Adaptation to climate change of products under geographical indication
(Preliminary version)

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Abstract

Current specifications and rules that define the conditions of production of agricultural goods under geographical indication are not likely to be suited to future weather conditions. This paper explores the mechanisms that frame the adaptation of the supply control of geographical indication in the face of climate change. To do so, we develop an analytical framework based on recent works in modern Ricardian trade models. Those works explain reallocation of land across producers through the shifts in comparative advantage induced by the spatially differentiated effect of climate change. We extend this framework to account for the case of geographical indication. We introduce supply control as *ex ante* restrictions on inputs, e.g. land, which result in some degree of market power on the GI good and impede a flexible reallocation of production across producers. Our analytical framework captures a simple trade-off at the core of the supply control adjustment to future weather conditions: loosening specifications to allow more flexibility in land allocation or maintaining current specifications to increase the price premium. The balance between these two opposite forces is determined by the change in the productivity differential across individuals induced by climate change and the degree of market power attainable under new climate conditions.

Keywords: Geographical indication, Ricardian model, Comparative advantage, Supply control, Global warming, Adaptation

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1. Introduction

Global world temperature has already increased by almost 1°C above its pre-industrial level, and this increase is expected to reach 1.5°C before 2050 unless global greenhouse gas emissions are massively and rapidly reduced (IPCC, 2018). The expected increase in the temperature distribution is likely to be accompanied by alterations of precipitations, changes in cloud cover, and/or increased occurrence of extreme weather events, which are all expected to affect agricultural yields (Challinor et al., 2014; Schlenker and Roberts, 2009). As a result, some crops may not be suited to future climate conditions where they are currently grown. Agricultural goods produced and marketed under geographical indication (GI hereafter)[1] are particularly vulnerable since they are characterized by a specific combination of human know-how, climate and soil characteristics, often termed as '*terroir*' (Cross et al., 2011; Gergaud and Ginsburgh, 2008). This is particularly true for wine, which quality is very much dependant on local weather conditions and for which *terroir* is seen as an important distinguishing feature that justifies the use of GI in many countries (Jones et al., 2005; Holland and Smit, 2010; van Leeuwen and Darriet, 2016). With some studies predicting that climate change will threaten the very existence of some historical wine *terroirs* (Moriondo et al., 2013), adaptation strategies that would allow to maintain *terroirs*' typicity have attracted increasing attention.

Adaptation options can take various forms, including changes in the varieties grown, production practices (e.g. irrigation, changes in harvesting dates, etc.), and/or the area of production (Hannah et al., 2013; Ollat et al., 2016; Wolkovich et al., 2018). In the case of products under GI, some of these options may be at odds with the requirements imposed for the product to be labelled as GI which are defined collectively, e.g. by the producers' organization (PO) that owns the GI. Therefore, adaptation has to combine responses at the farm level as well as at the PO level. This paper examines adaptation accounting for both its individual and collective dimensions, as well as the possible interactions between these two dimensions.

[1] We use the terminology geographical indication to refer to labels, publicly managed, which identify a good whose characteristics are attributable to its geographical origin. To obtain the label, producers voluntarily bundle together and have to achieve credible efforts that show how the quality attributes are tied up to the geographic origin. In the European Union, these schemes are the Protected Designation of Origin (PDO), the Protected Geographical Indication (PGI) and the Traditional Specialty Guaranteed (TSG) schemes. See Articles 22 and 23 for the definition in the World Trade Organization agreement on Trade-Related Aspects of Intellectual Property Rights: `https://www.wto.org/english/docs_e/legal_e/27-trips_04b_e.htm`).

The main incentive for farmers to produce a good under GI lies in the rent that can be extracted through product differentiation and supply control (Lence et al., 2007; Mérel and Sexton, 2012; Bonroy and Constantatos, 2015). If farmers located in eligible area chose to produce a GI rather than an undifferentiated good, they have to comply with specifications and rules set by the producers' organization (PO), which can take the form of restrictions in the quantity of outputs or inputs, or in the practices that farmers are allowed to use in the production process. In return, farmers receive a premium for the GI good that depends on the degree of market power resulting from the supply control imposed by the PO.

How the production of agricultural goods under GI will respond to climate change remains an open question. This will depend on the direct impact of climate change on yields in the area of consideration while taking into account current GI specifications and rules. This effect is the one that have been considered by projects examining how *terroirs* will be affected by climate change (Jones et al., 2005; Hannah et al., 2013; Moriondo et al., 2013). But, it will also result from the interplay between individual and collective adaptation to climate change.

As an illustration, consider producers who, under current market conditions, have a comparative advantage in producing the GI good, and therefore specialize in this good. Consider also that climate change results in a (possibly spatially differentiated) decrease of yields in the region of production. The changes in yields induced by climate change will affect the comparative advantages across the region, which may lead to the reallocation of (at least some) agricultural production. The decrease in the production of the GI good may lead to an increase of the price premium relative to the undifferentiated good,[2] as well as an increase in the cost of producing the good under current GI rules. If the specifications of the GI good are left unchanged under the new climate conditions, the restrictions imposed by the PO will distort individual reallocations and impede full flexibility in adaptation. Adaptation may also take the form of a change in the GI specifications and rules. In this regard, the trade-off faced by the PO is between (i) maintaining the current supply control to restrict output in order to benefit from a higher price premium, and (ii) relaxing the supply control in order to reduce production costs. The balance between these two opposite forces will be determined by the evolution of the productivity differential across individuals induced by climate

[2]This effect is also called the "supply limiting" or "supply restriction" effect in the literature (Mérel and Sexton, 2012; Bonroy and Constantatos, 2015)

change and the degree of market power attainable under new climate conditions.

The objective of this paper is to provide an analytical framework that allows to study these mechanisms. The proposed model describes the interactions between individual adjustments of land allocation induced by comparative advantage shifts in the presence of an *ex ante* supply control, which generates a rent on the GI good. This model combines elements from two strands of literature.

First, the model partly draws on recent developments in modern Ricardian trade models under climate change (Costinot et al., 2016; Gouel and Laborde, 2018), in particular with regard to the modeling of acreage decisions, the representation of the heterogeneity in productivity, and how climate change may affect comparative advantages and specialization patterns. Contrary to those works that consider only undifferentiated commodities, we introduce a differentiated good (GI) that can be subject to supply control by a PO. This representation extends this literature to situations where restrictions imposed by supply control and the rent extraction distort individual acreage decisions.

Second, welfare effects from supply control have given rise to an abundant literature in agricultural economics on labels and geographical indications (see Bonroy and Constantatos, 2015, for a recent and comprehensive review of the various settings). Introducing public labels for goods with credence attributes, such as GI, has been shown as welfare enhancing compared to the alternative situation without label since it solves assymetric information issues (Moschini et al., 2008). Moreover, GI supports producers to supply high quality by conferring market power, therefore allowing farmers to make some profits that can compensate for certification costs, and the adoption of technical requirements (Lence et al., 2007; Roe and Sheldon, 2007; Saitone and Sexton, 2010). Our approach departs from these works as we consider producers that have successfully marketed their GI good, to focus on the adjustment of the supply control to future shifts in productivity distributions induced by climate change. For now, supply control operates in our model through quotas in land use allocated to the GI, but we aim at encompassing other forms of restrictions, e.g. on outputs and/or on labour intensity as in Lence et al. (2007).

Our model highlights key features of adaptation mechanisms exerted by GI production to climate change. We derive a simple expression of acreage decision and supply of GI under land quotas using the assumption that potential yields follow an extreme value distribution. This result is an extension of the one obtained in Costinot et al. (2016) and Gouel and Laborde (2018) to the case with supply control. We show that the production of GI crucially depends on the absolute advantage of the region–i.e. the average level of yields–but also on the heterogeneity of yields within the region, i.e. the comparative advantage. This paper provides a preliminary frame of analysis to discuss how further results can be obtained to study the adjustment of the production of GI under climate change. We aim at introducing shifts in the yields distribution to model climate change, and leading comparative statics that would allow us to obtain the adjustment of the supply of GI.

