Mitigating Greenhouse Gas Emissions from the Cattle Sector: Land-Use Regulation as an Alternative to Emissions Pricing

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Abstract

Reducing animal-based food production would not only reduce agricultural greenhouse gas emissions but also free land that could sequester carbon. We examine the efficiency of a subsidy to cattle farmers for setting aside land for natural ecosystem regeneration. We develop a partial equilibrium model of the cattle sector that integrates land use, greenhouse gas emissions, and animal feeding. We compare the subsidy to alternative policies: a meat tax and a standard on animal feeding. We identify conditions under which the subsidy is the best alternative to these other second-best policies. The efficiency of the subsidy lies in its effects on both the extensive margin (reduced quantity of meat) and the intensive margin (production intensification, which reduces both the emissions and land-use intensities of meat). An empirical application to France, where spontaneous regeneration corresponds mostly to forest regrowth, shows that the subsidy dominates the other alternative policies considered for a wide range of parameter values but is sensitive to carbon leakage when the economy is open to trade.

Keywords: Beef, Climate Policy, Land Set Aside, Land-Use Regulation, Second-Best Policy

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1 Introduction

Shifting to less animal-based food production could lead to a double climate dividend. It could simultaneously reduce greenhouse gas (GHG) emissions from meat production and sequester carbon if the spared land is dedicated to natural ecosystem regeneration. According to estimates in the existing literature, the associated mitigation potential is considerable (Hayek et al. 2021; Sun et al. 2022; Theurl et al. 2020).

In theory, a Pigouvian policy taxing all sources of GHG and rewarding all carbon sinks would decentralize the optimal allocation of land among carbon sinks and livestock production. However, technical (emissions monitoring) and political (acceptability, lobbying) barriers hinder the enforcement of a first-best carbon pricing policy (Grosjean et al. 2016). In a context where some regions of the world consider extending their climate policies to the agricultural sector, such as the European Union (Edenhofer et al. 2023), the question of the best alternative instruments proves crucial.

Motivated by (i) the importance of land use in the climate impact of meat production, (ii) the difficulty of implementing a Pigouvian policy in the integrated land use - livestock sectors, and (iii) the need to go beyond carbon pricing in policy discussions,[1] this paper proposes a novel, alternative instrument that has been mostly overlooked in the literature: namely, land retirement. More precisely, we study incentives (i.e., subsidies) for farmers to set aside land for spontaneous regeneration of natural ecosystems, and compare the performance of such a policy with more usual instruments. Our aim is to assess the welfare performances of such a land-use policy instrument as a second-best alternative to a tax on agricultural emissions or meat. Our analytical results are complemented with an empirical application to the French beef sector.

The study focuses on the cattle sector, which accounts for a large proportion of the GHG emitted (Xu et al. 2021) and the land used (Mottet et al. 2017) by livestock farming. This choice is also motivated by the synergy that exists between land use and GHG emissions from cattle production: extensive grass-based systems emit more GHG and also require more land than more intensive concentrate-based systems.[2]

We build a parsimonious partial equilibrium model of the beef cattle sector. The model integrates three land uses – namely, grassland, cropland, and natural reserves – and accounts for direct emissions from livestock, indirect emissions from feed crops, as well as carbon sequestration from land. On the supply side, farmers choose not only the quantity of meat they produce but also the feed ration for their animals which determines the emission and land-use intensities of meat. Understanding how different policy instruments affect those extensive and intensive margins is crucial for policy design.

Equipped with this model, we analyze the following policies against the first-best Pigou-

1. For example, a recent report ordered by the European Commission on GHG mitigation in agriculture only considers pricing emissions and implementing an emission trading scheme for the agricultural sector (Trinomics 2023), and not alternative instruments.

