for $\delta \leq (>) \hat{\delta}_O$, $\frac{dy_O^*}{d\delta} \leq (>) 0$; otherwise if $\left(\alpha_C(y_O^{*H})(p - w) \geq -\alpha_G(y_O^{*H}) \frac{\partial p_G}{\partial Q_G} Q_G \right)$, then y_O^* monotonically increases with δ .*

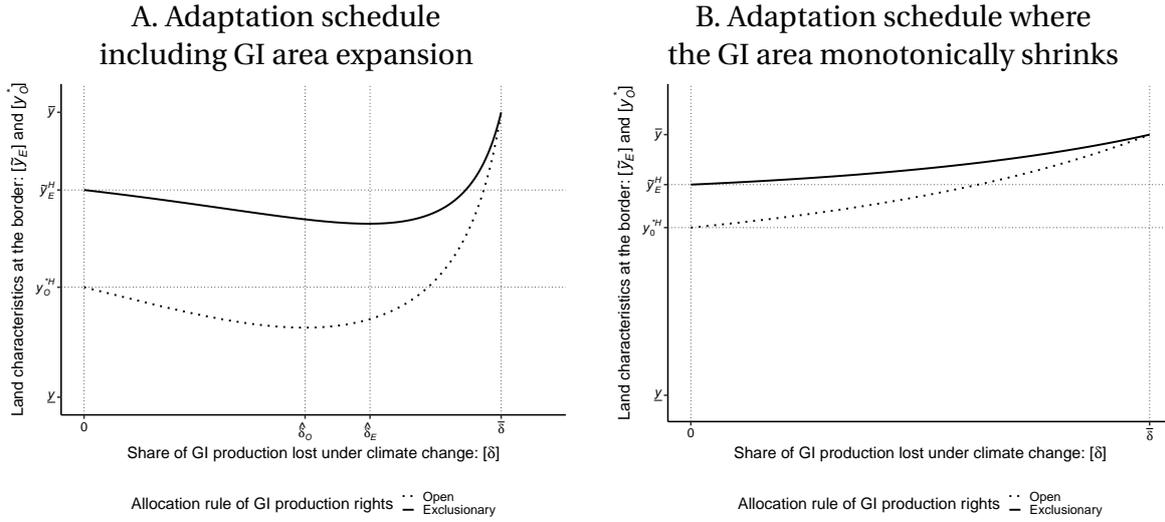
Proof. See 3.A.2 □

Proposition 3.2 gives the schedule of adaptation of the GI area of production under open delineation following a climate-induced decrease in supply. If the effects of climate change imply lower opportunity costs than the increase in revenue for the GI producers at the historical border (condition in parenthesis), then there are moderate climate change scenario where the GI area of production increases; otherwise, the GI area of production always shrinks with a climate-induced deterioration in the conditions of production. $\hat{\delta}_O$ is the climate change scenario where the GI area of production under open delineation is inert to climate change, and $\bar{\delta}$ is the most extreme climate scenario with $y_O^*(\delta | \delta = \bar{\delta}) = \bar{y}$.

Besides depending on the intensity of climate change effects, the direction of the adaptation is the result of comparison between the price effect and the comparative advantage effect induced by climate change at the border (See Equation 3.29 in Appendix 3.A.2). Climate change decreases GI supply, GI price increases, and the outside producers at the border receive a marginally higher revenue for the GI. Thus, the scarcity of the GI supply, strengthened under climate change, produces an interest in extending the border of the area. While climate change reinforces and further decreases land productivity for the GI, comparative advantages are progressively reversed in favor of the commodity. Then, the increase in the opportunity cost of producing the GI dominates the GI price increases, and inside producers progressively leave the GI label. Under severe climate scenarios, welfare in the GI market drastically deteriorates, as the GI supply is about to disappear. The Figure 3.2 illustrates the adaptation schedules under open delineation (dotted line).

Proposition 3.2 underlines that the adaptation of the GI supply under open delineation is characterized by (i) the extent of the extensive margin (when it exists) measured with $\hat{\delta}_O$, and (ii) the extent of the adaptation margin measured with $\bar{\delta}$. The former shows the maximum percentage of climate-induced reduction of individual supply that is compensated for by an extension of the GI area. The latter gives the maximum percentage of climate-induced reduction of individual supply until there is no more comparative advantage in the GI. Both margins are shaped by the technology and the costs of the supply as well as the preference parameters for the GI which determine the price-to-quantity variations ($-Q_G \frac{\partial p_G}{\partial \delta Q_G}$). In particular, the higher the comparative advantage for the GI in the historical situation, the greater the range of moderate climate scenarios leading the industry to extend its borders to outside producers (high $\hat{\delta}_O$, see Equation (3.33) in Appendix 3.A.2) and the more the supply can endure climate change (high $\bar{\delta}$, see Equation (3.32) in Appendix 3.A.2). The higher the opportunity costs ($p - w$) the lower endurable is climate change for the GI supply (low $\bar{\delta}$) and the lower the extensive margin of adaptation (low $\hat{\delta}_O$), since producers have an increased interest at the border in allocating their land to the commodity. Also, when the opportunity cost is zero, the GI area always adapts by integrating outside producers until reaching the boundaries of the finite set of producers, as depicted in Figure 3.B.1.

Figure 3.2: Illustrations of Proposition 3.2 and 3.3.



Note: The y -axis shows the level of land characteristics at the border, with the set of GI producers being those with land characteristics above \tilde{y}_E or y_O^* . The x -axis represents the percentage of GI production that is lost under climate change relative to the historical situation, where $\delta = 0$. The adaptation schedule depicted in Proposition (3.2) under open delineation, and Proposition (3.3) under exclusive delineation must be understood starting from the historical situation ($\delta = 0$), from which climate change occurs progressively until reaching the most extreme potential scenario ($\delta = \bar{\delta}$). As climatic conditions deteriorate the GI production, the allocation of GI production rights adapts by expanding to include outside producers (decreasing \tilde{y}_E or y_O^*) or by restricting to exclude inside producers (increasing \tilde{y}_E or y_O^*). The illustrations are obtained from simulations under Assumption 4.B and using a uniform distribution of land characteristics with $\mathcal{Y} = [1, 3]$. Panel A is obtained for a linear relationship between land characteristics and individual GI production where $\alpha_G(y) = 0.5y$, a constant individual commodity production where $\alpha_C(y) = 1$, and the other parameters are $p = 1$, $w = 0.75$, $v_G = 1.25$, $\Theta = [0, 1]$, and $N = 1.5$. Panel B is obtained with a concave relationship between individual GI production where $\alpha_G(y) = 0.25y^{1/2}$, with a constant individual commodity production where $\alpha_C(y) = 2$, and the other parameters are $p = 1$, $w = 0.75$, $v_G = 1.25$, $\Theta = [0, 1]$, and $N = 1$.

The following proposition illustrates the adaptation to climate change of the GI area of production under exclusionary delineation and when quality depends on land characteristics (Assumption 5.B and Assumption 4.B):

Proposition 3.3 (Adaptation of the GI area of production under exclusionary delineation).

If $(-2\varepsilon_{Q_G/\tilde{y}} > \varepsilon_{S_G/\tilde{y}})$ and if the effects of climate change imply $\left(\frac{\partial^2 \Pi_G}{\partial \delta \partial \tilde{y}} \Big|_{\delta=0} < 0\right)$, then there exists a $0 < \hat{\delta}_E < \bar{\delta}$ such that for $\delta \leq (>) \hat{\delta}_E$, $\frac{d\tilde{y}_E}{d\delta} \leq (>) 0$; otherwise if $(-2\varepsilon_{Q_G/\tilde{y}} \leq \varepsilon_{S_G/\tilde{y}})$ or $\left(\frac{\partial^2 \Pi_G}{\partial \delta \partial \tilde{y}} \Big|_{\delta=0} \geq 0\right)$, then \tilde{y}_E monotonically increases with δ .

Proof. See 3.A.3 □

$\hat{\delta}_E$ is the climate change scenario where the GI area of production under exclusionary delineation is inert to climate change, and $\bar{\delta}$ is the most extreme climate scenario with

$\tilde{y}_E(\delta | \delta = \bar{\delta}) = \bar{y}$. Proposition 3.3 gives the schedule of the adaptation of the GI area of production under exclusionary delineation following climate-induced decrease in the GI potential supply. The direction of the adaptation ultimately depends on the comparison between quantity and quality variation at the border (first condition in parenthesis). Indeed, this comparison determines the direction of variation in marginal revenue through marginal willingness to pay for quality and marginal revenue with variation in quantity. In a situation where the increase in quality is more than twice the decrease in quantity when restricting the border ($-2\varepsilon_{Q_G/\bar{y}} \leq \varepsilon_{s_G/\bar{y}}$), the GI industry always has an interest in further diminishing the area of production in the face of climate change. In other words, the maximum aggregate profit is sustained when the industry increases quality to compensate for revenue loss induced by the reduction in quantity under climate change. The area of production thus concentrates on top-quality producers, while the industry does not forego much of the quantity supplied, as quantity varies slowly. Conversely, if the quantity increase is more than half the quality decrease when extending the border, the industry in monopoly has an interest in expanding the area of production if at the historical delineation climate change decreases the marginal profitability of exclusion $\left(\frac{\partial^2 \Pi_G}{\partial \delta \partial \bar{y}} \Big|_{\delta=0} < 0 \right)$. This second condition means that the climate-induced diminution in the marginal costs of exclusion is smaller than the diminution in the marginal benefits of exclusion at the historical exclusionary delineation (see Equation (3.43) in 3.A.3), which furnishes an incentive to expand the area of production. When these two conditions on the elasticities and on the marginal profitability of exclusion are met, the aggregate industry profits increase under climate change by integrating more producers and quality does not diminish so much. The adaptation under exclusionary delineation is also represented in Figure 3.2 (solid line).

The extensive margin ($\hat{\delta}_E$) and the adaptation margin ($\bar{\delta}$) are determined by the technical characteristics of the GI supply and also the preference parameters for GI quantity and quality. Note that the adaptation margin is similar under monopoly as under free entry. A gap would be introduced if fixed costs of certification and marketing were considered in the model, as they could be more easily borne by an exclusionary industry than by an open industry and would increase the adaptation margin under exclusionary delineation relative to

open delineation (Lence et al., 2007). Concerning the extensive margin of adaptation, higher price elasticity for GI quantity notably increase $\hat{\delta}_E$, as climate-induced supply shortage leads to responsive price variations and increases the interest, for the industry in monopoly, in integrating the outside producers at the border. Also, note that, if $p - w$ is zero, $\hat{\delta}_E = 1$ and the GI industry always adapts to climate change by expanding the GI area until reaching the boundaries of the eligible producers. This situation is also represented in Figure (3.B.1).

When climate change simultaneously affects the potential supply of the GI and the commodity Propositions 3.2 and 3.3 assume that climate change does not alter the potential supply of the commodity, but this is not likely to be the actual case. Denote with δ_C the share of the historical potential supply of the commodity that would be lost under climate change. Three situations can be considered, according to the level of δ_C : (i) $\delta_C = \delta$, (ii) $\delta_C > \delta$ and (iii) $\delta_C < \delta$. In the first configuration, both the open and the exclusionary area of production enlarge (as long as $-2\varepsilon_{Q_G/\bar{y}} > \varepsilon_{s_G/\bar{y}}$, see 3.C.3.2 for detailed derivations). For the open delineation, this further increases the interest of the outside producers at the border in allocating their land to the GI production. Under exclusionary delineation, the effects of climate change on the commodity increase the exclusion costs, which in turn increase the interest in integrating the parcels at the border. In situation (ii), where $\delta_C > \delta$, the mechanisms described above are even further reinforced: the potential supply of the commodity is hit harder by climate change than the GI is, and interest in allocating nearby parcels to the GI production increases. However, in situation (iii), where $\delta_C < \delta$, the situation is not clear. As soon as climate change hits the GI much harder than the commodity, relative interest in producing the GI diminishes. In this situation, it is likely that the supply of GI under climate change is sustained for only a narrower set of climate change scenarios, as the comparative advantage for the GI disappears more rapidly.

The influence of land characteristic heterogeneity on adaptation response Modern Ricardian models have illustrated that technological heterogeneity shapes the adaptation margin (Costinot et al., 2016). The more the differences in the technological potential across producers, the more agriculture can adjust to climate change as it benefits from heterogeneous

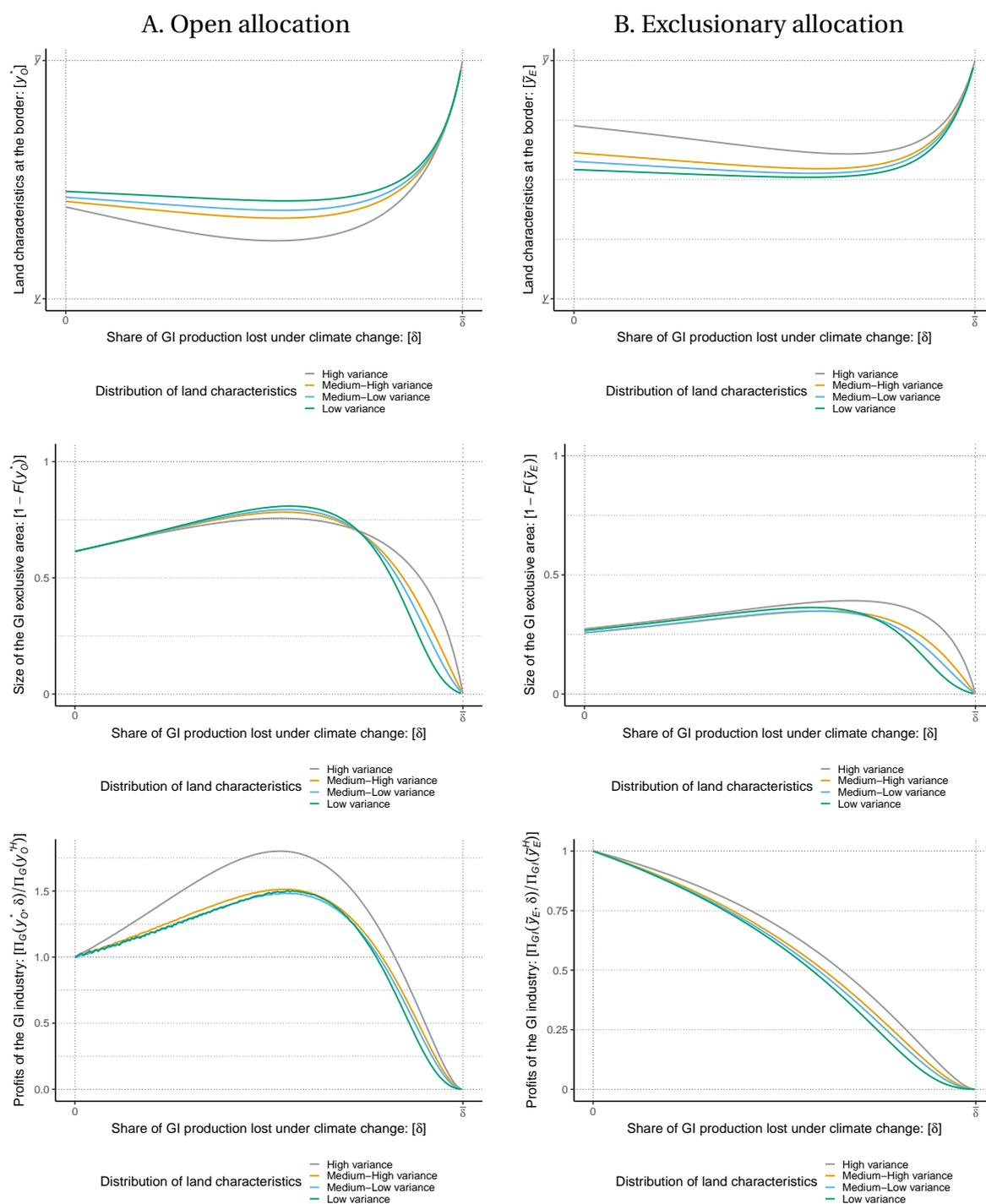
conditions to adjust land allocation. Since GIs across the world are different in their degree of heterogeneity of land characteristics within their area of production (Ay, 2021), their relocation margins are also potentially different. I conduct simulations to observe the importance of the land characteristic heterogeneity on the adaptation of the supply of GI. The effect of a mean-preserving spread of the distribution of land characteristics on the adaptation schedule (focusing on cases presenting some extension in the GI area, as in the first parts of the adaptation schedules in Propositions (3.2) and (3.3)), is presented in Figure 3.3.