The contribution of the paper is twofold. First, it bridges a gap between three literatures: the modern Ricardian assignment framework, the agricultural economics literature on GI and the adaptation economics to climate change literature. Merging these three literatures allows to progress within an analytical framework where collective rules and individual decisions are interacting which is key when considering adaptation to climate change (Fankhauser et al., 1999; Adger, 2003). Second, it formalizes the adaptation mechanisms of GI specifications and rules when conditions of production are evolving, which has not been questioned in an analytical framework so far. We provide an answer focusing on the production adjustments of GI that make abstraction from any strategic behaviours of producers, or adjustment of demand in relation with the ties between *terroir* and quality of the GI. These issues are better handled using a framework with vertical product differentiation as in Menapace and Moschini (2014).

For now, the contribution of the paper is analytical, to the extent that it elicits the underlying mechanisms of the production adjustments of GI. However, we later expect to apply our model to assess the potential harm of climate change on existing *terroir* sectors. The model can be calibrated using spatially explicit information on potential yields before and after climate change coming from the agronomic literature. Moreover, the advantage of the approach developped by Costinot et al. (2016) and Gouel and Laborde (2018) lies in the fact that the effects of shifts in comparative advantage on market outcome sum up few parameters: acreage elasticity and demand elasticity. Given that our approach draws on key elements from these works, we think that it could be used to empirically assess the adjustment of the production of goods under GI with a similar methodology.

The remainder of the paper is structured as follows. The analytical framework is presented in Section 2. We show how climate change can be introduced in our framework to assess its impact in Section 3. Then, we conclude by discussing our approach and developping further extensions in Section 4.

2. Model

The modeling framework builds on Costinot et al. (2016) and Lence et al. (2007). The economy consists of a region, made of a continuum of heterogeneous farms, which have sucessfully marketed a geographical indication. The GI market is of known size, and producers have already borne fixed costs on market developments. They set input restrictions, i.e. quotas on land, so that it maximizes the total net revenue. Each farmer in the region can produce the GI as soon as it complies with the input restrictions, and has also the possibility to produce an alternative crop, which we call the commodity. To produce both good, the farmer combines land and labor. Land is heterogeneous and varies in yields between farms. We consider first the conditions of production under current climate, and will study the effect of climate change in Section 3.

First, assuming that no control supply precludes in the market, farmers freely chose which good to produce on their land following a Ricardian assignment rule (Costinot and Vogel, 2015; Costinot et al., 2016; Gouel and Laborde, 2018). Farmers allocate their land to the production of the good that maximizes its rent, i.e. total revenues minus labour costs. When assuming that potential yields follow an extreme value distribution of type II (i.e. a Fréchet distribution), we are able to compute the share of land in the region devoted to the production of the GI good and the commodity. Thus, we obtain the aggregate supply of GI which ultimately depends on potential yields of both goods, parameters of yields dispersion, and goods' prices. Therefore, under a no-supply control assumption, the GI market equilibrium is defined by the price that equalizes demand for GI, and unconstrained aggregate supply.

However, for most GI, producers collectively design rules that they have to meet in order to produce the GI good. European anti-trust policy provide derogations so that producers of GI good are allowed to implement supply control, either direct supply control, i.e. restrictions on output, or indirect supply control, i.e. restrictions on the use of inputs (Mérel, 2011). For now, we consider the market outcome under indirect supply control and will leave for extensions its comparison with direct supply control. Producers chose which land in the region is eligible to the production of GI, so as to maximize the aggregate net revenue. The model assumes the following timing framework:

1. First, the producers' organization set the rules of the supply control, i.e. the parcels eligible to the GI production, so as to maximize the aggregate net revenue. During the decision process, the PO takes into account (i) the optimal individual farmers' response in land allocation happening in stage 2, and also (ii) the effect of restricting aggregate supply on the price via the demand function.

2. Second, farmers allocate their land between the GI and the commodity conditional on whether their land is eligible.

We solve this model by backward induction. First we solve the optimal farmer acreage response conditional on the acreage regulations. Second, we derive the optimal land restriction that maximizes the aggregate net revenue. The GI market equilibrium is defined by the price that equalizes the demand for GI good and the aggregate supply under land restrictions.

2.1. Background of the model and assumptions

We consider a region where producers have already succesfully marketed a GI good.[3] The region is composed of a continuum of hetorogeneous farmers of measure M indexed by $\omega \in \Omega = [0,1]$. Types of goods are indexed with $k \in \mathscr{K} \equiv \{C, GI\}$. The subscript GI corresponds to the geographical indication product, the subscript C denotes an other agricultural good which we call the commodity. Land is heterogeneous in productivity between farms, and every farm has the same surface s. Productivity heterogeneity is unobserved within the region. Thus, we later assume a distribution of land productivity across the continuum of farms.

Technological assumptions. Agricultural goods are produced by combining land and labor. To produce good $k \in \mathscr{K}$, farmer ω combines land and labor with the following technology:

Assumption 1 (Technology)**.** *For farmer ω, if the good k is produced, the farm-level production is given by:*

$$q^k(\omega) = s \min\left\{A^k(\omega) l^k(\omega), \frac{n^k(\omega)}{\nu^k}\right\} \tag{1}$$

where s is the total farmland, $l^k(\omega)$ is the fraction of land of farmer ω with $A^k(\omega) \geq 0$ its productivity (quantity produced per unit of land) if allocated to good k by farmer ω, $n^k(\omega)$ the number of

[3]This assumption allows us to concentrate on the adjustment of the supply control of an already existing GI good. Relaxing this assumption would imply the producers' organization to bear fixed costs to take into account marketing expenses and certification costs, as in (Lence et al., 2007).

hours worked per unit of land and $\nu^k > 0$ measures the unit labor requirement (labor intensity per unit of good k).

From here and throughout, capital letters denote aggregate quantities (i.e. at the regional scale) of labor, land and output, while lower case letters are farm-scale variables. We assume that labor and land are perfect complements in the production of each good. We here follow the technological assumption in Costinot et al. (2016) and Gouel and Laborde (2018).[4] Then, following Costinot et al. (2016) we assume that yields are independently and identically drawn for each individual ω from a Fréchet distribution:

Assumption 2 (Farm productivity distribution)**.** *The cumulative distribution function of the productivity of the land of farm ω when allocated to good k is the following:*

$$\Pr\left\{A^k(\omega) \leq a\right\} = G^k(a) = \exp\left\{-\left(\frac{\tilde{\gamma}A^k}{a}\right)^{\theta}\right\} \tag{2}$$

with $\theta > 1$ the shape parameter, and $\tilde{\gamma}A^k > 0$ the scale parameter, where $\tilde{\gamma} \equiv (\Gamma(1-1/\theta))^{-1}$ is a parameter such that A^k is the unconditional average yield in the region to produce good k, i.e. $A^k = \mathbb{E}\left[A^k(\omega)\right]$.[5] We denote by $G^k(\cdot)$ the cumulative distribution function of the yields of good k within the region.

θ is the dispersion parameter, i.e. the heterogeneity within the region. A greater θ illustrates a lower variation between farms' productivity. When θ tends to infinity, land is perfectly homogeneous. This specific situation mirrors the original ricardian approach where factors of production are homogeneous for a given sector within regions. The scale parameter illustrates the absolute advantage of the region: a greater $\tilde{\gamma}A^k$ implies a greater probability to draw a higher yield in the farms of the region. As the region is made of a continuum of farms, this probability also gives us the share of farms in the region with potential yields associated to good k lower or equal to a.