2. Life cycle assessments of beef cattle systems generally find that grass-based systems emit more GHG and use more land than systems based on energy-dense concentrates (Capper 2012; Vries, Middelaar, and Boer 2015). Supplemented with concentrates, animals grow and reach slaughter weight faster and emit less methane through enteric fermentation due to a higher digestibility of the feeds. Adding land-use emissions increases the gap between systems because of the higher land footprint (and carbon opportunity cost) of grass-based systems (see, e.g., Balmford et al. 2018; Blaustein-Rejto, Soltis, and Blomqvist 2023)

vian one: a subsidy for land set aside for spontaneous natural ecosystem regeneration, a meat tax, and a standard on animal feed ration. The policy instruments can act on two levers to mitigate emissions: a reduction of the quantity of meat (extensive margin), and an adjustment of the feed ration to decrease the emission intensity of meat (intensive margin). A Pigouvian policy affects both margins: it minimizes the social cost of meat at the intensive margin via production intensification, and efficiently reduces meat consumption at the extensive margin. A meat tax only reduces the quantity of meat. A standard on feed ration reduces the emission intensity of beef production, with a limited effect on the quantity. Like a Pigouvian policy, a subsidy for land set aside affects both margins but suboptimally since it targets land use instead of GHG sources and sinks. It creates an opportunity cost of land that acts as an implicit tax on meat which reduces consumption and also incentivizes farmers to intensify their production, which in turn reduces the carbon footprint of beef.

The results we derive from the model are the following. First, the subsidy for land set aside is welfare superior to the meat tax and the standard provided that the land-use and emission intensities of meat are sufficiently 'aligned'. Our calibration shows that it is the best alternative policy for a wide range of parameter values. Acting on both margins, its efficiency depends much less on the price elasticity of demand than the meat tax and on the cost of technical change than the standard. However, it depends critically on the potential for carbon sequestration on land set aside. Second, an optimal meat tax should integrate the carbon opportunity cost (COC) of land, i.e., the potential for carbon sequestration through ecosystem restoration on the land dedicated to beef production. We find that it could account for approximately 40% of the tax. Third, our simulations show that a standard performs poorly in general, as the reduction of beef production remains the main mitigation lever. Fourth, when allowing for carbon leakage through trade, the relative performance of the subsidy compared to the meat tax crucially depends on the emission intensity of foreign beef production.

Our main message is that a subsidy for land set aside could lead to significant welfare gains through mitigation at both margins, although the extensive margin remains the main mitigation lever. The meat tax performs relatively well by acting only on the extensive margin. Another merit of the subsidy is its potentially higher acceptability compared to a meat tax. The subsidy indirectly translates into higher meat prices because of the increased cost of agricultural land. Therefore, one can interpret the subsidy as a form of meat tax, the revenue from which is clearly earmarked for environmental purposes.[3] However, the risk of carbon leakage should be carefully considered when regulating domestic production.

The analysis of mitigation policies based on land use is not new in agricultural and environmental economics. A body of literature has examined the efficiency of incentives to set aside land for carbon sequestration (e.g., Feng et al. 2006; Mason and Plantinga 2013; Li, Sohngen, and Tian 2022). To our knowledge, our model is the first to represent the effect of such policies not only on carbon sequestration but also on agricultural production and GHG emissions through both margins.

Another growing body of literature has addressed the barriers to the implementation of

3. Earmarking the revenue of environmental taxes for environmental purposes generally increases public support (Kallbekken, Kroll, and Cherry 2011).

an emission tax in agriculture — especially the issue of emissions measurement — and proposed alternative policies (Bakam, Balana, and Matthews 2012; De Cara, Henry, and Jayet 2018; Garnache et al. 2017; Grosjean et al. 2016). However, land use policies have been mostly overlooked by those studies. Similarly, land use and the COC are absent from the literature on regulating livestock externalities, not only GHG emissions but also nutrient runoffs (see Lötjönen, Temmes, and Ollikainen 2020, and references therein). Furthermore, our framework allows to get explicit analytical results on the comparison of instruments. Our approach is therefore complementary to that based on large-scale numerical models (see e.g. Fellmann et al. 2021, for an application to GHG mitigation in European agriculture based on the CAPRI model). While such models provide a detailed representation of the heterogeneity of the agricultural supply, they do not offer a transparent representation of economic mechanisms, making it difficult to disentangle the welfare effects, especially when they involve changes at both the intensive and extensive margins.