With a higher degree of heterogeneity, supply adjustments are smoothed, as illustrated by the more flexible variations in the size of the GI area (middle panel). When land characteristics are more homogeneous, the supply overreacts, as more producers have similar land characteristics and simultaneously enter or exit the GI area. In terms of aggregate net revenues (bottom panel), higher heterogeneity—in the sense of a mean-preserving spread—benefits producers in the aggregate, because it increases the quality of the product and because producers are more efficient in the face of climate change. From the consumers' point of view, their surplus tends to benefit from more homogeneous land characteristics in cases where the GI area expands, as quantity adjustments are magnified (See Figure 3.B.2 in Appendix 3.B.2 for details). However, consumers suffer more from homogeneous producers as the GI area diminishes, because the quantities available diminish more rapidly.

3.5 Discussion on barriers to the relocation of GI production and their implications for the regulation of GI labels

When the GI area of production diminishes and under open delineation, producers progressively exit the GI market and produce the commodity. These exits intervene in a fluid way only if the conversion costs are negligible. In contrast, under exclusionary delineation or under open delineation and when the GI area of production extends at least for some range of climate scenarios, the transition is associated with significant changes that are not accounted for in the model for now but that can nevertheless affect the decision to adapt. In the current section, I discuss how the relocation of the GI sector can(not) operate in the

Figure 3.3: Adaptation of the GI area for different heterogeneity in land characteristics.



Note: The adaptation response on the GI market when the area is defined under open delineation (column A) and under exclusionary delineation (column B) for four distributions of land characteristics that are a mean-preserving spread transformation of each other. Detailed explanations on the construction and the results are given in Appendix 3.B.2. The adaptation response is represented using the evolution of the level of land characteristics at the border (upper panel), the variation in the size of the GI area of production (middle panel) and the variation of the aggregate profits of the GI industry (bottom panel), and for all as a function of the variations in the strength of climate change.

presence of barriers to adaptation.

Conflicting incentives under open delineation between historical producers and new entrants Under open delineation of the GI area of production, the producers are by definition free to enter or exit the GI market according to what is privately optimal in response to climate change. In other words, the aggregation of private production decisions leads to the adaptation in Proposition 3.2. However, the interest of the producers at the border in entering the GI market, under the conditions depicted in the first part of Proposition (3.2), can be offset by the interest of the historical GI producers in maintaining the historical situation. In a rent-seeking behavior, historical GI producers may impede adaptation using side-payments to potential entrants. To illustrate this, consider the comparison between the historical area of production, defined by y_O^{*H} , and the one occurring when extending to a discrete change in climatic conditions, defined by $y_O^{*C} \equiv y_O^*(\delta \mid 0 < \delta < \hat{\delta}_O)$ and where $y_O^{*C} < y_O^{*H}$. The historical GI producers, meaning those with y in $[y_O^{*H}, \bar{y}]$, consider paying the potential entrants, that is, the producers with y in $[y_O^{*C}, y_O^{*H}[$, to collude in blocking the historical area. This side-payment is a potential barrier to entry if (i) the revenue of historical producers after side-payments is larger than when the potential entrants enter the GI market and (ii) if side-payments compensate the potential entrants sufficiently to keep them outside. The amount that a historical GI producer with land characteristics y can transfer to the new entrants is $t(y, \delta) \equiv r_G(y, y_O^{*H}, \delta) - r_G(y, y_O^{*C}, \delta)$, where $t(y, \delta)$ corresponds to the difference in net revenue under climate change with the given historical area and with the extension of the area. The maximum aggregate amount transferable to potential entrants is denoted by $T(\delta)$ and is defined as follows:

$$T(\delta) \equiv \int_{y_O^{*H}}^{\bar{y}} t(u, \delta) f(u) du \quad (3.19)$$

This transfer will only take place if it is accepted by the potential entrants. The minimal amount that an individual potential entrant can accept to not enter the GI market is $z(y, \delta) \equiv r_G(y, y_O^{*C}, \delta) - r_C(y)$, where $z(y, \delta)$ corresponds to the difference in net revenue under climate change with entry into the GI area and with commodity production. For all producers with

y in $[y_O^{*C}, y_O^{*H}]$, the minimum aggregate amount $Z(\delta)$ that leaves them indifferent between producing the GI and the commodity under climate change δ is defined as follows:

$$Z(\delta) = \int_{y_O^{*C}}^{y_O^{*H}} z(u, \delta) f(u) du \quad (3.20)$$

Now, there are feasible side-payments if the following condition is verified:

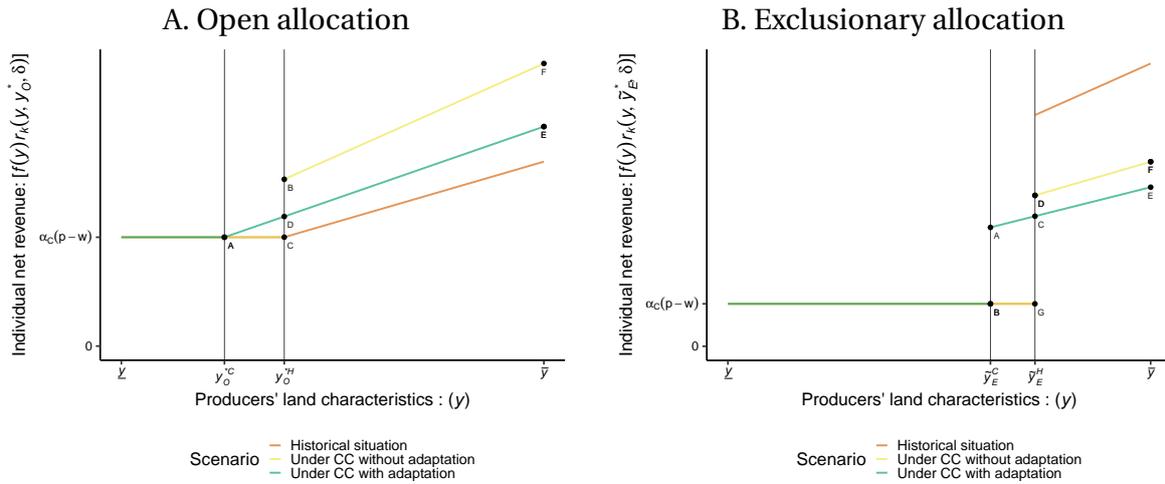
$$T(\delta) \geq Z(\delta). \quad (3.21)$$

Note that for $\delta = 0$, $T(\delta) = Z(\delta) = 0$ by definition; then, a marginal deterioration in climate-induced conditions of production in $\delta = 0$ yields $\left. \frac{\partial T(\delta)}{\partial \delta} \right|_{\delta=0} > 0$. Indeed, when maintaining the historical area of production, inside producers can obtain a rent as a result of the direct effect of climate change increasing the scarcity of their supply. On the other hand, a marginal decrease in δ from the historical situation yields $\left. \frac{\partial V(\delta)}{\partial \delta} \right|_{\delta=0} = 0$, since the outside producers at the border are indifferent between producing the GI and the commodity. Therefore, there are at least some moderate climate scenarios for which feasible side-payments from the historical producers to the potential entrants exist. Such a situation is illustrated in Figure 3.4.

Note that both the historical producers and the potential entrants are encouraged to collude on the already established past competitive allocation system of GI production rights. However, for the side-payment to effectively block the adaptation, it must be associated with a well-designed transfer system which accounts for the within- and between- information asymmetry of the groups of historical producers and potential entrants. Indeed, producers must truthfully report their willingness to pay and to receive, to deter free-riding behavior. Such a transfer system implies that the historical producers and the potential entrants form a cartel which manages to correctly divide their collective benefits and deter entry. The construction of such a stable cartel goes beyond this discussion and is left for further research (see e.g. McAfee and McMillan, 1992, for a general framework on this question).

Reaching an agreement to relocate under exclusionary delineation When the GI area is determined under exclusionary delineation, no such side-payments to block the adaptation

Figure 3.4: Individual net revenue for every producers with and without adaptation.



Note: Individual net revenue for every producers in function of their land characteristics when the GI area of production is determined under open delineation (column A) and under exclusionary delineation (column B) between three cases: the historical outcome (orange line), the outcome under climate change and without adaptation of the GI area of production (yellow line), and the outcome under climate change and with adaptation of the area of production (green line). Note that all three lines are superimposed to the left y_O^{*C} and \tilde{y}_E^C , because commodity producers are assumed not to be affected by climate change. This figure illustrates the (non-)feasibility of transfer from historical producers to new entrants to impede the adaptation. Concerning the open allocation, the total amount transferable by the historical producers—area $BDEF$ between their land rent without the entries and that with the entries—is greater than the minimum amount that incentivizes potential entrants to maintain their land allocation to the commodity—area ACD , between the land rent when they enter the GI market and that when producing the commodity. However, under monopoly allocation, the area $ABGC$ is always greater than the area $DCEF$. The illustration is obtained from simulations under Assumption 4.B and using a uniform distribution of land characteristics with $\mathcal{Y} = [1, 3]$. The relationship between land characteristics and individual GI production is linear with $\alpha_G(y) = 0.5y$, the individual commodity production is constant with $\alpha_C(y) = 1$, and the share of the historical production of GI under climate change is $\delta = 0.5$. The other parameters are $p = 1$, $w = 0.75$, $v_G = 1.25$, $\Theta = [0, 1]$, and $N = 1.5$.

are feasible, as the area results by definition from the maximization of all producers' welfare. Figure (3.5) illustrates the collective benefits from adaptation in the case of an extension, as depicted in the first part of the adaptation schedule in Proposition (3.3). However, the adaptation enacts a redistribution between the group of historical producers and the group of new entrants. Figure (3.4) illustrates the redistributive effect of an extension of GI production rights following a discrete change in climatic conditions, from the historical allocation \tilde{y}_E^H to $\tilde{y}_E^C \equiv \tilde{y}_E(\delta \mid 0 < \delta < \hat{\delta}_E)$ and where $\tilde{y}_E^C < \tilde{y}_E^H$. The historical GI producers have a higher net revenue without adaptation (yellow line) than with adaptation (green line); but the industry collectively prefers to adapt, since the aggregate net loss for historical GI producers, or area $DCEF$, is smaller than the aggregate gain for the new GI producers, area $ABGC$. Note that the same issue apply under a shrinkage of the exclusive area of production. Again, it is

collectively optimal to reduce the area of production, but these gains are concentrated on insiders while historical excluded producers lose from being outside the GI area of production. In both situations, the GI agency must find a way to compensate those who lose from the adaptation in order to effectively adapt.

As these gains are collective, the adaptation mechanism must be coordinated so as to align the conflicting interests. We have so far considered exclusionary allocation as emanating from an authority which seamlessly coordinates the producers of the region in question; however, if we neglect to consider the underlying democratic and enforcement processes, it leaves the acceptability of the extension or reduction unclear. A simple criterion for when it is appropriate to expect an adaptation to be voted for unanimously by historical producers and new entrants is whether it is Pareto improving relative to the no-adaptation situation. It can be made so by designing transfers so that every producer becomes better off under adaptation. However, there still remain delicate questions on transfer design under asymmetry of information, that is, on producers' private information about their land characteristics. Such transfers are subject to moral hazards encouraging new entrants and historical producers to respectively under and over report their gains and losses under adaptation to argue for a bigger net transfer income. The industrial organization literature using mechanism design applied to pricing schemes and quotas for farmers' cooperatives and/or cartels can enrich the discussion of our model from this perspective.¹¹

The implications for GI label regulation Climate change introduces a windfall effect in the GI sector. We can expect that historical GI producers aim to extract a situation rent from the exclusivity of their name as climate change makes their product increasingly scarce. GIs as publicly regulated labels can also adapt their rules in the face of climate change. If we consider GI labels as brands whose product's quality is not linked to the geographical characteristics of its location (Assumptions 4.A and 5.A), the GI production rights must be extendable at will to keep competitive conditions of supply. When we consider GI labels that

¹¹In a seminal work, Zago (1999) has demonstrated how producers democratically chose their level of quality and the fees of their GI with information asymmetry about the cost profile. In another context, Lewis et al. (1989) design a menu of output and payments for a continuum of heterogeneous producers to exclude some producers of the market, and under the constraint that producers accept the market organization. These works can help elucidate the design of transfers efficient for adaptation.

are framed to protect specific land characteristics (Assumptions 4.B and 5.B) and when these characteristics do not vary too much at the border, the coordination process in the GI label governance must be accompanied towards a pareto-improving solution.

To date, two EU PGI labels have successfully applied for a non-minor amendment to recently extend their geographical area.¹² Such a modification of the GI area is the result of a bargaining process between inside and outside producers and the administration which grants the label. In France, a GI label for wine can be modified publicly by decree, after experts examine the causality of the link between the wine quality and the proposed area (Mérel et al., 2021). The decree is published after having passed an opposition proceeding that enables potential competitors to contest the application. Conflicts between insiders and outsiders when delineating the GI area of production have been documented in the past in broader contexts and illustrate the apparent barriers to the adaptation of GIs (Landi and Stefani, 2015; Meloni and Swinnen, 2018).