[4] We could follow the assumption made in Sotelo (2015), where $q^k(\omega) = s(n^k(\omega))^{\alpha_k}(x^k(\omega))^{\beta_k}(l^k(\omega)A^k(\omega))^{\gamma_k}$ where n, x and l are labor per unit of land, intermediate inputs per unit of land and fraction of land allocated by farmer ω to produce $q^k(\omega)$ output of crop k with a Cobb-Douglas technology (which implies $\alpha_k + \beta_k + \gamma_k = 1$). We later ask on the importance of this technological assumption, and try to extend our result to a CES production function with elasticity of substitution $s = \dfrac{1}{1-\rho}$.

[5] By definition, a Fréchet distribution with shape parameter θ and scale parameter μ has the following cumulative distribution: $\Pr(X \leq x) = \exp\left\{\left(\frac{\mu}{x}\right)^{\theta}\right\}$, and mean $\mu \times \Gamma(1 + 1/\theta)$ with $\gamma(\cdot)$ the gamma function. Moreover, we assume that $\theta > 1$ in order to the mean to be finite.

Assumptions on preferences. We assume that the geographical indication enable consumers to distinguish between products from the region and those from outside, but they are still unable to discriminate between different producers inside the GI. We assume that consumer utility of a representative consumer is given by a utility function $u(Q)$, concave in quantity $\left(\frac{\partial u(Q)}{\partial Q} > 0\ ,\ \frac{\partial^2 u(Q)}{\partial Q^2} < 0\right)$. Given these assumptions, it leads to the following demand function:

Assumption 3 (Demand for GI product)**.** *The demand function for the GI good is denoted with $Q^D(p^{GI})$. It is decreasing in the price of the GI good, i.e. $\frac{\partial Q^D(p^{GI})}{\partial p^{GI}} < 0$, and its associated inverse demand function, denoted with $p^{GI}(Q)$ is downward sloping, i.e. $\frac{\partial p^{GI}(Q)}{\partial Q} < 0$.*

The demand side of our model assumes that demands for the GI product and the commodity are separated. Thus, producers in the region considered are the unique producers of the GI good, and no substitutes of this good exists. We have in mind a group of producers that have convinced consumers that the product from that area is worth a price premium, as in Lence et al. (2007). This is explained by the *terroir* in the area, which provides unique environmental conditions that favored the production of a superior product. Therefore, producers simply face a downward-sloping demand curve generated through a nondifferentiated framework.

The producers of the GI consist of a small subset of all commodity producers, so that they face a perfectly elastic demand for the commodity at price p^C.

2.2. The perfect competition case

Assume first that no control supply precludes in the market, so that farmers freely allocate their land. This situation can occur for some GI when anti-trust laws prevent the PO from exerting any type of supply control. To charaterize the market outcome under perfect competition, we need to compute the aggregate supply, which is the aggregation of quantity produced over the continuum of farmers. To do so, consider first the individual farmer's conditional demand for inputs: the fraction of their land to allocate to the production of each good $l^k(\omega)$ and the quantity of labor per unity of surface $n^k(\omega)$ in order to minimize costs. Then, we will aggregate the individual input demand over the continuum of farm using the productivity distribution in Assumption 2 to construct the regional supply function.

Conditional demand of factors and cost function. The program of farmer ω, conditionnally on good k being produce by this farmer ($q_i^k(\omega) > 0$) is the following:

$$\min_{l^k(\omega), n^k(\omega)} r^k(\omega) l^k(\omega) + w n^k(\omega)$$

$$\text{s.t. } sA^k(\omega) l^k(\omega) \leq q^k(\omega)$$

Since inputs are perfect complements, it implies the following conditional demand of inputs (all expressed per unit of land):

$$l^k(\omega) = \frac{q^k(\omega)}{sA^k(\omega)} \qquad\qquad n^k(\omega) = \frac{\nu^k q^k(\omega)}{s} \left(= \nu^k A^k(\omega) l^k(\omega)\right) \tag{3}$$

We can characterize the total cost function:

$$c^k(\omega) = q^k(\omega) \underbrace{\left[\frac{r^k(\omega)}{A^k(\omega)} + w\nu^k\right]}_{=\mu^k(\omega)} \tag{4}$$

with $\mu^k(\omega)$ the marginal cost (or equivalently the average cost because returns to scale are constant) borne by farmer ω when producing the good k. $r_i^k(\omega)$ is the land rent of parcel ω when allocated to the production of good k.

Land allocation rule. Factors are employed in the production of the good k conditionning it is the more profitable alternative to be produced on the land of farmer ω. As told in the Ricardian approach, factors should be employed in the good that maximizes the value of their marginal product (Costinot and Vogel, 2015). This is an expression of the perfectly competitive markets on inputs, and especially the land market. To do so, and having characterize the cost function, we can express the profit maximization problem of the farmer ω:

$$\max_{q^k(\omega)} \left[p^k - \frac{r^k(\omega)}{A^k(\omega)} - w\nu^k\right] q^k(\omega)$$

Since land market is perfectly competitive, we know that $p^k \leq \frac{r^k(\omega)}{A^k(\omega)} + w\nu^k$, with equality when $q^k(\omega) > 0$, i.e. price equal marginal costs. Thus, when good k is produced by farmer ω, profits must be zero at equilibrium. All the difference between revenues and labour costs is transferred to landowners such that farmers earn zero profit

This allows us to derive the net value of marginal products of good k, or in other words the difference between its revenue and labor costs:

$$r^k(\omega) = \left(p^k - wv^k\right) A^k(\omega) \tag{5}$$
$$\text{with } r^k \equiv p^k - wv^k.$$

This net value of marginal products is also the land rent, as it is entirely captured by landowners. According to Equation (5) the rent $r^k(\omega)$ accruing to the land of farmer ω when used to grow k is distributed Fréchet with shape parameter θ and scale parameter $\tilde{\gamma} r^k A^k$. r^k is the land rent expressed per unit of production. Therefore, in the competitive case, farmer will chose to produce the good such that the associated rental rate $r^k A^k(\omega)$ is the maximum that can be attained on his land.

Land is either allocated to the production of the GI good or the commodity. Thus, land allocation is a discrete choice problem with π^{GI} the probability that a farmer allocates his land to the production of the GI good, and $1 - \pi^{GI}$ the probability that farmer allocates his land to the production of the commodity:

$$\pi^{GI} \equiv \Pr\left\{r^{GI} A^{GI}(\omega) = \max\left\{r^{GI} A^{GI}(\omega), r^C A^C(\omega)\right\}\right\} \tag{6}$$

Given Assumption 2, there cannot be cases where both goods simultaneously maximizes net revenue. Then, there is complete specialization for every farmer ω. Thanks to Assumption 2 we can compute this probability (see Appendix A.1 for detailed derivations):

$$\pi^{GI}\left(r^{GI}, r^C, A^{GI}, A^C\right) = \frac{\left(r^{GI} A^{GI}\right)^\theta}{(r^{GI} A^{GI})^\theta + (r^C A^C)^\theta} \tag{7}$$

Each farmer has a probability π^{GI} to allocate its land to the production of the GI good. As there is a continuum of farms, we also get here the fraction of the land at the regional scale dedicated to the production of the GI good. This probability is driven by the distributional characteristics of land yields, the labour costs and prices (both comprised in r^{GI} and r^C). When the mean value of yields for the GI increases in the region more farmers allocate their land to its production, i.e.

$$\frac{\partial \pi^{GI}\left(r^{GI}, r^C, A^{GI}, A^C\right)}{\partial A^{GI}} = \frac{\theta}{A^{GI}} \pi^{GI}\left(1 - \pi^{GI}\right) \tag{8}$$

Computing the elasticity of demand in land to produce GI good with respect to its own price and we obtain the following expression:

$$\varepsilon_{\pi^{GI}/p^{GI}} = \frac{\theta p^{GI}}{r^{GI}}\left(1 - \pi^{GI}\right) \tag{9}$$

As a result, if the price of the GI good increases, the demand in land to produce the GI good increases (the elasticity in Equation (9) is positive). The acreage elasticity also depends on the yield distribution parameter. Recall that parameter θ determines the shape of the distribution: a higher θ means that land is more homogeneous in yields across farms. The acreage elasticity is higher when θ is high, meaning that it is easier to convert land since it is more similar in terms of yields.