Finally, several studies have analyzed the use of a consumption tax on meat (Bonnet, Bouamra-Mechemache, and Corre 2018; Funke et al. 2022; Katare et al. 2020; Wirsenius, Hedenus, and Mohlin 2011), arguing that the conditions on the welfare superiority of output taxes on emission taxes identified by Schmutzler and Goulder (1997) are met. Our results show that the optimal meat tax should integrate the COC and that it could miss significant welfare gains at the intensive margin, which is generally ruled out by this literature.

The rest of the paper is organized as follows. Section 2 presents the model, the policy instruments considered, and characterizes the social optimum. Alternative policies to the Pigouvian instrument are compared in Section 3. A numerical application for the French beef market is offered in Section 4. The model is extended to integrate international trade in Section 5. Limitations and policy implications are discussed in Section 6. Section 7 concludes.

2 Analytical Framework

2.1 Basic Set Up

We consider a partial equilibrium model of the cattle sector in a closed economy; an extension with international trade is discussed in Section 5. For the sake of simplicity, the model focuses on beef cattle, which are assumed to produce a homogeneous good, and exclude dairy cattle. Our stylized approach only includes the elements needed for the main trade-offs between direct GHG emissions, mainly due to enteric fermentation, and indirect emissions from feed production, land use, and land-use change.

The total quantity of beef produced and consumed is denoted q. On the demand side, the gross consumer surplus is $S(q)$, with $S'(q) > 0$ and $S''(q) < 0$. The consumer price is p and the net consumer surplus is $S(q) - pq$. The inverse demand function is $P(q) = S'(q)$, and the demand for meat at price p is denoted $D(p) = P^{-1}(p)$.

On the supply side, farmers choose the feed ration for their animals and the quantity of meat they produce. The feed ration consists of two components: grass (grazed, silage, and hay) and crops (including concentrates and fodder). Farmers choose the amount of grass per unit of meat, denoted x, which will be referred to as the *technique*. The associated amount of crops needed per unit of meat is $f(x) \geq 0$, with $f'(x) < 0$.[4] The cost of the feed ration per unit of meat is $c(x) > 0$, with $c''(x) > 0$. It is minimized at $x_0 > 0$, solution of $c'(x) = 0$. This cost do not only include the production costs of grass and crops, but also the labor and logistic costs of feeding the animals. We also integrate a function $i(q)$ that describes other variable costs (e.g., annual capital costs), assumed to be independent of the feed ration, with $i'(q) > 0$ and $i''(q) > 0$, reflecting decreasing returns to scale. Thus, the profit function of farmers is:

$$\pi(x, q) = (p - c(x))\, q - i(q). \tag{1}$$

Both consumers and producers are assumed to be price takers; they maximize their net surplus and profit, respectively.

Land use

The total available land $\bar{L}$ is allocated between cropland L_c, grassland L_g (pastures and meadows), and land set aside L_n on which spontaneous natural ecosystem regeneration is assumed. We further discuss this assumption in Section 6 and will refer to L_n as land set aside. With α_g and α_c the inverse of grassland and crop yields, respectively, the grassland area is $L_g = \alpha_g x q$, the crop area $L_c = \alpha_c f(x) q$, and the remaining land is set aside. We denote $l(x) = \alpha_g x + \alpha_c f(x)$, the land needed per unit of meat produced. Land set aside is then :

$$L_n = \bar{L} - (L_g + L_c) = \bar{L} - l(x)q. \tag{2}$$

The land used per unit of meat, $l(x)$, will play a critical role in assessing the efficiency of the subsidy for land set aside. For realistic parameter values, l is increasing with respect to x: the more grass-based the system, the higher the land requirements to produce one unit of meat (see, e.g., Capper 2012; Mogensen et al. 2015, for estimates of the land-use intensity of grass-based vs concentrate-based beef production systems).