In 2019, the French ministry of agriculture and INAO (the French administration managing the GI labels) launched a consultation strategy based on regional discussion groups involving producers and experts so as to converge adaptation actions for wine GI labels.¹³ This strategy can be construed as a public action to prevent potential coordination failure between producers that could arise in the face of climate change. Finally, the EU implements a yearly program to support EU quality labeling schemes for agricultural products.¹⁴ This financial support could also be directed towards the efforts of GI labels to adapt to climate change to lower the fixed-costs burden (Moschini et al., 2008). Indeed, the GI industry may incur supplementary expenses to adapt to climate change. The relocation of the GI supply can affect consumers' willingness to pay (Saïdi et al., 2020). To maintain consumers'

¹²The EU PGI label for Cornish sardines in 2017 and the EU PGI *Cítricos Valencianos* in 2012 extended their geographical area of production. See Introduction for more details.

¹³See the following link for more details about this national strategy: <https://www.inao.gouv.fr/eng/Our-News/Changement-climatique-une-convention-signe-entre-l-INA0-FranceAgriMer-et-l-IFV>

¹⁴The EU currently assists agricultural producers to promote their products. An aggregate amount of 200 million euros was granted in 2020 to help agricultural products gain market share, with a specific focus on EU's major non-EU markets, such as China, Japan, South Korea, Canada, and the USA. This program dedicates an approximated amount of EUR 50 million euros to marketing actions that improve the awareness and recognition of EU quality labeling schemes (GI and organic food labels), as only 18% of European consumers recognize the PDO logo. See: https://ec.europa.eu/info/sites/info/files/food-farming-fisheries/key_policies/documents/annex-commission-decision-c2019-8095_en.pdf

willingness to pay for quality, costly efforts to sustain the GI's collective reputation have to be undertaken (Lence et al., 2007).

3.6 Conclusion

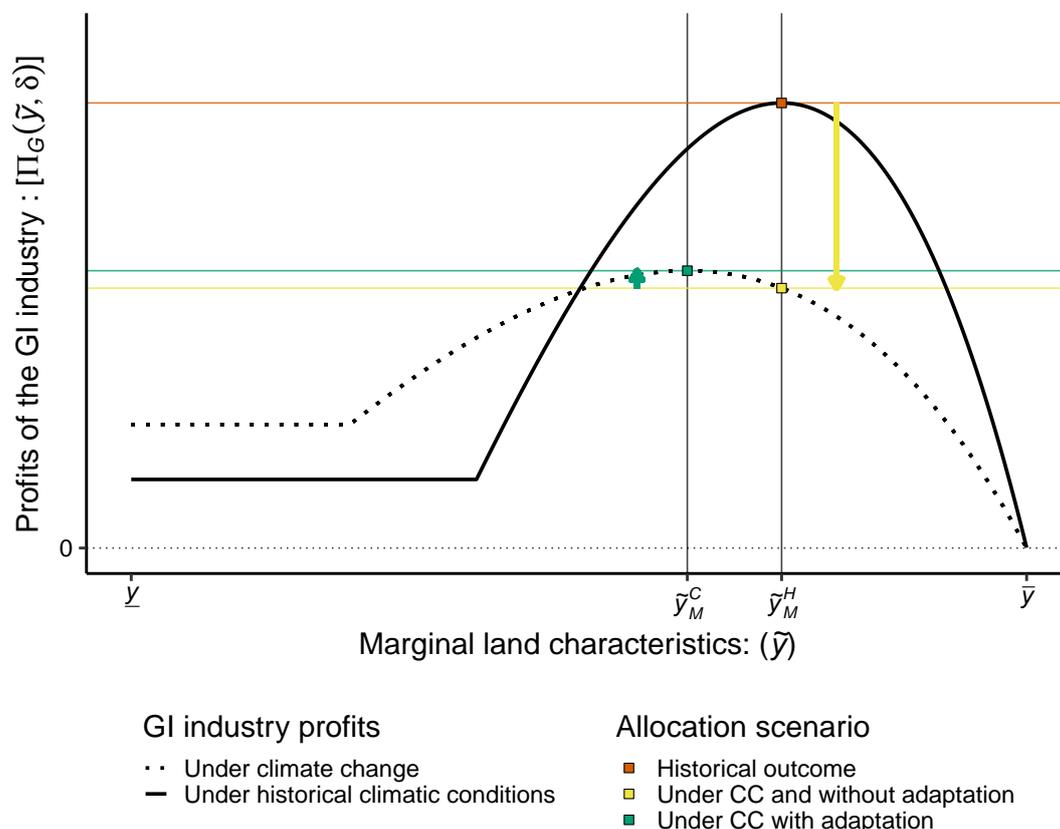
In this chapter, I have developed a stylized framework to understand the process of relocation of the agricultural production under GI labels in the face of climate change. The model considers GIs to be a label that perfectly inform consumers on the quality of a product, which may (not) be influenced by the characteristics of the area of production. The strength of the influence explains the degree of protection, which makes the supply exclusive to a given place and whose relocation has to occur at the border. The analysis emphasizes the differences in relocation that could occur across existing GI jurisdictions, that is, between an open entry situation and when the area is delineated to maximize the producers' welfare. The relocation process is conveniently modeled by accounting for comparative advantage, which is attractive because of its affordances to incorporate climate change effects on the evolution of opportunity costs.

The main conclusions can be summarized as follows. First, for GI areas of production determined under open entry, before climate change extensively deteriorates the conditions of production and diminishes the GI area of production, there are private interests for bordering producers to enter and enlarge the area under moderate effects of climate change. Second for GI areas of production determined under exclusionary delineation and under moderate climate scenarios, there is a collective interest for the GI industry to also enlarge the area of production, as soon as quality decreases not too quickly relative to the quantity increase associated with the integration of the producers at the border. Third, for both delineations and under moderate climate scenarios, the historical area of production can prevail rather than extending because historical producers can organize the preclusion of the extension since it redistributes their rent to the new entrants.

Finally, the results of the analysis are related to the stylized representation of the GI supply and climate change. In particular, the model only focuses on effects of climate change

that decrease the supply of GI homogeneously, to ease the interpretation of the results. It is possible to consider a progressive inversion in comparative advantage along the land characteristics dimension, so as to model the gradual relocation around a central point describing the optimal conditions to produce the GI. Also, the model studies the relocation of the GI product in isolation from the rest of the economy due to the unique specificities of its production area. It may be interesting to consider the competition of several GI products as closed substitutes in the same jurisdictions, or with different jurisdictions and facing different effects of climate change. These extensions can be explored in future research and should benefit from the benchmark analysis presented in this chapter.

Figure 3.5: Collective benefits of adaptation under exclusionary delineation.



Note: The solid line (dotted line) represents aggregate industry net revenues under the historical climatic conditions (under climate change), for every possible rules upon \bar{y} defining the border of the GI area of production. Aggregate profits are 'U-shaped' for land characteristics above \bar{y}_O^* , and constant below, since the resulting GI area corresponds to the free-entry situation. The maximum of profits is obtained for a GI area of production defined by \bar{y}_E^H in the historical situation, and \bar{y}_E^C under climate change. For the historical area of production, climate change diminishes aggregate profits, as historical producers cannot maintain their level of production of the GI product, which is not compensated by the GI price increases following its rarefaction. The yellow arrow measures this direct loss induced by climate change. In this configuration, the monopoly adapts to climate change by integrating new producers, and reducing \bar{y}_E^H to \bar{y}_E^C . By expanding its area of production, the monopoly can increase profits by selling more products. The increase in profits when adapting to climate change is measured by the green arrow. The illustration is obtained from simulations under Assumption 4.B and using a uniform distribution of land characteristics with $\mathcal{Y} = [1, 3]$. The relationship between land characteristics and individual GI production is linear with $\alpha_G(y) = 0.5y$, the individual commodity production is constant with $\alpha_C(y) = 1$, and the share of the historical production of GI under climate change is $\delta = 0.5$. The other parameters are $p = 1$, $w = 0.75$, $\nu_G = 1.25$, $\Theta = [0, 1]$, and $N = 1.5$.

Appendix

3.A Proofs

3.A.1 Proof of Proposition 3.1

Under Assumption 4.A, quality is independent of the supply composition, $s'_G(\tilde{y}) = 0$, and from Equations (3.11) and (3.14), the socially optimal allocation of GI rights corresponds to that under open allocation, that is, $\tilde{y}_B = y_O^*$. In these situations, the GI net land rent at the border satisfies:

$$\alpha_G(y_O^*) [p_G(Q_G(y_O^*), s_G) - v_G w] - \alpha_C(y_O^*) (p - w) = 0 \quad (3.22)$$

Taking Equation 3.12 and cancelling the term in s'_G , the exclusionary allocation of GI rights is such that the GI net land rent of the producers at the border equals the marginal revenue, which is positive. This implies the following inequality at the border:

$$\alpha_G(\tilde{y}_E) [p_G(Q_G(\tilde{y}_E), s_G) - v_G w] - \alpha_C(\tilde{y}_E) (p - w) > 0. \quad (3.23)$$

Now, we need to show that the marginal exclusion cost, that is, the GI net land rent in the left-hand term in expressions (3.22) and (3.23), is monotonically increasing in \tilde{y} . If this is the case, the exclusionary outcome is reached for \tilde{y}_E , greater than y_O^* . For the open allocation to exist, the land rent at the GI border when the land characteristics at the border correspond

to the boundaries of \mathcal{Y} , that is, when $y = \{\underline{y}, \bar{y}\}$, must satisfy:

$$\alpha_G(\underline{y}) [p_G(Q_G(\underline{y}), s_G) - v_G w] < \alpha_C(\underline{y}) (p - w) \quad (3.24)$$

$$\alpha_G(\bar{y}) [p_G(Q_G(\bar{y}), s_G) - v_G w] > \alpha_C(\bar{y}) (p - w). \quad (3.25)$$

The conditions in Equations (3.24) and (3.25) essentially mean that the producers at the boundaries of land characteristics distribution must always have a comparative advantage in the commodity for $y = \underline{y}$ and in the GI for $y = \bar{y}$. Now, as $\alpha(\cdot)$ is a monotonic function, the land characteristics at the border with a GI net land rent that is zero y_O^* are uniquely defined by:

$$y_O^* = \alpha^{-1} \left(\frac{p - w}{p_G(Q_G, s_G) - v_G w} \right) \quad (3.26)$$

Therefore, for the GI net land rent to be strictly positive in \tilde{y}_E , it requires $\tilde{y}_E > y_O^*$.

Now, we need to order the size of the GI area of production under Assumption 4.B. It is clear that \tilde{y}_B and \tilde{y}_E are greater than y_O^* . Following the reasoning above, characterizations in Equations (3.12) and (3.14) lead to a positive GI net land rent at the border and as a result a greater land characteristics at the border than under open delineation. Comparison of the socially optimal allocation and the exclusionary allocation is not straightforward. To get further insights, I study the slope of the welfare function in the neighborhood of \tilde{y}_E . Given the concavity of the welfare function $W(\tilde{y})$,¹⁵ the sign of the slope of $W(\cdot)$ in the neighborhood of \tilde{y}_E will determine whether the optimal exclusionary allocation is above or below the socially optimal allocation \tilde{y}_B . The derivative of W when evaluated at \tilde{y}_E yields:

$$\begin{aligned} \left. \frac{\partial W(\tilde{y})}{\partial \tilde{y}} \right|_{\tilde{y}=\tilde{y}_E} &= s'_G \int_0^{Q_G(\tilde{y})} \frac{\partial p_G(v, s_G(\tilde{y}))}{\partial s_G} dv - Q_G(\tilde{y}) \left[\frac{\partial p_G(Q_G, s_G)}{\partial Q_G} Q'_G(\tilde{y}) + \frac{\partial p_G(Q_G, s_G)}{\partial s_G} s'_G(\tilde{y}) \right] \\ &= Q(\tilde{y}_E) \frac{(\bar{\theta} - \theta)}{2N} [s'_G(\tilde{y}_E) Q_G(\tilde{y}_E) + 2s_G(\tilde{y}_E) Q'_G(\tilde{y}_E)] \\ &= CS(\tilde{y}_E) \left[\frac{s'_G(\tilde{y}_E)}{s_G(\tilde{y}_E)} + 2 \frac{Q'_G(\tilde{y}_E)}{Q_G(\tilde{y}_E)} \right]. \end{aligned} \quad (3.27)$$

¹⁵Note that sufficient conditions for the welfare function and the GI industry aggregate net revenue to be concave are presented in 3.C.2.

The variation in welfare induced by a marginal change in the exclusionary area of production corresponds to the change in consumer's surplus induced by the changes in quantity and quality. According to our assumption regarding preferences for the GI, quantity variation weighs twice as much as quality variation in the change in welfare at the margin of the exclusionary allocation. The sign of welfare variation when marginally changing the border of the exclusionary area of production corresponds to the sign of $\frac{s'_G(\tilde{y}_E)}{s_G(\tilde{y}_E)} + 2\frac{Q'_G(\tilde{y}_E)}{Q_G(\tilde{y}_E)}$. Studying the sign of this expression is equivalent to comparing $\varepsilon_{s_G/\tilde{y}} + 2\varepsilon_{Q_G/\tilde{y}}$, where $\varepsilon_{s_G/\tilde{y}}$ and $\varepsilon_{Q_G/\tilde{y}}$ are defined in Equations (3.18) and are respectively the elasticity of GI quality and the elasticity of GI quantity with marginal changes in the area of production. As a result, the derivative in Equation (3.27) is positive when $\varepsilon_{s_G/\tilde{y}} \geq -2\varepsilon_{Q_G/\tilde{y}}$, implying that \tilde{y}_E is lower than \tilde{y}_B , and is strictly negative when $\varepsilon_{s_G/\tilde{y}} < -2\varepsilon_{Q_G/\tilde{y}}$ implying that \tilde{y}_E is strictly greater than \tilde{y}_B .