Aggregate supply of GI. Now we know the probability that farmer ω allocates his land to the production of the GI good, we are able to derive the aggregate supply. It corresponds to the surface of land in the region allocated to the GI multiplied by the expected yields over the farms that have allocated their land to the production of GI:

$$Q^{GI} = Ms\pi^{GI}\mathbb{E}\left[A^{GI}(\omega) \mid r^{GI}A^{GI}(\omega) = \max\left\{r^{GI}A^{GI}(\omega), r^{C}A^{C}(\omega)\right\}\right] \tag{10}$$

Denote with $\dot{A}^{GI}(\omega)$ the following random variable:

$$\dot{A}^{GI}(\omega) = \left(A^{GI}(\omega) \mid r^{GI}A^{GI}(\omega) = \max\left\{r^{GI}A^{GI}(\omega), r^{C}A^{C}(\omega)\right\}\right) \tag{11}$$

From here and throughout, we will denote with $H^{GI}(\cdot)$ the cumulative distribution function of the conditonnal random variable defined above which is distributed Fréchet with shape parameter θ and scale parameter $\tilde{\gamma}Z$, where $\tilde{\gamma} \equiv [\Gamma(1 - 1/\theta)]^{-1}$ and $Z \equiv (1/r^{GI})\left[\left(r^{GI}A^{GI}\right)^{\theta} + \left(r^{C}A^{C}\right)^{\theta}\right]^{1/\theta}$. (see Appendix A.2 for proof). Thus, the mean of the above random variable is :

$$\mathbb{E}\left[A^{GI}(\omega) \mid r^{GI}A^{GI}(\omega) = \max\left\{r^{GI}A^{GI}(\omega), r^{C}A^{C}(\omega)\right\}\right] = A^{GI}\left[\pi^{GI}\left(r^{GI}, r^{C}, A^{GI}, A^{C}\right)\right]^{-1/\theta} \tag{12}$$

The interpretation of the above mean is as follows. Suppose that we went across all farms in the region where the GI good has been optimally allocated, and we measure the yields that are attained on those farms, the average of this measure would tend to the above expression. Then, the aggregate supply of GI good can be rewritten as :

$$Q^{GI}\left(r^{GI}, r^{C}, A^{GI}, A^{C}\right) = MsA^{GI}\left[\pi^{GI}\left(r^{GI}, r^{C}, A^{GI}, A^{C}\right)\right]^{(\theta-1)/\theta} \tag{13}$$

Our expression of the aggregate supply highlights the role played by the distributional parameters of yields, and input and output prices. In particular, when the absolute advantage increases, i.e. when the regional mean of yield for the GI increases, the aggregate supply shift upwards:

$$\frac{\partial Q^{GI}\left(r^{GI}, r^{C}, A^{GI}, A^{C}\right)}{\partial A^{GI}} = \frac{Q^{GI}}{A^{GI}}\left[1 + (\theta - 1)\left(1 - \pi^{GI}\right)\right]$$

Two margins of supply adjustment are identifiable: (i) the first term into brackets represent the marginal increase of supply induced by average yield increasing on the land already allocated to the production of GI, i.e. the intensive margin, (ii) the second term is the marginal increase of supply induced by more land allocated to the production, i.e. the extensive margin. The extensive margin is governed by θ: a higher theta implies more homogeneous farms which facilitate the conversion of farm to he GI when its average yield increase in the region.

The elasticity of GI supply with respect to its own price is the following:

$$\varepsilon_{Q^{GI}/p^{GI}} = (\theta - 1)\frac{p^{GI}}{r^{GI}}\left[1 - \pi^{GI}\left(r^{GI}, r^{C}, A^{GI}, A^{C}\right)\right] \tag{14}$$

This is a similar expression as the one exposed in Gouel and Laborde (2018). A higher θ implies that quantity is more sensitive to variation in prices: land can be easily converted to the GI production as it is more homogeneous in yields across farms. The last term, $1 - \pi^{GI}\left(r^{GI}, r^{C}, A^{GI}, A^{C}\right)$, shows that the elasticity is higher when there is a significant share of land in the region allocated to the commodity.

Note: To compute the aggregate supply of commodity from the region considered, we simply replace the share of land allocated to the GI by the one associated with the commodity, i.e. $\pi^{C}\left(r^{GI}, r^{C}, A^{GI}, A^{C}\right) = 1 - \pi^{GI}\left(r^{GI}, r^{C}, A^{GI}, A^{C}\right)$. Then, the expression of the aggregate supply of commodity produced in the region is $Q^{C}(r^{GI}, r^{C}, A^{GI}, A^{C}) = MsA^{C}\left[1 - \pi^{GI}\left(r^{GI}, r^{C}, A^{GI}, A^{C}\right)\right]^{(\theta-1)/\theta}$.

The market outcome in the perfect competition case. In the perfect competition case, producers are price takers and the market outcome is defined by the price p^{GI}_{PC} such that aggregate supply and demand for GI are equalized, i.e.:

$$Q^{GI}\left(p^{GI}_{PC} - wv^{GI}, r^{C}, A^{GI}, A^{C}\right) = Q^{D}(p^{GI}_{PC}) \tag{15}$$

Proofs for existence and uniqueness conditions of the price are left for future versions of the paper.

2.3. A cartel specification

First, we define the objective function of the PO: it maximizes the total land rent from the GI while integrating the demand function in the problem:

$$Q^{GI}_{Cartel} = \arg\max_{Q^{GI}}\left[p^{GI}(Q^{GI}) - wv^{GI}\right]Q^{GI} \tag{16}$$

The solution of this program is the aggregate quantity corresponding to the monopoly output, the one that equalizes marginal revenu with marginal costs:

$$p^{GI}(Q^{GI}_{Cartel}) + Q^{GI}_{Cartel}\frac{\partial p(Q^{GI}_{Cartel})}{\partial Q^{GI}} = wv^{GI} \tag{17}$$

Then, we need to determine the output quota using an *ad hoc* rule of output allocation within the GI producers'. We know the cartel pricing rule, we are looking for the indvidual quotas (or if it is not individual the aggregate landshare) that allows to verify this pricing rule. Currently deepening research in this direction for further results, we can also consider the case where the producers' organization implement indirect supply control, i.e. restrictions on land.

2.4. The case with supply control via *restrictions on land*

Introducing the Producers' Organization problem. We now consider the case where the PO can set restrictions on land use. More precisely, it decides the total share of land in the regions which is eligible to the production of the GI. Indeed in many GI, the PO controls defines the geographical area where land can be allocated to its production. Deconinck and Swinnen (2014) underlines the land restriction process in the case of wine appellation in France:

> In France, for instance, a request to create or change a GI area needs to be submitted at the *Institut National d'Appellations d'Origine* (INAO), which appoints a committee to study the request. The committee eventually proposes a delimitation of the GI area, which is then subject to a "national opposition procedure" whereby any interested party can voice complaints regarding the proposed GI area. In the end, INAO decides on the delimitation of the GI area which is then sent to the Ministry of Agriculture for approval. Since 2008, the European Commission ultimately approves or disapproves the proposed GI area after consulting the EU Member States.

We hereby consider that restrictions in land are introduced through a lower limit on yields, which we denote with $\underline{A}$. Thus, suppose that the PO decides a threshold $\underline{A}$ such that only farm with $A^k(\omega)$ higher to this threshold, i.e. $A^k(\omega) \geq \underline{A}$, can produce the GI good. When setting $\underline{A}$ in the second step of the model, the PO takes into account individual farmer response function in acreage, and the effect of land restrictions on the price premium.