GHG emissions

GHG emissions are decomposed into (i) direct emissions from meat production (including enteric fermentation, manure management, and housing), (ii) indirect emissions from feed crops (fertilization, harvest, and processing), and (iii) land-use emissions. Direct emissions per unit of meat are denoted by $e_d(x)$ and assumed positive and increasing with x.[5] Emissions per unit of feed from crops are summarized by the emission factor e_c. Finally, we consider the capacity of soils and plants to sequester carbon at different intensities depending on land uses. We assume that each land use $i \in \{g, c, n\}$ sequesters an amount θ_i of GHG per unit of area per year. Issues associated with the dynamic of carbon sequestration are discussed in Section 6. It should be stressed that, in the following analysis, only relative emissions rates matter and not their absolute values. Total emissions are then:

$$E(x, q) = e_d(x)q + e_c f(x)q - \theta_g L_g - \theta_c L_c - \theta_n L_n.$$

4. We summarize the production process to feeding animals because it is the main factor that explains the land and emission intensity of beef production (see, e.g., Capper 2012). The function $f(.)$ can be interpreted as a zootechnical constraint: the quantity of crops needed to produce one unit of beef given an amount of grass x.

5. Most direct emissions are enteric methane, and the higher the amount of grass in the ration, the higher the feed energy conversion into methane (IPCC 2019). In addition, life cycle analyses indicate that enteric methane emissions, and more generally direct emissions, are higher for grass-fed beef cattle than non-grass fed beef cattle (Capper 2012; Mogensen et al. 2015).

Replacing L_g and L_c by their expression and L_n with equation (2) gives:

$$(3)\quad E(q,x) = q\underbrace{\left[e_d(x) + e_c f(x) + (\theta_n - \theta_g)\alpha_g x + (\theta_n - \theta_c)\alpha_c f(x)\right]}_{\equiv e(x)} - \theta_n \bar{L} = e(x)q - \theta_n \bar{L}.$$

In equation (3), land-related carbon flows are gathered to highlight the COC of land use, $\theta_n - \theta_i$. This COC differs according to the use i of the land, in line with the literature that shows that carbon sequestration rates from ecosystem regeneration depend on the antecedent land use (see, e.g., Cook-Patton et al. 2020, in the case of natural forest regrowth). With this definition of the COC, land set aside has a zero COC and θ_g and θ_c should be interpreted as the effect of the land use on the COC rather than a pure sequestration rate of grassland and cropland, respectively.

Total net emissions per unit of meat, $e(x)$, encompass direct, indirect, and land-use emissions. They are positive if θ_n is larger than both θ_g and θ_c, consistent with empirical evidence (see Section 4).

The monotonicity of $e(x)$ is not straightforward because of the substitution between grass and crops captured by $f(x)$. Our assessment of the literature (see Section 4) indicates that $e(x)$ is increasing. Non-land-use effects are likely positive, i.e., $e'_d(x) > -e_c f'(x)$ (see, e.g., Balmford et al. 2018; Capper 2012; Vries, Middelaar, and Boer 2015), as well as land-use effects, i.e., $(\theta_n - \theta_g)\alpha_g > -f'(x)(\theta_n - \theta_c)\alpha_c$, given the relatively small amount of crops needed to substitute a unit of grass (Blaustein-Rejto, Soltis, and Blomqvist 2023).

We assume a linear damage function and denote the marginal damage per unit of GHG δ. The latter is referred to as the Social Cost of Carbon (SCC). Welfare is then:

$$(4)\qquad W(q,x) = S(q) - c(x)q - i(q) - \delta\left(e(x)q - \theta_n \bar{L}\right).$$

2.2 Social Optimum

The social optimum is a couple (q^*, x^*) that maximizes the welfare function given by (4) and satisfies the two following first-order conditions (if both are positive):

$$(5)\qquad S'(q) = c(x) + \delta e(x) + i'(q),$$

$$(6)\qquad -c'(x) = \delta e'(x).$$

The model allows for disentangling the technical choice from the quantity produced. The optimal quantity of meat (equation 5) is such that the marginal utility of meat consumption equals its marginal social cost. The optimal technique (equation 6) is such that the marginal increase in production costs per unit of meat from changing the feed ration is equal to the marginal environmental benefit. The direction of this change depends on the monotonicity of total unitary emissions $e(x)$ with respect to the quantity of grass per kg of meat. Indeed, unitary emissions are reduced at the optimum.