3.A.2 Proof of Proposition 3.2

Note that this proof is obtained under Assumption 4.B, and can be recovered under Assumption 4.A by replacing $s_G(y_O^*)$ with an exogeneous and invariant parameter. Characterization of y_O^* in Equation (3.11) can be rewritten as a function of δ (omitting for clarity the y_O^* argument inside p_G operating through the $Q_G(y_O^*)$ and $s_G(y_O^*)$ functions):

$$(1 - \delta) \alpha_G(y_O^*) [p_G(Q_G, s_G) - v_G w] - \alpha_C(y_O^*) (p - w) = 0. \quad (3.28)$$

Note that Q_G is a linear function of δ . By totally differentiating Equation (3.28), and cancelling it so that the GI area of production is still determined under open delineation and the GI market is at equilibrium, the variation in the GI area of production at the margin following an increase in δ is given by (omitting the Q_G and s_G arguments in the GI price function):

$$\frac{dy_O^*}{d\delta} = \frac{\alpha_G(y_O^*) (p_G - v_G w) + \alpha_G(y_O^*) \frac{\partial p_G}{\partial Q_G} Q_G(y_O^*)}{(1 - \delta) \alpha'_G(y_O^*) (p_G - v_G w) - \alpha'_C(y_O^*) (p - w) + (1 - \delta) \alpha_G(y_O^*) \left[\frac{\partial p_G}{\partial Q_G} Q'_G(y_O^*) + \frac{\partial p_G}{\partial s_G} s'_G(y_O^*) \right]}. \quad (3.29)$$

We have to determine the sign of Equation (3.29). Regarding the denominator, following Assumption 3 on preferences, we have $\frac{\partial p_G}{\partial Q_G} Q'_G(y_O^*) > 0$ and $\frac{\partial p_G}{\partial s_G} s'_G(y_O^*) > 0$. Following Assumption 1 regarding comparative advantage structure, we have $\frac{\alpha'_G(y)}{\alpha_G(y)} \geq \frac{\alpha'_C(y)}{\alpha_C(y)}$. For the producers at the border of the GI area under open delineation and for a given δ , we know that marginal net land rent for the commodity and for the GI are equal (Equation (3.11)), hence multiplying left-handside of Equation (3.11) by $\frac{\alpha'_G(y)}{\alpha_G(y)}$ and right-handside by $\frac{\alpha'_C(y)}{\alpha_C(y)}$ yields $(1 - \delta) \alpha'_G(y_O^*) (p_G - v_G w) \geq \alpha'_C(y_O^*) (p - w)$. So, the denominator is always positive.

The sign of the variation in y_O^* with increase in δ is thus determined by:

$$\text{sign} \left(\frac{dy_O^*}{d\delta} \right) = \text{sign} \left\{ \alpha_G(y_O^*) [p_G(Q_G, s_G) - v_G w] + \alpha_G(y_O^*) \frac{\partial p_G(Q_G, s_G)}{\partial Q_G} Q_G(y_O^*) \right\} \quad (3.30)$$

Now, we study the sign of the expression in Equation (3.30). As in the equilibrium under open delineation, we have $\alpha_G(y_O^*) [p_G(Q_G, s_G) - v_G w] = \alpha_C(y_O^*) (p - w)$, it can be written as:

$$\begin{aligned} \alpha_G(y_O^*) [p_G(Q_G, s_G) - v_G w] + \alpha_G(y_O^*) \frac{\partial p_G}{\partial Q_G} Q_G(y_O^*) &= \alpha_C(y_O^*) (p - w) + \alpha_G(y_O^*) \frac{\partial p_G}{\partial Q_G} Q_G(y_O^*) \\ &= \alpha_C(y_O^*) (p - w) + (1 - \delta) \alpha_G(y_O^*) \frac{\partial p_G}{\partial Q_G} \int_{y_O^*}^{\bar{y}} \alpha_G(u) f(u) du. \end{aligned} \quad (3.31)$$

First, note that expression in Equation (3.31) linearly increases with δ (since $\frac{\partial p_G}{\partial Q_G} < 0$). Second, consider the most extreme climate scenario, measured with parameter $\bar{\delta}$, where producers cannot any longer allocate their land to the GI, except the most efficient producers with land characteristics \bar{y} . Following characterization of y_O^* in Equation (3.11), $\bar{\delta}$ is defined by the following expression:

$$\bar{\delta} = 1 - \frac{\alpha_C(\bar{y}) (p - w)}{\alpha_G(\bar{y}) [\bar{y}\bar{\theta} - v_G w]}, \quad (3.32)$$

since $p_G(Q_G(\bar{y}), s_G(\bar{y})) = \bar{y}\bar{\theta}$. For $\delta = \bar{\delta}$, a marginal increase in δ implies that no producers are able anymore to sustain the production of the GI, since they now all have a comparative advantage in the commodity. Note that the aggregate quantity supplied when the marginal land characteristics are \bar{y} is zero. The expression in Equation (3.31) reduces to

$\alpha_C(y_O^*)(p-w)$, which must be positive, ensuring an interior equilibrium in the GI market (the condition in Equation (3.25)). Therefore, in the above neighborhood of $\bar{\delta}$, the numerator in Equation (3.29) is positive at $\bar{\delta}$, and $\frac{dy_O^*}{d\delta} > 0$.

Thus, at $\bar{\delta}$, the expression in Equation (3.31) is positive, then linearly decreases when δ decreases, until being zero for $\hat{\delta}_O$, which is the value of the climate parameter where there is no entry or exit with marginal deviations in climate conditions under open allocation. From Equation (3.31), $\hat{\delta}_O$ is defined by:

$$\hat{\delta}_O = 1 + \frac{p-w}{\alpha(y_O^*) \frac{\partial p_G}{\partial Q_G} \int_{y_O^*}^{\bar{y}} \alpha_G(u) f(u) du}, \quad (3.33)$$

where the second term in Equation (3.33) is negative. As a result, following Equation (3.30), if in the historical GI market equilibrium, $y_O^{*H} \equiv y_O^*(\delta | \delta = 0)$, the following condition is satisfied,

$$\frac{p-w}{\alpha(y_O^{*H})} \geq -Q_G(y_O^{*H}) \left. \frac{\partial p_G}{\partial Q_G} \right|_{y_O^*=y_O^{*H}}, \quad (3.34)$$

it implies that $\hat{\delta}_O \leq 0$ and that the numerator of Equation (3.29) is positive all along the interval of climate parameter $[0, \bar{\delta}]$. Thus, it results in the adaptation response where $\frac{dy_O^*}{d\delta} \geq 0$ for all δ in $[0, \bar{\delta}]$.

By contrast, if in the historical GI market equilibrium, the following condition is satisfied,

$$\frac{p-w}{\alpha((y_O^*)^H)} < -Q_G((y_O^*)^H) \left. \frac{\partial p_G}{\partial Q_G} \right|_{y_O^*=(y_O^*)^H}, \quad (3.35)$$

it implies that $\hat{\delta}_O > 0$, and that the numerator of Equation (3.30) is negative for δ in $[0, \hat{\delta}_O]$, and positive for δ in $]\hat{\delta}_O, \bar{\delta}]$, resulting in the adaptation response where $\frac{dy_O^*}{d\delta} \leq (>)0$ for $\delta \leq \hat{\delta}_O$.

3.A.3 Proof of Proposition 3.3

Note that this proof is obtained under Assumption 4.B, and can be recovered under Assumption 4.A by replacing $s_G(\tilde{y})$ with an exogenous and invariant parameter. Characterization of \tilde{y}_E in Equation(3.12) can be rewritten to account for the climate parameter δ (omitting the \tilde{y}_E argument inside p_G operating through the $Q_G(\tilde{y}_E)$ and $s_G(\tilde{y}_E)$ functions for clarity):

$$Q_G(\tilde{y}_E) \left[-f(\tilde{y}_E) (1-\delta) \alpha_G(\tilde{y}_E) \frac{\partial p_G(Q_G, s_G)}{\partial Q_G} + \frac{\partial p_G(Q_G, s_G)}{\partial s_G} s'_G(\tilde{y}_E) \right] = f(\tilde{y}_E) \{ (1-\delta) \alpha_G(\tilde{y}_E) [p_G(Q_G, s_G) - v_G w] - \alpha_C(\tilde{y}_E) (p-w) \}. \quad (3.36)$$

By totally differentiating Equation (3.36), and cancelling it so that the GI production rights are still allocated to producers under exclusionary delineation, we obtain the adaptation of the GI area of production at the margin following an increase in δ (omitting the Q_G and s_G arguments in the GI price function p_G , and the \tilde{y}_E argument in Q_G and s_G):

$$\frac{d\tilde{y}_E}{d\delta} = \frac{1}{1-\delta} \left\{ 3Q'_G Q_G \frac{\partial p_G}{\partial Q_G} + Q'_G (p_G - v_G w) + Q_G s'_G \left(\frac{\partial p_G}{\partial s_G} + \frac{\partial^2 p_G}{\partial Q_G \partial s_G} Q_G \right) \right\} \frac{\partial^2 \Pi_G(\tilde{y}_E, \delta)}{\partial \tilde{y}^2}. \quad (3.37)$$

where the denominator of Equation (3.37), namely $\frac{\partial^2 \Pi_G(\tilde{y}_E, \delta)}{\partial \tilde{y}^2}$ defined as in Equation (3.46) in 3.C.2, must be negative, to ensure concavity of profits. The numerator of Equation (3.37), which is $-\frac{\partial^2 \Pi_G(\tilde{y}_E, \delta)}{\partial \delta \partial \tilde{y}}$, measures the variation in marginal profitability of exclusion with marginal variations in climate conditions. Its sign is ambiguous¹⁶ and ultimately depends on the strength of climate change δ . Using the expression of inverse demand function in Equation (3.4), we simplify its expression and we obtain:

$$-\frac{\partial^2 \Pi_G(\tilde{y}_E, \delta)}{\partial \delta \partial \tilde{y}} = (1-\delta) \left[4 \frac{Q_G Q'_G}{(1-\delta)^2} \frac{\partial p_G}{\partial Q_G} + 2 \frac{Q_G^2}{(1-\delta)^2} s'_G \frac{\partial^2 p_G}{\partial Q_G \partial s_G} \right] + \bar{\theta} \left(\frac{Q'_G}{1-\delta} s_G + \frac{Q_G}{1-\delta} s'_G \right) - v_G w \frac{Q'_G}{1-\delta}. \quad (3.38)$$

¹⁶See 3.C.3.1 for detailed interpretations of the terms in Equation (3.37) and their respective signs.

Since $Q_G/(1-\delta) = \int \alpha_G(y) f(y) dy$ and $Q'_G/(1\delta) = -\alpha_G(\tilde{y}_E) f(\tilde{y}_E)$, the variations of the marginal profitability of exclusion with the climate-induced parameter, namely $-\frac{\partial^2 \Pi_G(\tilde{y}_E, \delta)}{\partial \delta \partial \tilde{y}}$, are a linear function of δ , where $-\left[4 \frac{Q_G Q'_G}{(1-\delta)^2} \frac{\partial p_G}{\partial Q_G} + 2 \frac{Q_G^2}{(1-\delta)^2} s'_G \frac{\partial^2 p_G}{\partial Q_G \partial s_G}\right]$ is the slope and the rest of the terms form the intercept.

Consider the most extreme climate scenario, measured with parameter $\bar{\delta}$, where producers cannot any longer allocate their land to the GI, except the most efficient producers with land characteristics \bar{y} . Further, $\bar{\delta}$ is defined equivalently as in the open delineation case by the expression in Equation (3.32). Note that for $\delta = \bar{\delta}$, the aggregate quantity of GI is zero and the variations of the marginal profitability of exclusion with the climate-induced parameter (numerator in Equation (3.37)) reduces to $Q'_G(p_G - v_G w)$, which is negative. Therefore, in the neighborhood of $\bar{\delta}$, $-\frac{\partial^2 \Pi_G(\tilde{y}_E, \delta)}{\partial \delta \partial \tilde{y}}$ is always negative, that is, the marginal profitability of exclusion increases with δ ($\frac{\partial^2 \Pi_G(\tilde{y}_E, \delta)}{\partial \delta \partial \tilde{y}} > 0$) and $\frac{d\tilde{y}_E}{d\delta} > 0$.

Next, the linear expression in Equation (3.38) increases with δ on $[0, \bar{\delta}]$ if the following condition is satisfied:

$$2Q'_G \frac{\partial p_G}{\partial Q_G} \leq -Q_G s'_G \frac{\partial^2 p_G}{\partial Q_G \partial s_G} \Leftrightarrow -2\varepsilon_{Q_G/\tilde{y}} \leq \varepsilon_{s_G/\tilde{y}}, \quad (3.39)$$

and the expression decreases with δ on $[0, \bar{\delta}]$ if the following condition is satisfied:

$$2Q'_G \frac{\partial p_G}{\partial Q_G} > -Q_G s'_G \frac{\partial^2 p_G}{\partial Q_G \partial s_G} \Leftrightarrow -2\varepsilon_{Q_G/\tilde{y}} > \varepsilon_{s_G/\tilde{y}}. \quad (3.40)$$

When $-2\varepsilon_{Q_G/\tilde{y}} \leq \varepsilon_{s_G/\tilde{y}}$, the linear expression in Equation (3.38) always increases with δ . As it is negative at $\delta = \bar{\delta}$; it is then always negative over the whole range of climate scenarios; in other words, $-\frac{\partial^2 \Pi_G(\tilde{y}_E, \delta)}{\partial \delta \partial \tilde{y}} \leq 0$ for all δ in $[0, \bar{\delta}]$. As a result, $\frac{d\tilde{y}_E}{d\delta} > 0$ and we obtain the second part of the adaptation response in Proposition 3.3.

Now, in the situation where $-2\varepsilon_{Q_G/\tilde{y}} > \varepsilon_{s_G/\tilde{y}}$, the linear expression in Equation (3.38) always decreases with δ . Therefore, at $\delta = \bar{\delta}$ we have that $-\frac{\partial^2 \Pi_G(\tilde{y}_E, \delta)}{\partial \delta \partial \tilde{y}} < 0$, and $-\frac{\partial^2 \Pi_G(\tilde{y}_E, \delta)}{\partial \delta \partial \tilde{y}} = 0$ for $\delta < \hat{\delta}$ at $\hat{\delta}_E$, which is the value of the climate parameter where there are no adaptation in GI area with changes in climatic conditions under exclusionary delineation. From Equ-

tion (3.37), $\hat{\delta}_E$ is implicitly defined by:

$$3Q'_G Q_G \frac{\partial p_G}{\partial Q_G} + Q'_G (p_G - v_G w) + Q_G s'_G \left(\frac{\partial p_G}{\partial s_G} + \frac{\partial^2 p_G}{\partial Q_G \partial s_G} Q_G \right) = 0. \quad (3.41)$$

As we consider deviations from the optimum of the GI industry profits under exclusionary delineation, the term $Q'_G (p_G - v_G w)$ corresponds to the opposite of the marginal revenue of exclusion minus the land rent for the commodity at the border (see the FOC of the exclusionary delineation program in Equation (3.12)), the implicit expression of $\hat{\delta}_E$ in Equation (3.41) can be expressed as follows:

$$\hat{\delta}_E = 1 - \left\{ \frac{f(\tilde{y}_E) \alpha_C(\tilde{y}_E) (p - w)}{\int_{\tilde{y}_E}^{\bar{y}} \alpha_G(u) f(u) du \left[\frac{\partial^2 p_G}{\partial Q_G \partial s_G} s'_G(\tilde{y}_E) \int_{\tilde{y}_E}^{\bar{y}} \alpha_G(u) f(u) du - 2 \frac{\partial p_G}{\partial Q_G} f(\tilde{y}_E) \alpha_G(\tilde{y}_E) \right]} \right\}^{1/2}. \quad (3.42)$$

Finally, if in the historical exclusionary delineation, $\tilde{y}_E(\delta | \delta = 0)$, the marginal profitability of exclusion increases with climate-induced deterioration in the GI conditions of production, $\left. \frac{\partial^2 \Pi_G(\tilde{y}_E, \delta)}{\partial \delta \partial \tilde{y}} \right|_{\delta=0} \geq 0$, then $\hat{\delta}_E \leq 0$. So, the numerator in Equation (3.37) is always negative all along the interval of climate parameter, that is $-\frac{\partial^2 \Pi_G(\tilde{y}_E, \delta)}{\partial \delta \partial \tilde{y}} \leq 0$ for all δ in $[0, \bar{\delta}]$. Thus, it results in the second part of the adaptation response in Proposition 3.3, i.e. $\frac{d\tilde{y}_E}{d\delta} \geq 0$ for all δ in $[0, \bar{\delta}]$.