Land allocation under land restrictions. First, we reconsider the individual acreage decision presented in Subsection 2.2 to consider restrictions on land. Denote with $\tilde{\pi}^{GI}$, the probability to observe a farm that allocates its land to the production of the GI good when there is such land restrictions. The following proposition derives the acreage share under restrictions in land use:

Proposition 1 (Land allocation under restrictions in land use)**.** *Under Assumptions 1 and 2, when the producers' organization can control the supply by setting a lower limit on yields $\underline{A}$, so that farms with potential yields lower than this threshold cannot produce the GI, the probability that a farm allocates his land to the production of GI is:*

$$\tilde{\pi}^{GI}\left(r^{GI}, r^{C}, A^{GI}, A^{C}, \underline{A}\right) = \left[1 - H^{GI}(\underline{A})\right] \times \pi^{GI}\left(r^{GI}, r^{C}, A^{GI}, A^{C}\right) \tag{18}$$

where $H^{GI}(\cdot)$ is the cumulative distribution function of a Fréchet law with:

- *shape parameter θ*
- *scale parameter $\tilde{\gamma}\times Z$ where $Z \equiv (1/r^{GI})\left[\left(r^{GI}A^{GI}\right)^{\theta} + \left(r^{C}A^{C}\right)^{\theta}\right]^{1/\theta} = A^{GI}\left[\pi^{GI}\left(r^{GI}, r^{C}, A^{GI}, A^{C}\right)\right]^{-1/\theta}$ and with $\tilde{\gamma} \equiv [\Gamma(1 - 1/\theta)]^{-1}$*

Proof. A farm will allocate its land to the production of GI, both when its potential yield are higher than $\underline{A}$ and when the land rent accruing from the production of the GI is the maximum compared to the one from the commodity. We can write down this probability:

$$\begin{aligned}
\tilde{\pi}^{GI} &= \Pr\left\{\left[A^{GI}(\omega) \geq \underline{A}\right] \cap \left[r^{C}A^{C}(\omega) \leq r^{GI}A^{GI}(\omega)\right]\right\} \\
\tilde{\pi}^{GI} &= \Pr\left\{A^{GI}(\omega) \geq \underline{A} \mid r^{C}A^{C}(\omega) \leq r^{GI}A^{GI}(\omega)\right\} \times \Pr\left\{r^{C}A^{C}(\omega) \leq r^{GI}A^{GI}(\omega)\right\} \\
\tilde{\pi}^{GI} &= \left[1 - \Pr\left\{A^{GI}(\omega) \leq \underline{A} \mid r^{C}A^{C}(\omega) \leq r^{GI}A^{GI}(\omega)\right\}\right] \times \Pr\left\{r^{C}A^{C}(\omega) \leq r^{GI}A^{GI}(\omega)\right\}
\end{aligned}$$

$$\tilde{\pi}^{GI}\left(r^{GI}, r^{C}, A^{GI}, A^{C}, \underline{A}\right) = [1 - H(\underline{A})] \times \pi^{GI}\left(r^{GI}, r^{C}, A^{GI}, A^{C}\right)$$

as $\left(A^{GI}(\omega) \leq \underline{A} \mid r^{C}A^{C}(\omega) \leq r^{GI}A^{GI}(\omega)\right)$ is the Fréchet random variable introduced in equation (11). □

We can here identify the distorsive effect induced by land restrictions. The expression of land share under land restrictions corresponds to the land share under perfect competition, i.e. $\tilde{\pi}^{GI}$, adjusted by the share of farms with land productivity higher than the threshold that maximizes the land rent, i.e. $1 - H(\underline{A})$.

The land share crucially depends on the lower bound $\underline{A}$. Under no land restriction, i.e. $\underline{A} = 0$, it matches the perfect competition acreage outcome, $\tilde{\pi}^{GI} = \pi^{GI}$. It is decreasing with $\underline{A}$:

$$\frac{\partial \tilde{\pi}^{GI}(\underline{A})}{\partial \underline{A}} = -h(\underline{A}) \times \pi^{GI} \tag{19}$$

An increase in the lower bound on yields decreases the share of farms allocating their land to the GI. This decrease correspond to the frequency of farm allocating their land to the GI with potential yields equalizing the threshold.

Finally, the effect of a variation of the mean of GI productivity in the region:

$$\begin{aligned}\frac{\partial \tilde{\pi}^{GI}\left(r^{GI}, r^{C}, A^{GI}, A^{C}, \underline{A}\right)}{\partial A^{GI}} &= -\frac{\partial H(\underline{A})}{\partial A^{GI}}\pi^{GI} + \left[1 - H(\underline{A})\frac{\partial \pi^{GI}}{\partial A^{GI}}\right] \\ &= \frac{\theta}{A^{GI}}\pi^{GI}\left[\tilde{\gamma}^{\theta}\left(\frac{A^{GI}}{\underline{A}}\right)^{\theta} H(\underline{A}) + (1 - H(\underline{A}))\left(1 - \pi^{GI}\right)\right] \end{aligned} \quad (20)$$

We can identify the distortion caused by the land restrictions when there is a change in the production conditions, e.g. an upward shift in the mean of potential GI yields in the region. The second term of the partial derivative corresponds to the variation specified in Equation 8, adjusted to the share of farm allowed to produce the GI. The first term represents the fraction of farm that are now allowed to produce the GI since their potential yield outweighs the threshold.

Aggregate supply under land restrictions. The aggregate supply of GI under land restrictions corresponds to the total surface in the region allocated to the GI times the mean of potential yields measured on the farm effectively producing the GI. These farms both have potential yields for the GI higher than $\underline{A}$ and the production of GI maximizes their land rent among the alternatives, i.e. $r^{GI}A^{GI}(\omega) \geq r^{C}A^{C}(\omega)$ and $r^{GI}A^{GI}(\omega) \geq \underline{A}$. Then, the following proposition characterizes the aggregate supply of GI under land restrictions:

Proposition 2 (Aggregate supply of GI under land restrictions)**.** *Under Assumptions 1 and 2, when the producers' organization can control the supply by setting a lower limit on yields $\underline{A}$ so that farms with potential yields lower than this threshold cannot produce the GI, the aggregate supply of GI is the following:*

$$\tilde{Q}^{GI}\left(r^{GI}, r^{C}, A^{GI}, A^{C}, \underline{A}\right) = MsA^{GI}\left[\pi^{GI}(r^{GI}, r^{C}, A^{GI}, A^{C})\right]^{(\theta-1)/\theta}\left[1 - P\left(1 - 1/\theta, (\tilde{\gamma}Z/\underline{A})^{\theta}\right)\right]$$

with $\tilde{\gamma} \equiv [\Gamma(1 - 1/\theta)]^{-1}$, $Z \equiv A^{GI}\pi^{GI}\left(r^{GI}, r^{C}, A^{GI}, A^{C}\right)$ and $P(\cdot, \cdot)$ is the regularized upper incomplete gamma function.