2.3 Policy Instruments Considered

Equipped with this model, we compare the mechanism and welfare implications of the following policy instruments:

- A Pigouvian price τ on all GHG emissions and removals;
- A tax on meat t;
- A technical standard on animal feed ration $\bar{x}$;
- A subsidy s to set aside land. It is equivalent to a zoning policy that would enforce a total area L_n for natural ecosystem regeneration.

Each instrument induces a quantity q of meat produced with a technique x through market equilibrium. The specific expression of the profit function depends on the instrument used, but we can write the profit if all instruments are combined:

$$\Pi(x, q, \mathbf{r}) = [p - t - c(x)]q - i(q) - \tau[e(x)q - \theta_n \bar{L}] + s[\bar{L} - l(x)q], \tag{7}$$
$$\text{subject to } x = \bar{x} \text{ if a standard is used.}$$

Note that this profit aggregates the profits of farmers and landowners. If we consider that farmers rent land to landowners, the instruments will influence the price of land and transfers between landowners and farmers.

3 Decentralization and Instruments Comparison

3.1 First Best and Combination of Instruments

In a simple model without heterogeneity, several combinations of instruments can decentralize the first best.

Lemma 1 *The optimal allocation x^* and q^* can be obtained with several combinations of policies:*

- *an exhaustive Pigouvian tax on emissions $\tau = \delta$*
- *a regulatory standard $\bar{x} = x^*$ and a tax on meat $t = \delta e(x^*)$*
- *a regulatory standard $\bar{x} = x^*$ and a subsidy to set aside land $s = \frac{\delta e(x^*)}{l(x^*)}$*
- *a tax $t = \delta\left(e(x^*) - \frac{e'(x^*)}{l'(x^*)} l(x^*)\right)$ and a subsidy $s = \delta e'(x^*)/l'(x^*)$*

With a Pigouvian policy on all carbon flows, notably the (negative) ones associated with carbon sequestration, the optimum is decentralized. In the absence of heterogeneity, with only two variables q and x, any combination of two instruments can implement the optimal allocation.

3.2 Second-Best Policies and the Two Levers

The first-best strategy consists in adjusting the two levers: the quantity of beef q and the technique x. Imperfect instruments mobilize these two levers sub-optimally, and each instrument favors one of the levers compared to the first-best allocation. A meat tax only affects the quantity (Lemma 2) and does not allow technical adjustment at the intensive margin. The technical standard mainly affects the technique and only indirectly reduces the quantity by increasing the marginal cost of beef production (Lemma 3). The subsidy for land set aside works as an imperfect mix of a tax and a technical standard. Whether the subsidy favors the extensive margin (quantity) or intensive margin (technique) depends on the 'alignment' between land use and GHG emissions. More precisely, it depends on the x-elasticity of the emission intensity relative to that of the land-use intensity (Proposition 1).

For each instrument, we analyze the second-best allocation obtained by maximizing social welfare given by equation (4). For the meat tax and the subsidy, the two variables (q, x) at the second-best allocation are denoted q_r^{SB} and x_r^{SB} with $r \in \{tax, sub\}$, respectively. We assume here that welfare is quasi-concave for the standard and the subsidy. To describe these second-best situations, it is useful to define the optimal quantity for a given technique x.

Definition 1 *The quantity that maximizes the welfare function (4) for a given technique x is denoted $q^\times(x)$ and satisfies $S'(q^\times(x)) = c(x) + i'(q^\times(x)) + \delta e(x)$.*

This optimal quantity is a decreasing function of the cost $c(x) + \delta e(x)$. It reaches its maximum at the optimal technique x^*, which minimizes that cost.

With a **meat tax** t, at the market equilibrium (from eq. (7)):

$$S'(q) = p = c(x) + i'(q) + t \text{ and } c'(x) = 0. \tag{8}$$

The technique remains at x_0, and the meat tax is chosen so that the quantity consumed is $q^\times(x_0)$ (cf. Definition 1).