By contrast, if in the historical exclusionary delineation, the marginal profitability of exclusion decreases with climate-induced deterioration in the GI conditions of production, $\left. \frac{\partial^2 \Pi_G(\tilde{y}_E, \delta)}{\partial \delta \partial \tilde{y}} \right|_{\delta=1} < 0$, then $\hat{\delta}_E$ is such that $0 < \hat{\delta}_E < \bar{\delta}$. In this case, there is an incentive to increase the area of production because the marginal profitability of exclusion decreases for some climate-induced deterioration in the conditions of GI production. Then, the numerator in Equation (3.37) is positive, that is, $-\frac{\partial^2 \Pi_G(\tilde{y}_E, \delta)}{\partial \delta \partial \tilde{y}} \geq 0$ for δ in $[0, \hat{\delta}_E]$, and strictly negative for δ in $]\hat{\delta}_E, \bar{\delta}]$, resulting in the adaptation response in the first part of Proposition (3.3).

Also, note that the variations of the marginal profitability of exclusion with climate-

induced deterioration in the conditions of GI production when evaluated at the historical monopoly outcome derives as follows:

$$\begin{aligned} \left. \frac{\partial^2 \Pi_G(\tilde{y}_E, \delta)}{\partial \delta \partial \tilde{y}} \right|_{\delta=0} &= -Q_G(\tilde{y}_E^H) \left[\left. \frac{\partial^2 p_G}{\partial Q_G \partial s_G} \right|_{\tilde{y}_E=\tilde{y}_E^H} Q_G(\tilde{y}_E^H) s'_G(\tilde{y}_E^H) + 2 \left. \frac{\partial p_G}{\partial Q_G} \right|_{\tilde{y}_E=\tilde{y}_E^H} Q'_G(\tilde{y}_E^H) \right] \\ &\quad + f(\tilde{y}_E^H) \alpha_C(\tilde{y}_E^H) (p - w), \end{aligned} \quad (3.43)$$

where the first term in Equation (3.43) measures the diminution in the marginal profitability of exclusion under a climate-induced deterioration in the GI conditions of production, which is associated with the diminution in the marginal benefits of exclusion. This diminution in the marginal benefits of exclusion results from the decrease of the GI production from the included producers under climate change, and this is not compensated for by the increase in willingness to pay for quality. The second term in Equation (3.43) measures the increase in the marginal profitability of exclusion under a climate-induced deterioration in the GI conditions of production, which is associated with the diminution of the marginal costs of exclusion. This component interpretes also as the decrease of the foregone profits associated to the marginally excluded producers under climate change, because the producers at the border potentially produce less GI under climate change.

the same market size and taste preferences, and the same unit labor requirement), the differences between their adaptation can be interpreted as being due to the differences in land characteristics heterogeneity. The effect of a mean-preserving spread of the land characteristic distribution on the adaptation schedule (focusing on cases presenting some extension in the GI area, as in the first parts of Propositions 3.2 and 3.3) is illustrated in the Figures 3.3.

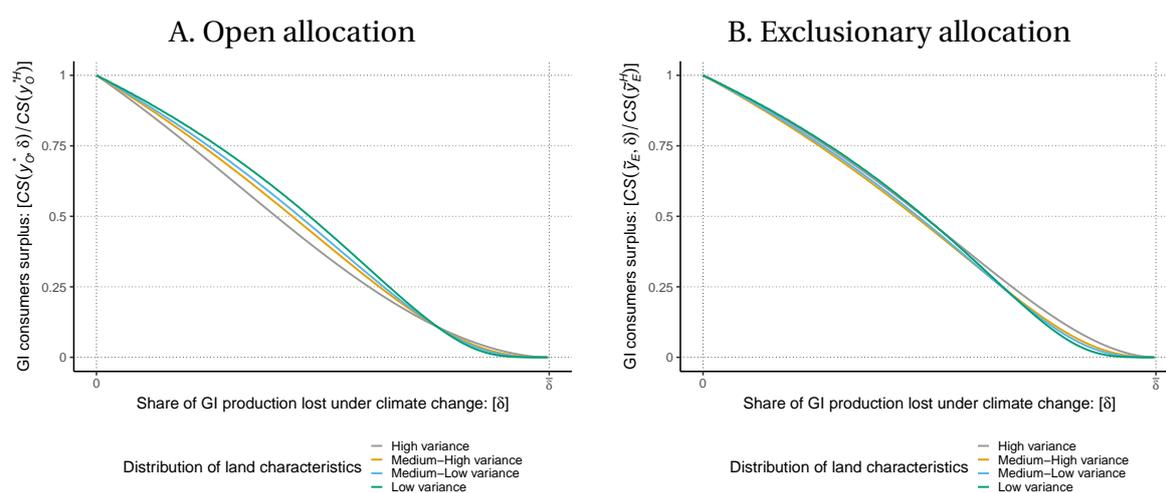
The four distributions considered are bounded on $\mathcal{Y} = [1, 3]$ with a mean of 2, using a uniform distribution (high variance), and three upper-truncated Frechet distributions with shape and scale parameters of approximately (2.2, 0.85), (3.5, 0.85) and (6, 0.9) for the medium-high variance, medium-low variance and low variance respectively. Illustrations are obtained for a linear relationship between land characteristics and individual GI production where $\alpha_G(y) = 0.5y$, for a constant individual commodity production with $\alpha_C(y) = 1$, and the other parameters are $p = 1$, $w = 0.75$, $v_G = 1.25$, $\Theta = [0, 1]$, and $N = 1.5$.

With a higher degree of heterogeneity, the level of land characteristics at the border is more adjustable both under open and under exclusionary delineation and allows for more flexible adaptation of land allocation (upper panel). The adaptation of the quantity adjustment, however, is not as clear, since marginal variation of the GI border can lead to different variations of the quantity of producers between distributions (middle panel). It appears that quantity adjustments are more responsive both in open and in exclusionary delineations with homogeneous land characteristics, since inward and outward adjustments of the border at the aggregate scale are magnified when producers tend to have homogeneous conditions of production. In addition, aggregate profit losses tend to be mitigated when the variance in land characteristics is high (bottom panel; note that variations are expressed relative to the historical situation, so as to be able to compare variation between distributions). Under exclusionary delineation and for moderate climate scenarios, the industry can benefit both from more various producers, to more easily extend the exclusive area of production, and from a higher concentration of producers with high land characteristics, which maintain a higher level of quality under Assumption 4.B. All else equal, a higher heterogeneity of land seems to increase the extensive margin of relocation for the exclusionary industry. For extreme climate scenarios, the exclusionary industry can generate higher profits when land

is heterogeneous, as it can concentrate its production on more numerous efficient GI producers than in a situation with low variance. Under open delineation, homogeneous land characteristics tend to accelerate the loss of comparative advantage of all producers, and may lead in the case of perfectly homogeneous producers to a binary situation in which the GI industry brutally disappears under marginal deterioration of climate conditions.

From the perspective of GI consumers, the heterogeneity of land characteristics has ambiguous effects. GI consumers' surplus as a function of the potential loss under climate change is represented on Figure 3.B.2. Under open delineation and for moderate climate scenarios, homogeneous parcels limit shrinkage in consumers surplus as more producers tend to allocate their land to the GI in response to supply rarefaction, and therefore better limit the supply shortage. However, under more extreme climate scenarios, the GI industry shrinks more rapidly with more homogeneous producers, so that GI consumer's surplus diminishes more rapidly. Under exclusionary delineation, differences in GI consumer surplus are tenuous, and for extreme climate scenarios, a higher degree of heterogeneity in land characteristics allows the production of GI to better resist climate change and better improve consumer surplus.

Figure 3.B.2: GI consumers surplus under climate change.



Variations of the GI consumers' surplus as a function of the variations in the strength of climate change, under open delineation (column A) and under exclusionary delineation (column B) for the four distributions of land characteristics which are a mean-preserving spread transformation of each other.

3.C Additional materials

3.C.1 Details on the construction of the demand for the GI, and alternative assumption regarding the substitution for a lower quality product

3.C.1.1 Details on the construction of the demand for the GI

In the framework of the chapter, I consider the simple unit-demand model of the vertical product differentiation literature as in Mussa and Rosen (1978). In addition, there is only one quality available on the market, i.e. the GI quality, denoted with s_G . When consuming the GI good of quality s_G at price p_G , the consumer of type θ has utility of the form $u = \theta s_G - p_G$, while utility is zero when not consuming the GI good. Then the consumer chooses to consume when his utility accruing from the consumption of the GI good is positive. Consumers with $\theta \in [\hat{\theta}, \bar{\theta}]$ consume the GI good, where $\hat{\theta} \equiv \frac{p_G}{s_G}$ is the indifferent consumer, i.e. the one indifferent between buying and not buying the GI good. The integration of the unit demand over the uniformly distributed consumers that effectively consume gives the quantity demanded for a given price p_G and quality s_G , i.e. $Q_G^d(p_G, s_G) = N \frac{(\bar{\theta} - p_G/s_G)}{\bar{\theta} - \hat{\theta}}$. Then, inverting this demand yields the inverse demand function in Equation (3.4), under the restriction that price for the GI is positive i.e. $Q_G < N \frac{\bar{\theta}}{\bar{\theta} - \hat{\theta}}$.

According to the inverse demand function in Equation (3.4), to observe an additional sell of the GI product the price must decrease or quality increases, or both. The inverse demand function is decreasing in quantity, i.e. $\frac{\partial p_G(Q_G, s_G)}{\partial Q_G} < 0$, or in other words marginal utility of consumption is decreasing. In addition, the marginal willingness to pay for a given quantity increases with the quality, i.e. $\frac{\partial p_G(Q_G, s_G)}{\partial s_G} > 0$, meaning quality s_G operates as a demand shifter. Finally, the demand schedule incorporates a negative effect of quality variation on the slope of the inverse demand curve, i.e. $\frac{\partial^2 p_G(Q_G, s_G)}{\partial s_G \partial Q_G} < 0$. In other words, it means that the marginal value of quality is below the average valuation of quality for a given quantity consumed.

3.C.1.2 Alternative assumption to allow for a lower quality substitute of the GI

In this paragraph, I present an alternative representation of the demand structure. I now assume that the commodity is the low quality substitute of the GI, with quality denoted s . The quality of the commodity is set by some regulatory standards and is exogenous. For our results to be valid under this framework, I must additionally assume that the market segment of the GI is of small size relative to that of the commodity. In other words, the commodity producers supply to a broad range of consumers preferences while the GI is consumed by a relatively small portion of consumers, that is, those with the highest preferences for quality.¹⁷ This ensures that the supply from the producers considered has no effect on the commodity market and that the commodity market will not react to quality and quantity changes occurring on the GI market. In other words, the demand can substitute between the consumption of the GI and the commodity, but only the outcome on the commodity market affects the GI market while the converse is not true.

Again, consumers are heterogeneous in their preferences for quality, and θ the taste parameter is uniformly distributed on $[\underline{\theta}, \bar{\theta}]$. The consumer decision consist in buying the product that brings the highest utility:

$$u = \begin{cases} \theta s_G - p_G & \text{when the GI product is bought} \\ \theta s - p & \text{when the commodity is bought} \\ 0 & \text{otherwise} \end{cases} \quad (3.44)$$

The consumers with θ in $[\hat{\theta}, \bar{\theta}]$, where $\hat{\theta} = \frac{p_G - p}{s_G - s}$, buy the GI product. Then, the consumers with θ in $[\tilde{\theta}, \hat{\theta}]$, where $\tilde{\theta} = \frac{p}{s}$, consume the low quality product, and consumers with θ in $[0, \tilde{\theta}]$ buy nothing. By integrating the demand of each individual consumer over the subset

$[\hat{\theta}, \bar{\theta}]$, we obtain the demand for the GI, as follows, $Q_G = N \frac{\bar{\theta} - \frac{p_G - p}{s_G - s}}{\bar{\theta} - \hat{\theta}}$. Then, inverting the

¹⁷This can be further modeled with restrictions on the range of possible quality supplied \mathcal{Q} relative to the range of preferred quality Θ . The situation depicted here corresponds to a significantly larger range of preferences for quality, namely $[\underline{\theta}, \bar{\theta}]$, than the range of potential quality supplied, namely $[\underline{y}, \bar{y}]$. In this situation, there is an important demand for differentiation, but the differentiation of the GI product supplied is limited.

demand, it yields:

$$p_G(Q_G, s_G) = (s_G - s) \left[\bar{\theta} - \frac{Q_G}{N} (\bar{\theta} - \theta) \right] + p. \quad (3.45)$$

In this framework, the demand price for the GI corresponds now to the price of the commodity plus a premium depending on the quality differential, measured by $s_G - s$. The greater is the additional quality of the GI relative to the commodity the higher the demand price, all else equal. Using the demand schedule in Equation (3.45) only changes interpretations, as variations in quality are now expressed relatively to the quality standard of the commodity.

3.C.2 On the concavity of the GI aggregate net land rent and the welfare function

In this appendix, I present sufficient conditions for the GI aggregate net land rent and the welfare function to be concave so that $\Pi_G(\tilde{y}_E)$ defined by first-order condition in Equation (3.12) is a global maximum, and that $W(\tilde{y}_B)$ defined by the first-order condition in Equation (3.14) is also a global maximum. Necessary *and* sufficient conditions to obtain a global maximum are not directly interpretable and are beyond the scope of this appendix.