Proof. The GI yields of farms that produce the GI under land restictions are characterized by the following random variable:

$$\tilde{A}^{GI} \equiv \left(A^{GI}(\omega) \mid \left(A^{GI}(\omega) \geq \underline{A}\right) \cap \left(r^{C}A^{C}(\omega) \leq r^{GI}A^{GI}(\omega)\right)\right) \quad (21)$$

This random variable follows a lower truncated Frechet distribution, whose mean can be expressed as (see Appendix A.3 for detailled derivations):

$$\mathbb{E}\left[\tilde{A}^{GI}(\omega)\right] = \frac{A^{GI}\left(\pi^{GI}\right)^{-1/\theta}\left[1 - P\left(1 - 1/\theta, \left(\tilde{\gamma}A^{GI}(\pi^{GI})^{-1/\theta}/\underline{A}\right)^{\theta}\right)\right]}{1 - H(\underline{A})} \tag{22}$$

where $P\left(1 - 1/\theta, \left(\tilde{\gamma}A^{GI}(\pi^{GI})^{-1/\theta}/\underline{A}\right)^{\theta}\right)$ is the regularized upper incomplete gamma function.[6] □

Optimal land restrictions. Once we know the expression of the aggregate supply under supply control, the PO can integrate the individual farmer's response to shift in the lower bound $\underline{A}$ in its program. The PO seeks the lower bound $\underline{A}$ to maximize the net revenue from the sells of GI:

$$\max_{\underline{A}} \left[p^{GI}\left(\tilde{Q}^{GI}\left(r^{GI}, r^{C}, A^{GI}, A^{C}, \underline{A}\right)\right) - wv^{GI}\right] \times \tilde{Q}^{GI}\left(r^{GI}, r^{C}, A^{GI}, A^{C}, \underline{A}\right)$$

The first order condition of this program illustrates the key trade-off faced by the PO:

$$\frac{\partial p^{GI}\left(\tilde{Q}^{GI}\right)}{\partial \tilde{Q}^{GI}} \times \frac{\partial \tilde{Q}^{GI}\left(r^{GI}, r^{C}, A^{GI}, A^{C}, \underline{A}\right)}{\partial \underline{A}} \times \tilde{Q}^{GI}\left(r^{GI}, r^{C}, A^{GI}, A^{C}, \underline{A}\right) + (p^{GI} - wv^{GI}) \times \frac{\partial \tilde{Q}^{GI}\left(r^{GI}, r^{C}, A^{GI}, A^{C}, \underline{A}\right)}{\partial \underline{A}} = 0$$

We leave for further versions of the paper detailled interpretations of the mechanisms underlying the optimal setting of $\underline{A}$.

3. Climate change impact

In this section, we introduce our approach to deal with the effects of climate change in the model. Then, we give some insights on the method that can be deployed to analyze the adjustment of supply control to shifts in weather conditions.

Climate change can be introduced in our model by shifts in land productivity. In their work, Costinot et al. (2016) takes into account the effect of climate change thorough exogeneous changes in crop productivity. This is easily handled in our framework with shifts in land productivity distribution using the two key parameters of the Frechet: θ the shape parameter, and A^k the mean of potential yields of good k in the region.

[6] The regularized upper incomplete gamma function is the function defined by the ratio between an upper incomplete Gamma function and the Gamma function, i.e. $P(\gamma, \nu) = \frac{\Gamma(\gamma, \nu)}{\Gamma(\gamma)}$.

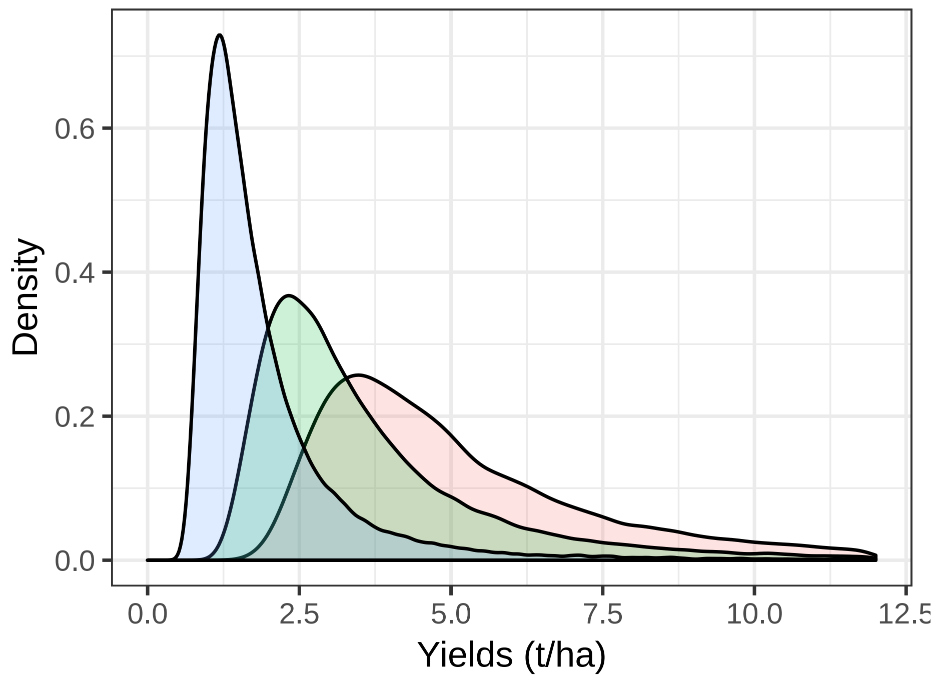

Figure 1: Distributions of yields following Fréchet law, simulating shifts in potential yields in the region. *Note: All three distributions are calibrated using the shape parameter value found in Costinot et al. (2016), i.e.* $\theta = 2.46$. *The distribution represented in green has a mean of 4 tons per hactare which is roughly the average yields for cereal in the world according to the FAO. The red distribution represents an increase of the mean to 6 tons per hectare and the blue distribution a deacrease to 2 tons per hectare.*

Figure 1 displays three Frechet distributions, simulating distributions of land productivity, that differ only in their mean. It illustrates the method used by Costinot et al. (2016); Gouel and Laborde (2018) where comparative advantage shifts within countries according to the mean value of yields.

Following this approach, Gouel and Laborde (2018) express their model in relative changes using the exact hat algebra and compare the market outcome under the two distributions. It allows to derive welfare changes expressed in equivalent variations between current weather and future conditions and thus evaluate the harm induced by climate change.

Another approach is to consider marginal deviations in the distribution of yields. Considering equilibrium conditions in the GI market under supply control, some comparative statics could give intuitions on the effect of deviations in the yield distribution on the market outcome. The envelop theorem would allow to derive properties on the directions of the optimal land restrictions following a variation in the mean of potential yield.

To assess the role played by the two margins of adjustment, i.e. the individual reallocation of land and the collective adjustment of supply control, we can compare two scenarios:

- In a first situation, we can suppose that the PO hasn't adapted its rules to the upcoming climate. This case can occur in the short run, since adjustments in specifications and rules for GI can take some time, or because the PO is reluctant to adjust its supply control to future conditions for reasons that are not accounted in the model, e.g. maintaining its reputation needs to keep the same geographical area. In that case, only individual farmers adapt through adjusting their acreage decisions but still being constrained by preexisting supply coontrol.
- In the long run, POs can adapt to climate change and they revise their supply control accordingly so that it maximizes aggregate net revenue from GDAP with the anticipated distribution of potential yields.

Comparing the market outcome under these two scenarios can indicate the role played by each margin of adjustment on the adaptation of the supply of GI in the face of climate change.

4. Conclusion

Current specifications and rules that define the conditions of production of agricultural goods under geographical indication are not likely to be suited to future weather conditions. In this paper, we explore mechanisms that frame the adjustment of the supply control of GI in the face of climate change. To do so, we develop an analytical framework based on recent works in modern Ricardian trade models (Costinot et al., 2016; Gouel and Laborde, 2018). Those works explain reallocation of land across producers through the shifts in comparative advantage induced by the spatially differentiated effect of climate change. Our model presents similar features, with regard to the modeling of acreage decisions, the representation of the heterogeneity in productivity, and how climate change may affect comparative advantages and specialization patterns. We extend this framework to consider goods under GI that can be subject to supply control design by a producers' organization.

Supply control is introduced by quotas on land. The restriction on land distorts individual acreage decisions and generates a price premium on the GI good. This extension allows to capture a simple trade-off at the core of the supply control adjustment to future weather conditions: loosening specifications to allow more flexibility in land allocation or maintaining current specifications to increase the price premium. The balance between these two opposite forces is determined by the change in the productivity differential across individuals induced by climate change and the degree of market power attainable under new climate conditions.