Lemma 2 *The optimal meat tax is $t^{SB} = \delta e(x_0)$. It is larger than the optimal net Pigouvian tax $\delta e(x^*)$. At the optimal tax, the quantity of meat consumed, q_{tax}^{SB}, is lower than the optimal quantity, q^*, and the quantity of grass per unit of meat, x_{tax}^{SB}, is larger than the optimal quantity x^* if and only if $e'(x^*) > 0$. Formally, $q_{tax}^{SB} = q^\times(x_0) \leq q^*$ and*

$$x_{tax}^{SB} = x_0 \geq x^* \;\Leftrightarrow\; e'(x^*) \geq 0.$$

A **technical standard** $\bar{x}$ mainly acts on the technique and indirectly influences the quantity through the marginal cost. At the market equilibrium, $S'(q) - i'(q) = c(x)$ (from eq (7)), and the cost being minimized at x_0, any change of x away from x_0 induces an increase in the marginal cost and a reduction in the equilibrium quantity of meat. The optimal standard implies a larger technical change than the first-best technique, i.e. $|\bar{x} - x_0| \geq |x^* - x_0|$, because of its effect on the quantity produced. So, if net emissions increase with the grass intensity, then the optimal technique is more stringent, and meat production is less grass-based than at first best.

Lemma 3 *Technical change is larger with an optimal second-best standard $\bar{x}^{SB}$ than in the first-best allocation. Formally, $x_0 > x^* > \bar{x}^{SB}$ if and only if $e'(x^*) > 0$, and $x_0 \leq x^* \leq \bar{x}^{SB}$ if and only if $e'(x^*) \leq 0$.*

The quantity produced is larger than $q^\times(\bar{x}^{SB})$ and may be higher or lower than the first-best quantity q^*.

Proof in Appendix A.

With a **subsidy** s to land set aside, the farming sector maximizes the profit $\pi_{sub} = (p - c(x) - sl(x))q - i(q) + s\bar{L}$. At market equilibrium, the quantity $q_{sub}(s)$ and technique

$x_{sub}(s)$ solve the two following equations:

$$S'(q) - c(x) - i'(q) = p - c(x) - i'(q) = sl(x), \tag{9}$$

$$-c'(x) = sl'(x). \tag{10}$$

If the land required per unit of meat is increasing with the amount of grass, i.e., $l'(x) > 0$, which is likely, then both the quantity produced and the amount of grass per unit of meat decrease with the subsidy. In that case, and if $e'(x^*) > 0$, then both levers move in the right direction relative to the first-best, but not optimally.

The optimal subsidy solves

$$0 = \frac{\partial W}{\partial q}\frac{\partial q}{\partial s} + \frac{\partial W}{\partial x}\frac{\partial x}{\partial s} = [sl(x) - \delta e(x)]\frac{\partial q}{\partial s} + [sl'(x) - \delta e'(x)]\, q\frac{\partial x}{\partial s} \tag{11}$$

The subsidy affects both the quantity produced and the technique chosen. Equation (11) highlights the trade-off between the two levers as, at the optimum, $\partial W/\partial q$ and $\partial W/\partial x$ have opposite signs (with $l'(x) > 0$). The optimal subsidy lies between $\delta e(x)/l(x)$ and $\delta e'(x)/l'(x)$, and the comparison between the two bounds determines which lever is favored.

Rearranging Equation (11) gives:

$$s\left[l'(x)q\frac{\partial x}{\partial s} + l(x)\frac{\partial q}{\partial s}\right] - \delta\left[e'(x)q\frac{\partial x}{\partial s} + e(x)\frac{\partial q}{\partial s}\right] = 0 \tag{12}$$

Equation (12) highlights the trade-off between total land use (first bracket) and total emissions (second bracket). It also shows that the optimal subsidy equals the SCC times the ratio of its marginal effect on total emissions ($e(x)q$) and its marginal effect on total land use ($l(x)q$).

The performance of the subsidy and the allocation of effort between levers depends on the 'alignment' between the two objectives: reducing land use and reducing GHG emissions. This alignment can be characterized by comparing the x-elasticities of the land-use and emission intensities of meat production at the optimal technique $x = x^*$. To avoid multiplying the possible cases, we focus on the most likely situation, in which e and l are increasing functions of x.