3.C.2.1 Sufficient conditions for the GI aggregate net land rent to be concave

I hereby use the prime notation to refer to first-order and second-order derivative of the functions of one variable, such as $Q_G(y)$ and $s_G(y)$. I also simplify notations of p_G by voluntarily omitting the arguments Q_G and s_G . When derivating function $\Pi_G(\tilde{y})$ twice, it yields:

$$\begin{aligned} \frac{\partial^2 \Pi_G(\tilde{y})}{\partial \tilde{y}^2} &= 2Q'_G \left(\frac{\partial p_G}{\partial Q_G} Q'_G + \frac{\partial p_G}{\partial s_G} s'_G \right) + Q_G \left(\frac{\partial p_G}{\partial Q_G} Q''_G + 2 \frac{\partial^2 p_G}{\partial s_G \partial Q_G} s'_G Q'_G + \frac{\partial p_G}{\partial s_G} s''_G \right) + Q''_G p_G \\ &\quad - Q''_G v_G w - [\alpha_C(\tilde{y}) f'(\tilde{y}) + \alpha'_C(\tilde{y}) f(\tilde{y})] (p - w). \end{aligned} \quad (3.46)$$

As standard in the monopoly theory, there is a maximum for the monopoly's program when the objective function is concave, that is when the slope of the marginal revenue (three first terms in Equation (3.46)) is smaller than the slope of the marginal costs (two last terms in

Equation (3.46)). However, what is not standard here is that the GI industry in monopoly operates on a variety of parcels which can produce varying quantities, have different opportunity costs, and can affect quality. More precisely, looking at Equation (3.46), the concavity of aggregate net land rent depends on (i) the shape of the GI supply $Q_G(\tilde{y})$, (ii) the shape of the commodity supply (i.e. the convexity of the opportunity costs), and (iii) the shape of the quality s_G with respect to the delineated area. All three of them ultimately depend on the distribution of land characteristics f . By reordering terms in Equation (3.46), it yields:

$$\begin{aligned} \frac{\partial^2 \Pi_G(\tilde{y})}{\partial \tilde{y}^2} &= \frac{\partial p_G}{\partial Q_G} \left[2(Q'_G)^2 + Q_G Q''_G \right] + 2Q'_G s'_G \left(\frac{\partial p_G}{\partial s_G} + Q_G \frac{\partial^2 p_G}{\partial s_G \partial Q_G} \right) + \frac{\partial p_G}{\partial s_G} Q_G s''_G \\ &+ Q''_G (p_G - v_G w) - [\alpha_C(\tilde{y}) f'(\tilde{y}) + \alpha'_C(\tilde{y}) f(\tilde{y})] (p - w). \end{aligned} \quad (3.47)$$

I decompose this function in three parts and show that their respective sign can be determined according to global properties of the supply function and the distribution of land attributes. The GI aggregate net land rent is concave when the following three conditions are verified:

1. $\frac{\partial p_G}{\partial Q_G} \left[2(Q'_G)^2 + Q_G Q''_G \right] < 0$

This condition is always satisfied when the supply function is log-concave. Note that $\frac{\partial p_G}{\partial Q_G}$ is negative. For the terms in the square brackets to be positive, and to ensure the negativity of the whole term, the log-concavity of Q_G is a sufficient condition. Indeed, Q_G log-concave ensures $(Q'_G)^2 \geq Q_G Q''_G$.

2. $2Q'_G s'_G \left(\frac{\partial p_G}{\partial s_G} + Q_G \frac{\partial^2 p_G}{\partial s_G \partial Q_G} \right) + \frac{\partial p_G}{\partial s_G} s''_G < 0$

This condition is satisfied when the survival function of the land characteristics, that is, $1 - F(\tilde{y})$, is log-concave, or if not, when $s_G(\tilde{y})$ not too convex. In other words quality must increase at a decreasing rate, or at a not too increasing rate for the aggregate net land rent to be concave. Note that under Assumption 4.A, this term does not occur in the determination of the concavity. Let us show this point in detail.

The combination of these two terms is negative when the following inequality is veri-

fied:

$$-\frac{s''_G}{s'_G} \geq 2Q'_G s'_G \left[1 + Q \frac{\frac{\partial^2 p_G}{\partial s_G \partial Q_G}}{\frac{\partial p_G}{\partial s_G}} \right] \quad (3.48)$$

The right-handside term of inequality (3.48) is always negative. Indeed, $\frac{\partial p_G}{\partial s_G} + Q \frac{\partial^2 p_G}{\partial s_G \partial Q_G}$ is always positive. This term interpretes as the marginal revenue associated with quantity variation, which is always increasing with quality increments on the portion where marginal revenue with quantity is positive. To show this, recall that marginal revenue with quantity variation is $\frac{\partial p_G}{\partial Q_G} Q_G + p = s_G \left[\bar{\theta} - 2 \frac{Q_G}{N} (\bar{\theta} - \underline{\theta}) \right]$, which derivative with respect to quality is $\frac{\partial^2 p_G}{\partial s_G \partial Q_G} Q_G + \frac{\partial p_G}{\partial s_G} = \bar{\theta} - 2 \frac{Q_G}{N} (\bar{\theta} - \underline{\theta})$. Using our assumption on demand, it is positive if the following condition is satisfied:

$$\frac{\partial p_G}{\partial s_G} + Q_G \frac{\partial^2 p_G}{\partial s_G \partial Q_G} \geq 0 \Leftrightarrow 2 \frac{\partial p_G}{\partial s_G} - \bar{\theta} > 0 \Leftrightarrow \frac{\partial p_G}{\partial s_G} \geq \bar{\theta}/2 \Leftrightarrow \hat{\theta} \geq \bar{\theta}/2 \quad (3.49)$$

where $\hat{\theta} = p_G/s_G = \frac{\partial p_G}{\partial s_G}$ corresponds to the indifferent consumer, i.e. the consumer at the margin. The above condition in Equation (3.49) is always verified for the positive portion of marginal revenue (in other words the increasing part of total revenue). Marginal revenue is decreasing in Q_G , equals $s_G \bar{\theta}$ for $Q_G = 0$ and equals zero at $Q_G = N \frac{\bar{\theta}/2}{\bar{\theta} - \underline{\theta}}$, which corresponds to the situation where the marginal consumer is $\hat{\theta} = \bar{\theta}/2$. Thus, $\frac{\partial p_G}{\partial s_G} + Q \frac{\partial^2 p_G}{\partial s_G \partial Q_G}$ is positive as long as the optimum is defined on positive portion of marginal revenue, which is here the case, as marginal cost is positive.

Now, coming back to the condition in Equation (3.48). The condition is always satisfied when s''_G is negative (as s'_G is positive), or the ratio s''_G/s'_G being positive and small. In other words quality must increase but not too quickly with the supply control. Note that there is a family of distribution of land characteristics that will always verify the concavity of s_G : the log-concave survival function of land characteristics,

namely $1 - F(\tilde{y})$. Indeed, s''_G and s'_G have the following derivations:

$$s'_G(\tilde{y}) = \frac{f(\tilde{y})}{[1 - F(\tilde{y})]} [s_G(\tilde{y}) - \tilde{y}] \quad (3.50)$$

$$s''_G(\tilde{y}) = \frac{f'(\tilde{y}_G) [1 - F(\tilde{y}_G)] - f(\tilde{y})^2}{[1 - F(\tilde{y}_G)]^2} [s(\tilde{y}_G) - \tilde{y}_G] + \frac{f(\tilde{y}_G)}{1 - F(\tilde{y}_G)} (s_{\tilde{y}} - 1) \quad (3.51)$$

As a result, the ratio of the two reduces to:

$$\frac{s''_G(\tilde{y})}{s'_G(\tilde{y})} = \frac{f' [1 - F(\tilde{y})] - (f(\tilde{y}))^2}{f(\tilde{y}) [1 - F(\tilde{y})]} + \frac{s'_G(\tilde{y}) - 1}{s_G(\tilde{y}) - \tilde{y}} \quad (3.52)$$

s''_G/s'_G is always negative if $1 - F$ (also called the survival function) is a log-concave function. According to An (1998), when $1 - F$ is log-concave, it implies $f'(\tilde{y}) [1 - F(\tilde{y})] - [f(\tilde{y})]^2 \leq 0$ and $s'_G(\tilde{y}) \leq 1$, and as a result $s''_G/s'_G < 1$.

$$3. Q''_G(p_G - v_G w) - [\alpha_C(\tilde{y}) f'(\tilde{y}) + \alpha'_C(\tilde{y}) f(\tilde{y})] (p - w) < 0:$$

This condition is satisfied when marginal cost is increasing. Indeed, the opposite of the above left-handside terms measure the shape of the marginal cost (variable production cost plus opportunity costs), at constant GI price. As standard in monopoly literature, profits are concave as long as the marginal cost is increasing (and thus costs are convex). This condition can be further interpreted in terms of properties on the land characteristics distribution and on the influence of land characteristics on the productivity of land parcels. Developing these two terms using expressions of supply and opportunity costs, and evaluating them at the optimum value \tilde{y}_E :

$$\begin{aligned} & -Q''_G(p_G - v_G w) + [\alpha_C(\tilde{y}) f'(\tilde{y}) + \alpha'_C(\tilde{y}) f(\tilde{y})] (p - w) = \\ & -[-\alpha'_G(\tilde{y}_E) f(\tilde{y}_E) - \alpha_G(\tilde{y}_E) f'(\tilde{y}_E)] (p_G - v_G w) + [-\alpha'_C(\tilde{y}_E) f(\tilde{y}_E) - \alpha_C(\tilde{y}_E) f'(\tilde{y}_E)] (p - w) = \\ & f'(\tilde{y}_E) [\alpha_G(\tilde{y}_E) (p_G - v_G w) - \alpha_C(\tilde{y}_E) (p - w)] + f(\tilde{y}_E) [\alpha'_G(\tilde{y}_E) (p_G - v_G w) - \alpha'_C(\tilde{y}_E) (p - w)] \end{aligned} \quad (3.53)$$

The condition for marginal cost to be increasing is therefore the following:

$$f(\tilde{y}_E) [\alpha'_G(\tilde{y}_E)(p_G - v_G w) - \alpha'_C(\tilde{y}_E)(p - w)] + f'(\tilde{y}_E) [\alpha_G(\tilde{y}_E)(p_G - v_G w) - \alpha_C(\tilde{y}_E)(p - w)] \geq 0 \quad (3.54)$$

which is always locally verified as long as f is increasing or not too decreasing in the neighborhood of \tilde{y}_E . Indeed, placing at the optimum of the GI industry under exclusionary delineation, we know that the marginal parcel has a greater net land rent for the GI, i.e.:

$$\alpha_G(\tilde{y}_E)(p_G - v_G w) > \alpha_C(\tilde{y}_E)(p - w) \quad (3.55)$$

In addition, the increasing shape of α along \mathcal{Y} implies $\alpha'_G/\alpha_G > \alpha'_C/\alpha_C$. Multiplying the left-handside by α'_C/α_C and the right-handside by α'_G/α_G of Equation (3.55) maintains the inequality, and it yields:

$$\alpha'_G(\tilde{y}_E)(p_G - v_G w) > \alpha'_C(\tilde{y}_E)(p - w) \quad (3.56)$$

Hence, from inequality (3.54), as long as f' is positive, the condition is always verified. Now, if f' is negative, the following condition must be satisfied for the marginal cost to be increasing:

$$\frac{\left[\frac{\alpha'_G(\tilde{y}_E)(p_G - v_G w) - \alpha'_C(\tilde{y}_E)(p - w)}{\alpha_G(\tilde{y}_E)(p_G - v_G w) - \alpha_C(\tilde{y}_E)(p - w)} \right]}{\frac{f'(\tilde{y}_E)}{f(\tilde{y}_E)}} \geq 1 \quad (3.57)$$

The left-handside term in inequality (3.57) measures the elasticity of the exclusion costs at the margin. It measures the percentage variation of the individual amount that the industry has to pay to compensate the parcel at the margin of its exclusion, for a constant GI price. In other words, Inequality (3.57) says that when the number of excluded producers decreases at the border, that is, $f'/f < 0$, the marginal cost

convexity is ensured when the exclusion cost marginally increases more than a unit rate increase.

3.C.2.2 Sufficient conditions for the welfare function to be concave

When deriving twice the welfare function with respect to \tilde{y} , it yields:

$$\begin{aligned} \frac{\partial^2 W(\tilde{y})}{\partial \tilde{y}^2} = & s_G''(\tilde{y}) \int_0^{Q_G(\tilde{y})} \frac{\partial p_G(v, s_G(\tilde{y}))}{\partial s_G} dv + Q_G'(\tilde{y}) \left[\frac{\partial p_G}{\partial Q_G} Q_G'(\tilde{y}) + 2 \frac{\partial p_G}{\partial s_G} s_G'(\tilde{y}) \right] \\ & + (p_G - v_G w) Q_G'' + (p - w) [f'(\tilde{y}) \alpha_G(\tilde{y}_E) + f(\tilde{y}) \alpha_G'(\tilde{y})] \end{aligned} \quad (3.58)$$

I analyze the sign of $\frac{\partial^2 W(\tilde{y})}{\partial \tilde{y}^2}$ term by term. First, the concavity of the welfare function is ensured as long as the survival function of land characteristics, that is, $1 - F(\tilde{y})$ is log-concave since it ensures $s_G'' \leq 0$, or if not, $s_G(\tilde{y})$ needs to be not too convex. Note that this condition also ensures the profit function to be concave and is given in more details in the above subsection. The second term, namely $Q_G'(\tilde{y}) \left[\frac{\partial p_G}{\partial Q_G} Q_G'(\tilde{y}) + 2 \frac{\partial p_G}{\partial s_G} s_G'(\tilde{y}) \right]$, is always negative. Finally, the marginal cost of exclusion (two last terms of Equation (3.58)) must be increasing (similar condition than for the aggregate net land rent function to be concave, as in Equation (3.54)).

3.C.3 Detailed derivatives of the comparative statics of the area of production under climate change

In this appendix, I first present the detailed derivations of the comparative statics of the GI area of production with a climate-induced change in the conditions of GI production, as presented in Proposition 3.3. Then, I present the derivative of the comparative statics when assuming that commodity production is also altered by climate change.