Other types of supply control, e.g. restrictions on outputs, could be investigated. Also, further analytical results are expected to assess the interplay between collective and individual production adjustments in the face of climate change. Last, this framework can lay the groundwork for future empirical investigations of the adaptation of GI to climate change.

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Appendix A. Proofs and derivations of the model

Appendix A.1. Optimal farmer acreage choice

We recall that the probability of good k being produced by farmer ω is defined by Equation (6). We know that both $r^{GI}A^{GI}(\omega)$ and $r^{C}A^{C}(\omega)$ follows a Frechet distribution with shape parameter θ and scale parameter $\tilde{\gamma}r^{GI}A^{GI}$ and $\tilde{\gamma}r^{C}A^{C}$ respectively, where $\tilde{\gamma} = [\Gamma(1-1/\theta)]^{-1}$. Starting from Equation (6) and using the fact that $A^{GI}(\omega)$ and $A^{C}(\omega)$ are independantly distributed we get:

$$
\begin{aligned}
\pi^{GI} &= \Pr\left\{r^{GI}A^{GI}(\omega) = \max\left\{r^{GI}A^{GI}(\omega), r^{C}A^{C}(\omega),\right\}\right\} \\
\pi^{GI} &= \Pr\left\{r^{C}A^{C}(\omega) \leq r^{GI}A^{GI}(\omega)\right\} \\
\pi^{GI} &= \int_0^{\infty} \Pr\left\{r^{C}A^{C}(\omega) \leq a\right\} \mathrm{d}G^{GI}(a) \;\text{ where } G^{GI} \text{ is the C.D.F. of the Fréchet}(\theta, \tilde{\gamma}r^{GI}A^{GI}) \\
\pi^{GI} &= \int_0^{\infty} G^{C}(a)\mathrm{d}G^{GI}(a) \text{ with } \; G^{C} \text{ the C.D.F. of the Fréchet}(\theta, \tilde{\gamma}r^{C}A^{C}) \\
\pi^{GI} &= \int_0^{\infty} \exp\left[\left(-\tilde{\gamma}r^{C}A^{C}\right)^{\theta} a^{-\theta}\right] \mathrm{d}G^{GI}(a) \\
\pi^{GI} &= \int_0^{\infty} \exp\left\{-\left(\frac{\tilde{\gamma}r^{C}A^{C}}{a}\right)^{\theta}\right\} \frac{\mathrm{d}\left\{\exp\left[-\left(\frac{\tilde{\gamma}r^{GI}A^{GI}}{a}\right)^{\theta}\right]\right\}}{\mathrm{d}a}\mathrm{d}a \\
\pi^{GI} &= \int_0^{\infty} \theta\left(\tilde{\gamma}r^{GI}A^{GI}\right)^{\theta} a^{-\theta-1} \exp\left\{-\left(\frac{\tilde{\gamma}}{a}\right)^{\theta}\left[\left(r^{GI}A^{GI}\right)^{\theta} + \left(r^{C}A^{C}\right)^{\theta}\right]\right\} \mathrm{d}a \\
\pi^{GI} &= \theta\left(\tilde{\gamma}r^{GI}A^{GI}\right)^{\theta} \left[\frac{\exp\left\{-\left(\frac{\tilde{\gamma}}{a}\right)^{\theta}\left[\left(r^{GI}A^{GI}\right)^{\theta} + \left(r^{C}A^{C}\right)^{\theta}\right]\right\}}{\theta\tilde{\gamma}^{\theta}\left[(r^{GI}A^{GI})^{\theta} + (r^{C}A^{C})^{\theta}\right]}\right]_0^{\infty} \\
\pi^{GI} &= \frac{\left(r^{GI}A^{GI}\right)^{\theta}}{(r^{GI}A^{GI})^{\theta} + (r^{C}A^{C})^{\theta}} \left[\underbrace{\lim_{a\to+\infty} \exp\left\{-\frac{c}{a^{\theta}}\right\}}_{=1} - \underbrace{\lim_{a\to 0} \exp\left\{-\frac{c}{a^{\theta}}\right\}}_{=0}\right]
\end{aligned}
$$

with $c = \tilde{\gamma}^{\theta}\left[\left(r^{GI}A^{GI}\right)^{\theta} + \left(r^{C}A^{C}\right)^{\theta}\right]$ a constant term.

Appendix A.2. Conditional expected yields

Consider two random variables $r^{GI}A^{GI}(\omega)$ and $r^{C}A^{C}(\omega)$ that are both distributed Frechet with shape parameter θ and scale parameters $\tilde{\gamma}r^{GI}A^{GI}$ and $\tilde{\gamma}r^{C}A^{C}$ respectively, with $\tilde{\gamma} \equiv [\Gamma(1-1/\theta)]^{-1}$.

We want to show that:

$$\mathbb{E}\left[\left(A^{GI}(\omega) \mid r^{GI}A^{GI}(\omega) = \max\left\{r^{GI}A^{GI}(\omega), r^{C}A^{C}(\omega)\right\}\right)\right] = A^{GI}\left[\pi^{GI}\right]^{-1/\theta} \tag{A.1}$$

Proof. Denote with $\dot{A}^{GI}(\omega)$ the following random variable:

$$\dot{A}^{GI}(\omega) = \left(A^{GI}(\omega) \mid r^{GI}A^{GI}(\omega) = \max\left\{r^{GI}A^{GI}(\omega), r^{C}A^{C}(\omega)\right\}\right)$$

The distribution followed by $\dot{A}^{GI}(\omega)$ is then:

$$\Pr\left\{\dot{A}^{GI}(\omega) \le t\right\} = \Pr\left\{A^{GI}(\omega) \le t \mid r^{GI}A^{GI}(\omega) = \max\left\{r^{GI}A^{GI}(\omega), r^{C}A^{C}(\omega)\right\}\right\}$$

$$\Pr\left\{\dot{A}^{GI}(\omega) \le t\right\} = \frac{\Pr\left\{\left[A^{GI}(\omega) \le t\right] \cap \left[r^{GI}A^{GI}(\omega) = \max\left\{r^{GI}A^{GI}(\omega), r^{C}A^{C}(\omega)\right\}\right]\right\}}{\Pr\left\{r^{GI}A^{GI}(\omega) = \max\left\{r^{GI}A^{GI}(\omega), r^{C}A^{C}(\omega)\right\}\right\}}$$

$$\Pr\left\{\dot{A}^{GI}(\omega) \le t\right\} = \frac{\Pr\left\{(r^{C}/r^{GI})A^{C}(\omega) \le A^{GI}(\omega) \le t\right\}}{\pi^{GI}}$$

$$\Pr\left\{\dot{A}^{GI}(\omega) \le t\right\} = \frac{1}{\pi^{GI}}\int_0^t \Pr\left\{(r^{C}/r^{GI})A^{C}(\omega) \le v\right\} g^{GI}(v)\,\mathrm{d}v$$

$$\text{where } g^{GI}(a) = \theta\left(\tilde{\gamma}A^{GI}\right)^{\theta} a^{-\theta-1}\exp\left\{-\left(\frac{\tilde{\gamma}A^{GI}}{a}\right)^{\theta}\right\}$$

$$\Pr\left\{\dot{A}^{GI}(\omega) \le t\right\} = \frac{1}{\pi^{GI}}\int_0^t \theta\left(\tilde{\gamma}A^{GI}\right)^{\theta} v^{-\theta-1}\exp\left\{-\left(\frac{\tilde{\gamma}}{v}\right)^{\theta}\left[\left(A^{GI}\right)^{\theta} + \left((r^{C}/r^{GI})A^{C}\right)^{\theta}\right]\right\}\mathrm{d}v$$