Proposition 1 *The optimal subsidy for land set aside induces either an over-reliance on meat reduction (extensive margin) and an under-reliance on technical adjustment (intensive margin) or vice versa.*

Formally, if $l'(x) > 0$ and $e'(x) > 0$, then

- *If $l'(x^*)/l(x^*) = e'(x^*)/e(x^*)$, the subsidy for land set aside decentralizes the first-best with $s^{SB} = \delta e(x^*)/l(x^*)$,*
- *If $l'(x^*)/l(x^*) < e'(x^*)/e(x^*)$, then $x_0 > x_{sub}^{SB} > x^*$ and $q_{sub}^{SB} < q^{\times}(x_{sub}^{SB}) < q^*$,*
- *If $l'(x^*)/l(x^*) > e'(x^*)/e(x^*)$, then $x_{sub}^{SB} < x^* < x_0$ and $q_{sub}^{SB} > q^{\times}(x_{sub}^{SB})$. q_{sub}^{SB} can be higher or lower than q^*.*

Proof in Appendix B.

The intuition for Proposition 1 is the following. Suppose the land-use intensity of meat is more sensitive to a reduction in the quantity of grass than the emission intensity of meat (i.e., $l'/l > e'/e$). In that case, farmers will be more incentivized to reduce their quantity of grass with a subsidy than with an emission tax. The opportunity cost of land ($sl(x)$) is reduced through intensification, and the quantity of meat at equilibrium with the subsidy remains high compared to the first-best. The optimal subsidy is then such that

$$\delta \frac{e'}{l'} < s < \delta \frac{e}{l}.$$

The results are illustrated in Figure 1 which depicts iso-welfare curves in the (q, x) plan, together with the paths (thick lines) followed with each instrument. All instruments start at the business-as-usual (BAU) point, in the top right, and progressively ascend the 'welfare mount'. Only an emission tax reaches the 'Pigou summit', corresponding to the first-best allocation (q^*, x^*). Other instruments reach a lower welfare level at the point of tangency between their path and an isoquant (dashed lines).