3.C.3.1 Adaptation of the exclusionary GI industry

When totally differentiating Equation (3.12) and cancelling it so that GI production rights are still allocated to producers under exclusionary delineation, we obtain the following expression (omitting the \tilde{y}_E argument in α_G , Q_G and s_G functions for clarity):

$$\begin{aligned} \frac{d\tilde{y}_E}{d\delta} &= -\frac{\frac{\partial^2 \Pi_G(\tilde{y}_E, \delta)}{\partial \delta \partial \tilde{y}}}{\frac{\partial^2 \Pi_G(\tilde{y}_E, \delta)}{\partial \tilde{y}^2}} \\ &= -\frac{\frac{1}{1-\delta} \left[-Q_G \left(\frac{\partial p_G}{\partial Q_G} Q'_G + \frac{\partial p_G}{\partial s_G} s'_G \right) - Q_G \left(\frac{\partial p_G}{\partial Q_G} Q'_G + \frac{\partial^2 p_G}{\partial Q_G \partial s_G} s'_G Q_G \right) - Q'_G (p_G - v_G w) - Q'_G \frac{\partial p_G}{\partial Q_G} Q_G \right]}{\frac{\partial^2 \Pi_G(\tilde{y}_E, \delta)}{\partial \tilde{y}^2}} \end{aligned} \quad (3.59)$$

The term $\frac{\partial^2 \Pi_G(\tilde{y}_E, \delta)}{\partial \delta \partial \tilde{y}}$ in the numerator of Equation (3.59) measures the variation of marginal profitability of exclusion with climate-induced deteriorations in the conditions of production. The term-by-term interpretation of the numerator of the expression in Equation (3.59) is the following:

- The first term measures the increase of the marginal benefits from exclusion for all inside producers in the given area of production, which is induced by the decrease in GI aggregate supply following climate change. Associated with a deterioration in climatic conditions, $d\delta < 0$, this term is always negative, as for the given \tilde{y}_E , a lower amount of GI is produced, hence reducing marginal revenue from exclusion. This effect tends to push down marginal profits from exclusion.
- The second term measures the variation of the marginal benefits from exclusion induced by the price variation following climate-induced changes in GI supply, that is, whether the value of marginal benefits from exclusion accelerates or decelerates. Its sign is ambiguous. The first component measures the price deceleration associated with the negative effect of climate change on quantity. Indeed, the increase in price induced by the exclusion tends to be reduced as the rarefaction of supply following a marginal exclusion becomes lower. Meanwhile, the second component measures the price acceleration from the drop in quantity. Indeed, the marginal willingness to pay for quality improvement increases as the quantity supplied shrinks. A lower portion of demand is served by the industry, which under Assumption 3 has a greater marginal

willingness to pay for quality.

- The third term measures the variation of marginal exclusion costs for a given supply control when the GI quantity varies with climate change. For an increase in \tilde{y} , the marginal costs of exclusion of the industry corresponds to the foregone opportunities associated with the marginally excluded producers, or equivalently it corresponds to the compensation given to the producers outside the border that leaves them unchanged. But when climate change deteriorates the potential supply of all producers in the same proportion, the amount renounced by the industry is reduced, and therefore the marginal costs from exclusion are reduced. This effect tends to push up the marginal profits from exclusion when associated with a deterioration in climatic conditions.
- The final term measures the change in the value of the marginal exclusion costs, which is always negative as climate change decreases the quantity and in turn increases the GI price ($-Q'_G \frac{\partial p_G}{\partial Q_G} Q_G < 0$). So this effect tends to reduce the marginal profitability of exclusion and pushes to expand the area.

Finally, the sign of $\frac{\partial^2 \Pi_G(\tilde{y}_E, \delta_G)}{\partial \delta_G \partial \tilde{y}}$ is ambiguous and depends on the relative size of the effects that increase marginal profitability of exclusion, compared with the effects that decrease the marginal profitability from exclusion, which both depend on the strength of the effects of climate change. The resulting sign is explored in the proof of Proposition 3.3 in 3.A.3.

3.C.3.2 Comparative statics when climate change also alters the commodity production

The comparative statics of the market outcome under open and under exclusionary delimitations in Equation (3.28) and (3.36) in the case where $\delta_C = \delta$ are the following:

$$\frac{dy_O^*}{d\delta} = \frac{(1-\delta)\alpha_G \frac{\partial p_G}{\partial Q_G} Q_G}{(1-\delta)\alpha'_G [p_G(Q_G, s_G) - v_G w] - \alpha'_C (p-w) + (1-\delta)\alpha_G \left[\frac{\partial p_G(Q_G, s_G)}{\partial Q_G} Q'_G + \frac{\partial p_G(Q_G, s_G)}{\partial s_G} s'_G \right]} \quad (3.60)$$

$$\frac{d\tilde{y}_E}{d\delta} = \frac{Q_G \left(2 \frac{\partial p_G}{\partial Q_G} Q'_G + \frac{\partial^2 p_G}{\partial Q_G \partial s_G} s'_G Q_G \right)}{\frac{\partial^2 \Pi_G}{\partial \tilde{y}^2}} \quad (3.61)$$

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Conclusion

The work presented in this thesis addresses some of the economic issues related to climate change, and their application to the agricultural sector. Three levels of analysis have been successively privileged: the way economics is seizing on climate change; the design of policy instruments to mitigate greenhouse gas emissions; the analysis of the adaptation of agricultural production under Geographical Indication.

This thesis therefore examines three main questions. (i) How does economics, as a discipline, study climate change? (ii) What is the regulator's margin to implement a mitigation policy when there are costs to monitor greenhouse gases emissions? (iii) To what extent can production relocation strategies be implemented in an agricultural industry as constrained as that under Geographical Indication?

Main results

Chapter 1 shows that economics has produced a similar share of work on climate change as science as a whole. This production originates mainly from the field of energy and environmental economics. General economics journals and journals in the fields of development or transportation economics are giving a larger place to the topic in the recent years. In addition, articles related to climate change benefit from increased visibility by being published in journals with a higher than average impact factor, and by being cited more than other articles in the same journal. Finally, this production is characterized by a wide variety of issues addressed, which have changed over time. Initially, the central questions concerned mitigation policy instruments, and global welfare calculation under future and uncertain damages. In recent years, the field has been expanded to include the study of the impli-

cations of climate change by sector, and the analysis of the mechanisms between specific features of economic activity and greenhouse gas emissions.

Chapter 2, written with Stéphane De Cara and Pierre Alain Jayet, studies a neglected feature of carbon taxation when there are costs to monitor emissions: the possibility to still mitigate greenhouse gases emissions while optimally exempting agents from the scope of the policy. First, it highlights simple theoretical conditions for implementing a partial coverage that optimally reduces emissions and save monitoring costs. It stresses that the benefits from implementing a partial coverage depend on the ability for the regulator to efficiently select agents. This in turn ultimately depends on the quality of the information available to the regulator on the heterogeneity of abatement and monitoring costs. Second, it provides empirical assessments of the potential gains issued from a partial coverage on emissions from the agriculture in the European Union. Our work argues that even with substantial transaction costs, mitigation policy targeting agriculture can still be implemented when the regulator can exempt some farms from any requirements. Having detailed information regarding the distribution of per-farm abatement and monitoring costs allow to better approximate the optimal threshold than when relying on aggregate sectoral information.

Chapter 3, analyzes the potential for the agricultural supply under Geographical Indication to marginally relocate its production in the face of climate change. I build an original model which accounts for four features associated to the supply of agricultural products under Geographical Indication in the face of climate change. First, the product's quality depends on characteristics of land also affecting comparative advantage, and which are heterogeneously distributed across producers. Second, the area of production of the Geographical Indication is either open to any producers having a comparative advantage or delimited by the producers' organization to maximize the GI industry profits. Third, the relocation is materialized by changes in the area of production at the border of the historical one. Fourth, the relocation occurs as a result of a climate-related decline in the productivity of the Geographical Indication for all producers. Using this model, I explore whether the border marginally expands or shrinks in reaction to climate change. When the opportunity costs is less than the absolute value of the revenue variation due to climate change for the

producer at the border, the area of the Geographical Indication in the open-delimitation case can increase under moderate climate scenario. When decided by the producers' organization, the direction of the relocation crucially depends on the magnitude of the variation of the GI quality and quantity supplied with the marginal inclusion (or exclusion) of the producers at the border. Finally, the model points out that climate change reduces the rent associated with the Geographical Indication label, and the relocation redistributes the rent between historical producers and new entrants (or excluded producers). This relocation must necessarily be accompanied by transfers between producers if the Geographical indication is to succeed in adapting the area.

Limits and future research perspectives

One main limit of Chapter 1 is to constrain the corpus of economic works related to climate change to economic journals. I thus miss parts of the economists' contributions on the understanding of issues related to climate change. Economists join forces with scientists from other fields perhaps even more so in the case of climate change.

The bibliographic data extraction protocols could be adapted in order to identify economic contributions in general scientific journals. This would then require to characterize the economic dimension of these contributions. In addition, it may be difficult to balance contributions aimed at economists with contributions aimed at a general scientific audience. If a way of quantifying these contributions is possible, an additional research question would be to understand the role of these interdisciplinary collaborations in the field of climate change economics. What are they about and what do they provide to the economics of climate change? Then, a broader question also emerges about the place of economics in climate science as a whole: what does economics bring to the knowledge of climate change? In this respect, we could imagine studying the volume and the research questions of economic references in the IPCC reports.

Second, a general limitation of our categorization of research questions—also valid for any classification system—is that some categories do not form a fully consistent class. The

LDA used to categorize articles by topics can be further developed. It can be improved at the expense of a heavier computational burden by not restricting the vocabulary size. Also, instead of selecting the best number of topic using the AIC criterion, we could use the perplexity score (Griffiths and Steyvers, 2004). Perplexity is a statistical measure of how well a probability model predicts a sample. Given our word distributions in each topics, we can compare that to the actual distribution of words in our articles. This selection method does not negatively depend on the number of topics, as in the case of the AIC criterion. Using this approach, we would possibly obtain a richer categorization of the field, with potentially more consistent and narrower topics.

Chapter 2 shows that the magnitude of control costs is not a prohibitive argument for excluding the sector from climate policy. However, there are other arguments that override the need for rapid and effective actions to limit greenhouse gas emissions, and that apply to the policy design proposed in the chapter. I identify three arguments for which we might consider ways to address and overcome them: (i) the benefits of an environmental policy with partial coverage could be altered by strategic manipulation of the exemption threshold by agents, (ii) the potentially regressive effect of the carbon tax does not make it politically acceptable, (iii) the agricultural sector by forming an interest group could affect the setting of the threshold or the level of the tax.

First, the framework in Chapter 2 assumes that the exemption threshold is not manipulable by the firms. If this threshold is based on initial emissions, and if there is a delay between the announcement of the policy design and its implementation, firms are likely to adjust their outputs to be exempted from the tax. The extent and ease of these opportunistic behaviors raises questions.

Several avenues can be explored to incorporate the strategic manipulation of the exemption criterion by firms in our framework. An alternative policy design would be to let firms decide whether to be part of the mitigation policy and to be monitored while receiving a lump sum transfer in return. By using a standard principal-agent framework, we could determine the level of the tax, the lump-sum transfer and limiting the incentive for firms to manipulate the exemption criterion.

Also, instead of exempting on initial emissions, one solution is to exempt agents using secondary characteristics which are not, in the spirit of the attribute-based regulation presented in Ito and Sallee (2018). In our context, we could consider that the farm size is less manipulable than initial emissions. Then, to estimate the ease for farmers to manipulate the exemption criterion, we may benefit from the bunching approach Saez (2010). This empirical method has been developed in the context of public taxation to measure how individuals bunch at income levels with discontinuities in tax rates. This approach has also been used in the context of command-and-control policies, such as energy efficiency standards. For instance, Ito and Sallee (2018) use the approach to measure the extent to which car-makers adjust the weight of their vehicles in response to discontinuous fuel economy standards. Given the important discontinuities in current payments and transfers in the Common Agricultural Policy according to farm size, we might get an idea on the extent to which farmers adapt their farming decisions to discontinuities in policy design.

Second, the motivation for adopting a partial coverage was based on cost-effectiveness arguments. It might also have consequences for the income distribution among agents. In the benchmark configuration examined in Chapter 2 (emission tax of 25 €/tCO₂eq, constant per-farm MRV costs of 343 €) and in the absence of any other redistribution mechanism, an emission tax affecting all farms (full coverage) would increase farm income inequalities compared to the *laissez-faire* situation (Gini index up from 0.700 to 0.707). By contrast, taxing only the top 9% emitting farms (i.e those emitting above the optimal emission threshold) would reduce these inequalities (Gini index down to 0.695). This illustrates that the exemption of the lowest emitting farms may also serve the purpose of reducing farm income inequalities. The redistributive effect of the tax system can also be improved if reemploying the tax revenue. It might be possible to limit the negative effects of the tax burden on the included agents through lump sum transfers.

Third, the level of the tax and the exemption threshold can be potentially distorted by interest groups. In the European Union, the dominance of interest groups of farmers in the process of the Common Agricultural Policy reform leads to direct the political discourse towards production, and water down environmental targets (Erjavec and Erjavec, 2015; Alons,

2017). Exemptions can thus be the result from bargaining between the regulator and interest groups, or the pursuit of private interests within the administration. One possible avenue to limit the distortion induced by interest groups is to also recycle the tax revenue. We need to consider a redistribution that negates the incentives of the interest groups and does not limit the environmental benefit of the tax.

The political economy aspect is also a key determinant of the adaptation of Geographical indication in the face of climate change. Bargaining relationships within the appellations to decide whether or not to adapt are neglected in the work presented here. However, since a Geographical Indication is made of a group of heterogeneous producers, finding a consensus in the decision to adapt is not so obvious. Future works could consider including collective decisions to modify the specifications within Geographical Indications. The idea would be to understand how an organization made of heterogeneous firms, which have managed to agree on standards to produce a homogeneous product, can collectively face a climate-induced deterioration (potentially non-homogeneous) in their conditions of production.

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Résumé long

Le changement climatique est le principal défi environnemental mondial de l'époque contemporaine. L'accumulation dans l'atmosphère des émissions de gaz à effets de serre émises par les activités humaines modifie le bilan énergétique de la Terre, et entraîne une augmentation des températures moyennes, une modification de la couverture nuageuse et des précipitations, ainsi qu'une augmentation de l'occurrence des phénomènes météorologiques extrêmes. Le changement climatique est susceptible d'affecter les actifs naturels (écosystèmes, ressources en eau, biodiversité, etc.) et ceux créés par l'homme (bâtiments, infrastructures, etc.). Il aura des répercussions profondes, à long terme et de multiples manières sur de nombreux secteurs de l'économie, si ce n'est tous.

Les enjeux sont particulièrement forts pour le secteur agricole, qui fait l'objet de cette thèse. L'agriculture est l'un des principaux secteurs émetteurs de gaz à effet de serre. L'élevage et l'utilisation d'engrais azotés sont les principales sources de méthane (CH₄) et de protoxyde d'azote (N₂O), deux importants gaz à effet de serre autres que le CO₂. Environ 10% des émissions nettes totales dans l'Union européenne (UE) et 18% en France proviennent de l'agriculture. Dans le même temps, le climat est un facteur important dans les systèmes de production agricole. Les changements de températures moyennes et extrêmes, de précipitations et de ressources en eau affecteront les rendements agricoles et exerceront une pression supplémentaire sur le fonctionnement des écosystèmes, avec des conséquences potentiellement importantes sur la sécurité alimentaire, la vulnérabilité des ménages ruraux et la biodiversité.