$$\Pr\left\{\dot{A}^{GI}(\omega) \le t\right\} = \frac{\theta\left(\tilde{\gamma}A^{GI}\right)^{\theta}}{\pi^{GI}}\left[\frac{\exp\left\{-\left(\frac{\tilde{\gamma}}{v}\right)^{\theta}\left[\left(A^{GI}\right)^{\theta} + \left((r^{C}/r^{GI})A^{C}\right)^{\theta}\right]\right\}}{\theta\tilde{\gamma}^{\theta}\left[(A^{GI})^{\theta} + ((r^{C}/r^{GI})A^{C})^{\theta}\right]}\right]_0^t$$

$$\Pr\left\{\dot{A}^{GI}(\omega) \le t\right\} = \frac{\left(A^{GI}\right)^{\theta}}{\pi^{GI}}\left[\frac{\exp\left\{-\left(\frac{\tilde{\gamma}}{r^{GI}v}\right)^{\theta}\left[\left(r^{GI}A^{GI}\right)^{\theta} + \left(r^{C}A^{C}\right)^{\theta}\right]\right\}}{(r^{GI})^{-\theta}\left[(r^{GI}A^{GI})^{\theta} + (r^{C}A^{C})^{\theta}\right]}\right]_0^t$$

$$\Pr\left\{\dot{A}^{GI}(\omega) \le t\right\} = \exp\left\{-\left(\frac{(\tilde{\gamma}/r^{GI})\left[\left(r^{GI}A^{GI}\right)^{\theta} + \left(r^{C}A^{C}\right)^{\theta}\right]^{1/\theta}}{t}\right)^{\theta}\right\}$$

Therefore :

$$\left(A^{GI}(\omega) \mid r^{GI}A^{GI}(\omega) \;=\; \max\left\{r^{GI}A^{GI}(\omega), r^{C}A^{C}(\omega)\right\}\right) \sim \text{Fréchet}\,(\tilde{\gamma}Z, \theta) \tag{A.2}$$

$$\text{where } \tilde{\gamma} \equiv [\Gamma(1-1/\theta)]^{-1} \text{ and } Z \equiv (1/r^{GI})\left[\left(r^{GI}A^{GI}\right)^{\theta} + \left(r^{C}A^{C}\right)^{\theta}\right]^{1/\theta} = A^{GI}\left[\pi^{GI}\left(r^{GI}, r^{C}, A^{GI}, A^{C}\right)\right]^{-1/\theta}$$

and denote with $H(\cdot)$ its associated C.D.F.:

$$H(a) = \exp\left\{-\left(\frac{\tilde{\gamma}Z}{a}\right)^{\theta}\right\} \tag{A.3}$$

□

Appendix A.3. Aggregate supply under land restrictions

Denote with $\tilde{A}^{GI}$ the following conditional random variable:

$$\tilde{A}^{GI}(\omega) = \left\{A^{GI}(\omega) \mid \left(A^{GI}(\omega) \geq \underline{A}\right) \cap \left(r^{C}A^{c}(\omega) \leq r^{GI}A^{GI}(\omega)\right)\right\} \tag{A.4}$$

$r^{GI}A^{GI}(\omega)$ and $r^{C}A^{C}(\omega)$ that are both distributed Frechet with shape parameter θ and scale parameters $\tilde{\gamma}r^{GI}A^{GI}$ and $\tilde{\gamma}r^{C}A^{C}$ respectively, with $\tilde{\gamma} \equiv [\Gamma(1-1/\theta)]^{-1}$. We can write the probability distribution of $\tilde{A}^{GI}(\omega)$ as:

$$\Pr\left\{\tilde{A}^{GI}(\omega) \leq t\right\} = \frac{\Pr\left\{\underline{A} \leq A^{GI}(\omega) \leq t \mid r^{C}A^{C}(\omega) \leq r^{GI}A^{GI}(\omega)\right\}}{\Pr\left\{\underline{A} \leq A^{GI(\omega)} \mid r^{C}A^{C} \leq r^{GI}A^{GI}(\omega)\right\}}$$

$$\Pr\left\{\tilde{A}^{GI}(\omega) \leq t\right\} = \frac{H(t) - H(\underline{A})}{1 - H(\underline{A})} \text{ if } t \geq \underline{A} \text{ and 0 otherwise} \tag{A.5}$$

where $H(\cdot)$ is the C.D.F. of the Fréchet law defined in equation (A.3) with shape parameter θ and scale parameter $\tilde{\gamma}Z$, where $\tilde{\gamma} \equiv [\Gamma(1-1/\theta)]^{-1}$ and $Z \equiv A^{GI}\left[\pi^{GI}\left(r^{GI}, r^{C}, A^{GI}, A^{C}\right)\right]^{-1/\theta}$. Then, denote with $\tilde{H}(\cdot)$ the C.D.F. of the truncated Fréchet law defined above with lower limit $\underline{A}$, and its associated partial distribution function $\tilde{h}(\cdot)$. Then, their expressions are:

$$\tilde{H}(a) = \frac{\exp\left\{-\left(\frac{\tilde{\gamma}Z}{a}\right)^{\theta}\right\} - \exp\left\{-\left(\frac{\tilde{\gamma}Z}{\underline{A}}\right)\right\}}{1 - \exp\left\{-\left(\frac{\tilde{\gamma}Z}{\underline{A}}\right)\right\}} \tag{A.6}$$

$$\tilde{h}(a) = \frac{\theta\,(\tilde{\gamma}Z)^{\theta}\,a^{-\theta-1}\exp\left\{-\left(\frac{\tilde{\gamma}Z}{a}\right)^{\theta}\right\}}{1 - H(\underline{A})} \tag{A.7}$$

Thus, we can compute the mean of $\tilde{A}^{GI}(\omega)$:

$$\mathbb{E}\left[\tilde{A}^{GI}(\omega)\right] = \frac{1}{1 - H(\underline{A})}\left[\int_0^{\infty} a\tilde{h}(a)\mathrm{d}a - \int_0^{\underline{A}} a\tilde{h}(a)\mathrm{d}a\right]$$

with changing variable $a = (\tilde{\gamma}Z/y)^{\theta}$

$$\mathbb{E}\left[\tilde{A}^{GI}(\omega)\right] = \frac{1}{1 - H(\underline{A})}\left[Z - \int_{(\tilde{\gamma}Z/\underline{A})^{\theta}}^{\infty} \tilde{\gamma}Zy^{-1/\theta}\exp\{-y\}\,\mathrm{d}y\right]$$

$$\mathbb{E}\left[\tilde{A}^{GI}(\omega)\right] = \frac{Z}{1 - H(\underline{A})}\left[[\Gamma(1-1/\theta)]^{-1} \times \Gamma\left(1 - 1/\theta, (\tilde{\gamma}Z/\underline{A})^{\theta}\right)\right]$$

Then, pose $P(1-1/\theta, (\tilde{\gamma}Z/\underline{A})^{\theta}) = \frac{\Gamma\left(1-1/\theta, (\tilde{\gamma}Z/\underline{A})^{\theta}\right)}{\Gamma(1-1/\theta)}$, which is also called the regularized gamma function, or the ratio between the upper incumplete gamma function and the corresponding gamma function. Thus, the mean is:

$$\mathbb{E}\left[\tilde{A}^{GI}(\omega)\right] = \frac{Z\left[1 - P(1 - 1/\theta, (\tilde{\gamma}Z/\underline{A})^{\theta})\right]}{1 - H(\underline{A})} \tag{A.8}$$

$$\text{where } Z \equiv (1/r^{GI})\left[\left(r^{GI}A^{GI}\right)^{\theta} + \left(r^{C}A^{C}\right)^{\theta}\right]^{1/\theta} = A^{GI}\left[\pi^{GI}\left(r^{GI}, r^{C}, A^{GI}, A^{C}\right)\right]^{-1/\theta}$$

$$\text{and } \tilde{\gamma} \equiv \left[\Gamma\left(1 - 1/\theta\right)\right]^{-1}$$