L'objectif des recherches menées dans cette thèse est d'explorer comment les méthodes économiques peuvent aider à impliquer l'agriculture dans un effort d'atténuation des émis-

sions de gaz à effet de serre et peuvent améliorer notre compréhension des stratégies efficaces pour que le secteur s'adapte au changement climatique.

Le Chapitre 1 trouve son origine dans la déclaration de Oswald et Stern (2019), qui appelle les économistes à accroître leurs contributions à la compréhension des questions liées au changement climatique et à jouer un rôle dans l'orientation des politiques de lutte contre le changement climatique. Ce chapitre apporte une réponse en discutant quantitativement l'ensemble de la production académique en économie sur le changement climatique. Ce travail vise à répertorier les évolutions des contributions sur le changement climatique en économie au fil du temps. En particulier, je me concentre sur le nombre de publications, leur structure par revue, et les thématiques abordées. Dans une optique plus globale, l'idée est de comprendre le rôle de la discipline économique face au changement climatique.

Pour ce faire, je construis un corpus d'articles représentatifs de la recherche économique sur le changement climatique. Les principaux enjeux relatifs à la construction du corpus sont de définir les limites de la littérature économique sur le changement climatique, et de développer une technique automatisée pour identifier les publications pertinentes étant donné le volume de la littérature considérée. Après avoir développé un protocole automatisé d'extraction des références bibliographiques, j'obtiens un corpus d'environ 14 000 articles d'économie sur le changement climatique référencés sur Web of Science et Scopus.

En utilisant ce corpus, je peux davantage illustrer la faible part d'articles liés au changement climatique dans les revues du *top-5* (c'est-à-dire *Econometrica*, *the American Economic Review*, *the Review of Economic Studies*, *the Journal of Political Economy* et *The Quarterly Journal of Economics*) soulignée par Oswald et Stern. Cependant, en se concentrant sur ces revues, ces chercheurs ne tiennent pas compte du fait que l'économie a développé une vaste littérature sur le sujet en dehors de ces revues de premier plan. En particulier, la couverture donnée par la totalité des revues économiques est d'une ampleur similaire à celle de la science dans son ensemble.

Je montre ensuite que le changement climatique continue à se disséminer dans l'ensemble de l'économie, en étant de plus en plus présent dans des champs de l'économie historiquement non spécialisés sur le sujet et dans certaines revues d'économie générale.

En outre, la part laissée à des articles traitant du changement climatique dans une revue est positivement corrélée avec le facteur d'impact de la revue. De plus, les articles liés au changement climatique reçoivent en moyenne plus de citations que les autres articles de la même revue. Cette approche bibliométrique nuance l'affirmation d'Oswald et Stern, en montrant que la profession a accordé une attention croissante au changement climatique ces dernières années.

Je fournis également une évaluation quantitative de la prévalence de certaines questions de recherche et de certains sujets dans l'économie du changement climatique. Sur la base d'un modèle thématique, je classe les articles à partir de leur *abstract* au sein de thèmes, qui sont définis à partir des cooccurrences fréquentes de mots. Cette approche montre l'importance de l'analyse des instruments de politique d'atténuation des émissions et des modèles d'évaluation intégrée dans la littérature jusqu'en 2005. Depuis lors, la littérature a étendu son champ d'action. En particulier, la part des approches empiriques sur les implications sectorielles du changement climatique dans l'agriculture ou les transports, et la part des travaux empiriques identifiant l'effet causal de la croissance ou du commerce sur les régimes d'émissions de gaz à effet de serre ont augmenté. Ceci illustre comment et sous quels angles l'économie s'est appropriée le sujet du changement climatique.

Le Chapitre 2 examine la couverture optimale d'un instrument de politique d'atténuation des émissions de gaz à effet de serre en présence de coûts de surveillance, de déclaration et de vérification, *Monitoring, Reporting and Verifying costs* (MRV) en anglais. Bien que cette question ait été étudiée dans la littérature en économie publique, comme dans le domaine de la taxation optimale, le présent travail se concentre sur la couverture optimale d'une taxe sur la pollution environnementale en supposant que les coûts individuels sont inconnus.

Le problème de fond est que toutes les entreprises polluantes génèrent des dommages environnementaux. Cependant, la taxation de certaines entreprises peut entraîner un bénéfice social net négatif si le coût marginal de réduction et les coûts administratifs de surveillance des émissions dépassent les dommages environnementaux marginaux évités. Par conséquent, la couverture totale peut ne pas maximiser le bien-être et, dans certains cas, le laissez-faire peut même être plus performant que la couverture totale. Ainsi, le régulateur

souhaite taxer uniquement les entreprises pour lesquelles le fait d'être taxé génère un avantage social net positif. Le problème est que le régulateur ne peut pas distinguer les entreprises apportant un bénéfice social net positif de celles dont le bénéfice social net est négatif lorsqu'elles sont taxées, car les coûts individuels de réduction et de contrôle des émissions ne sont généralement pas observables.

Avec mes co-auteurs Stéphane De Cara et Pierre-Alain Jayet, nous proposons une autre conception de l'instrument d'atténuation, qui ajoute un seuil d'exemption en plus du montant de la taxe. En d'autres termes, le régulateur fixe un seuil en fonction de certaines caractéristiques observables et non manipulables, où les entreprises dont les caractéristiques sont supérieures au seuil sont incluses dans la taxe et où celles dont les caractéristiques sont inférieures au seuil sont exclues. Les exemptions fiscales par le biais d'une couverture fiscale partielle sont courantes dans la taxation publique. Les exonérations existent également dans la politique environnementale. Par exemple, les installations émettant plus d'une quantité donnée sont couvertes par le système d'échange de quotas d'émission de l'Union européenne. Nous justifions ici ces exemptions pour réduire les coûts de contrôle, et nous cherchons le niveau optimal de ces exemptions.

En utilisant un cadre analytique, nous identifions les conditions requises concernant l'hétérogénéité des coûts de réduction et des coûts de surveillance pour l'existence d'un seuil optimal en tant qu'instrument de politique de premier rang. Nous mettons également en évidence une formule simple d'approximation du seuil optimal basée sur des spécifications flexibles pour les coûts administratifs de contrôle et les coûts d'abattement. Comme cette formule ne repose que sur des informations agrégées ou sectorielles, nous considérons que cette méthode est facilement applicable.

Ensuite, nous appliquons ces réflexions théoriques à la question de l'atténuation des émissions de gaz à effet de serre du secteur agricole en UE, qui est actuellement dispensé d'efforts de réduction des émissions. Nous cherchons à déterminer la couverture d'une taxe sur les émissions et à caractériser les effets sur le bien-être de ce système de taxe lorsqu'il est appliqué au secteur. Nous utilisons un modèle d'offre agricole détaillé au niveau du type d'exploitation pour en déduire l'offre de réduction des émissions individuelle et agrégée.

Nous calibrons les coûts de contrôle des émissions en utilisant les valeurs publiées pour d'autres secteurs économiques. En relâchant certaines des restrictions requises sur l'hétérogénéité des coûts de réduction entre les exploitations pour que le seuil optimal existe, nous pouvons étudier comment la formule simple d'approximation du seuil se comporte dans une situation de second rang. Nous montrons enfin que seul un petit nombre de gros émetteurs de gaz à effet de serre devraient être couverts de sorte à adopter un instrument d'atténuation des émissions optimal dans le cas de l'agriculture. Ce travail contribue ainsi à une littérature qui souligne l'importance des coûts de contrôle des émissions dans le secteur agricole et qui s'en sert pour justifier l'exclusion de ce secteur du champ d'application de la politique climatique en Europe. Nous illustrons que la décision de limiter ou non les émissions agricoles n'est pas nécessairement restreinte au laisser-faire ou à la couverture totale. Le fait de ne cibler qu'une fraction des exploitations agricoles peut limiter les coûts de contrôle, tout en incitant à des réductions coût-efficaces des émissions.

Le déplacement des cultures, de la production et de la transformation vers de nouvelles zones géographiques est un moyen de limiter les dommages dus au changement climatique. Cette stratégie n'a pas été envisagée pour les Indications Géographiques. Le Chapitre 3 traite de la relocalisation de la production agricole comme stratégie d'adaptation au changement climatique lorsque la modification des zones de production est rendue difficile par la présence d'une Indication Géographique.

En particulier, j'interroge comment le changement climatique peut affecter la délimitation de la zone géographique dans laquelle les producteurs ont le droit de revendiquer le label. Ce chapitre développe un modèle théorique pour examiner cette question. Premièrement, la zone historique de l'Indication Géographique est soit ouverte à tous les producteurs ayant un avantage comparatif, soit délimitée par le groupement de producteurs en la limitant aux parcelles qui maximisent les profits de l'industrie. Ces deux hypothèses alternatives visent à rendre compte de la force de la contrainte d'exclusivité exercée par le label et à refléter le fait que les systèmes d'Indication Géographique existants dans le monde diffèrent quant au degré de pouvoir de marché laissé aux producteurs. Ensuite, je compare à l'optimum social le résultat sous les deux systèmes de délimitation, et je retrouve et étend

des résultats existants dans la littérature d'organisation industrielle sur les Indications Géographiques.

Ensuite, j'étudie dans quelle direction la frontière de la zone sous Indication Géographique est modifiée en réaction à une détérioration des conditions de production due au changement du climat. Se rétracte-t-elle ou s'étend-elle pour inclure les producteurs qui produisaient auparavant un produit non-différencié? La détérioration des conditions de production est ici considérée comme réduisant l'avantage comparatif de tous les producteurs pour le produit sous indication géographique. Pour le cas de la délimitation ouverte, le modèle montre que l'effet du changement climatique sur la zone sous Indication Géographique dépend essentiellement de la relation qui existe pour le producteur à la frontière entre la valeur absolue de la variation du revenu due au changement climatique et le coût d'opportunité de la production du produit. Si le coût d'opportunité est inférieur à la valeur absolue de la variation du revenu, alors, pour une petite détérioration du climat, la zone sous Indication Géographique s'étend, tandis que pour une détérioration plus importante, la zone se rétrécit. Lorsque le producteur à la frontière constate que le coût d'opportunité lié au fait de rester dans la zone sous Indication Géographique est supérieur à la réduction de ses revenus provenant de la production du produit labellisé, la zone se rétrécit de façon monotone avec la sévérité du changement climatique. Lorsque la zone sous indication géographique est déterminée de manière monopolistique par le groupement de producteurs, la relation cruciale pour la direction de l'adaptation se situe désormais entre l'élasticité de la qualité et celle de la quantité à la frontière de la zone de production, en fonction également du déplacement de la profitabilité marginale causé par le changement climatique.

Ce travail de recherche met en évidence les modes d'adaptation spécifiques des produits sous Indication Géographique. Il modélise les déterminants des incitations des producteurs d'Indication Géographique à relocaliser leur production. Lorsque le groupement de producteurs sous Indication Géographique se comporte comme un monopole, les changements de qualité à la frontière sont cruciaux pour déterminer les extensions potentielles de la zone exclusive de production. Ceci illustre les problèmes auxquels certaines appellations peuvent être confrontées, pour décider si elles doivent ou non relocaliser leur production face au

changement climatique.

Titre : Essais sur l'économie du changement climatique : atténuation et adaptation du secteur agricole

Mots clés : Changement climatique, Economie de l'environnement, Economie agricole, Atténuation, Adaptation

Résumé : Cette thèse aborde des questions économiques liées au changement climatique, à la fois sous l'angle de l'atténuation et de l'adaptation, avec un accent mis sur les implications pour le secteur agricole. Dans le premier chapitre, je propose une analyse quantitative de la littérature économique sur le changement climatique depuis plus de quarante ans. Je mets en évidence une visibilité croissante de ce sujet au sein de la discipline. A partir d'une catégorisation textuelle des articles de la littérature à l'aide d'une Allocation de Dirichlet Latente, j'illustre sa structuration autour d'approches sur l'atténuation globale du changement climatique d'une part, et d'analyses empiriques des implications sectorielles du changement climatique d'autre part. Le deuxième chapitre examine les performances d'une taxe sur les émissions agricoles de gaz à effet de serre en présence de coûts de contrôle des émissions. A l'aide d'un modèle analytique, je caractérise la couverture partielle optimale de la taxe

sur les émissions. La question est ensuite étudiée à l'aide d'un modèle d'offre agricole représentatif de l'agriculture européenne. L'application empirique montre que l'exemption des exploitations les moins émettrices en Europe permet de limiter les coûts de contrôle tout en incitant à réduire efficacement les émissions. Dans le troisième chapitre, j'étudie les stratégies d'adaptation en agriculture lorsque la modification des zones de production est rendue difficile du fait de la présence d'une Indication Géographique. Je développe un modèle théorique stylisé permettant d'analyser les modes d'adaptation en tenant compte du lien étroit entre la qualité du produit et les attributs de la zone géographique de production. Le modèle montre que la relocalisation de la production comme stratégie d'adaptation peut être rendue difficile par la redistribution des rentes qu'elle induit entre producteurs historiques et nouveaux entrants.

Title : Essays on the economics of climate change: mitigation and adaptation in the agricultural sector

Keywords : Climate change, Environmental economics, Agricultural economics, Mitigation, Adaptation

Abstract : This thesis addresses economic issues related to climate change, from both a mitigation and an adaptation perspective and with a focus on the implications for agriculture. In the first chapter, I propose a quantitative analysis of the economics literature on climate change for over more than forty years. I show that climate change has become increasingly prominent in the discipline. From a textual categorization of the content of articles using Latent Dirichlet Allocation, I suggest that the literature is structured around approaches on global mitigation of climate change on the one hand and empirical analyses of the sectoral implications of climate change on the other hand. The second chapter examines the performances of a tax on greenhouse gas from agriculture in the presence of monitoring costs. Using an analytical model, I characterize the optimal partial coverage of an emis-

sions tax. The issue is then investigated using an agricultural supply model representative of European agriculture. The empirical application shows that exempting the lowest emitting farms limits monitoring costs, while providing an incentive to efficiently reduce emissions. In the third chapter, I study the adaptation strategies in agriculture when modifying the production areas is made difficult by the presence of Geographical Indication. I develop a stylized model to analyze adaptation patterns taking into account the strong link between the quality of the product and the characteristics of the area of production. The model shows that the relocation of production as an adaptation strategy can be made difficult by the induced redistribution of rents between historical producers and new entrants.