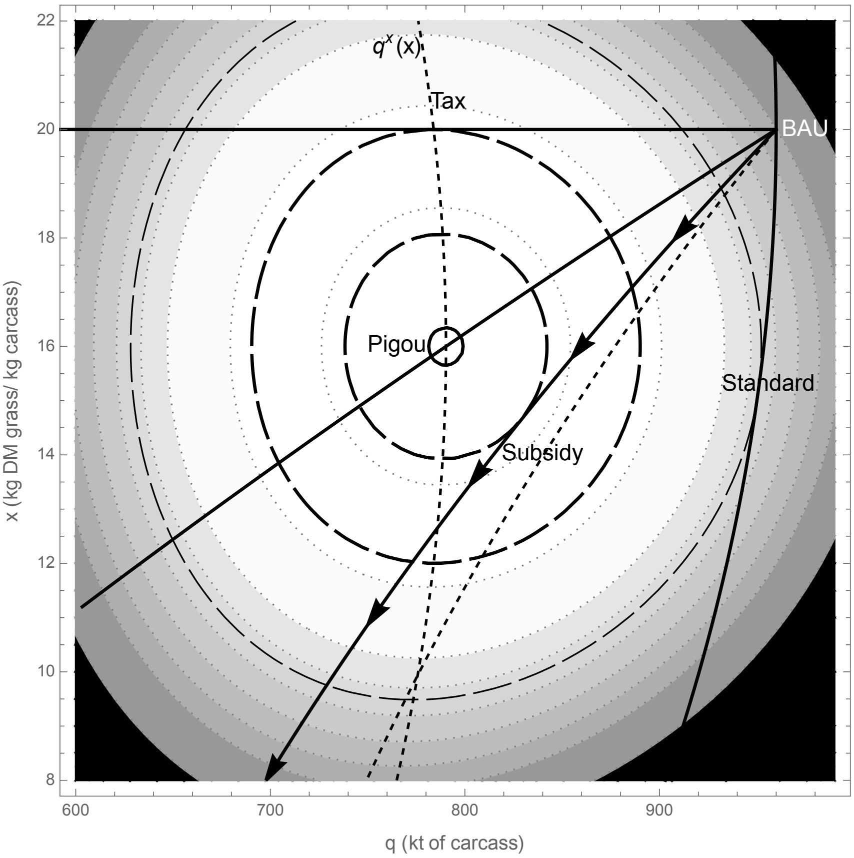

Figure 1: Iso-welfare curves in the (q, x) plan with paths followed by each instrument. Lighter shades represent larger welfare values. Parameter values are as in the baseline calibration. The dashed line corresponds to a larger l' (lower alignment, see Proposition 1).

As the subsidy increases, with $e'(x) > 0$ and $l'(x) > 0$, the quantity consumed and the chosen technique move in the right direction. In Figure 1, the couple (q_{sub}, x_{sub}) follows the line with arrows when the subsidy increases. The path taken with the subsidy differs from the one followed with an emission tax (that reaches the Pigou summit). If land use is more elastic than emissions to x, then the technique is relatively more responsive to the subsidy than to an emission tax (the subsidy path is below the emission tax path). In that case, the optimal subsidy is associated with an over-intensification of beef production and excessive meat production. When the difference between l'/l and e'/e is larger, as illustrated by the dotted line, the subsidy path is further away from the emission tax path. It reaches a lower maximum level of welfare.

3.3 Welfare Comparison

Anticipating that the model will be calibrated below, and to get explicit formulas, we use in this section the following specification:

$$S(q) = (a - \frac{b}{2}q)q \tag{13a}$$

$$c(x) = c_0 + \frac{\gamma}{2}(x - x_0)^2 \tag{13b}$$

$$i(q) = \frac{i_0}{2}q^2 \tag{13c}$$

$$e_d(x) = e_{d0} + \epsilon_d(x - x_0) \tag{13d}$$

$$f(x) = f_0 + \phi(x_0 - x) \tag{13e}$$

In this specification, a is the maximal willingness to pay for beef meat and $1/b$ can be interpreted as the market size. Without any regulation, the technique chosen is x_0, and the parameters e_{d0}, and f_0 correspond to the direct emissions, and amount of crops per unit of meat, respectively, while c_0 is the marginal cost of the first unit of meat produced. To ensure a positive production for reasonable values of the external damage, one needs $a > c_0 + \delta e(x_0)$. With this specification, both $e(x)$ and $l(x)$ are linear functions of x. They are minimized at $x = 0$ if their slope is positive, as is the case in our simulations (see Table 1).

Before formally comparing the different policy instruments, let us consider some specific cases. If mitigation at the intensive margin is not possible ($\gamma = +\infty$) or useless ($e'(x) = 0$), then a meat tax implements the first-best. A technical standard is optimal if emissions are null at the optimal technique ($e(x^*) = 0$) or with an inelastic demand ($a = +\infty$). A subsidy for land set aside is optimal when the land-use intensity and the emission intensity of meat production have the same x-elasticity ($e'(x)/e(x) = l'(x)/l(x)$). Those specific cases provide intuition on the influence of parameters on the comparison of instruments that we explore below.

The welfare can be expressed as the difference between the first-best and two terms related to each margin:

$$W(q, x) = W(q^*, x^*) - \frac{b + i_0}{2}(q - q^*)^2 - \frac{\gamma}{2}(x - x^*)^2 q. \tag{14}$$

While we cannot obtain an explicit formula for second-best welfare with a standard or a subsidy, the welfare losses can be bounded.

Proposition 2 *With specification (13), the welfare losses induced by the different instruments compared to the first best allocation have the following characteristics.*

- *The welfare loss with an optimal meat tax is:*

$$\left[W(q^*, x^*) - W_{tax}^{SB}\right] = \frac{\delta^2}{2(b+i_0)} \frac{e'^2}{\gamma} \left[a - (c_0 + \delta e(x_0)) + \frac{(\delta e')^2}{4\gamma}\right].$$

- *The welfare loss with an optimal standard is bounded as follows:*

$$\frac{\delta^2}{2(b+i_0)} e(x_0)^2 \leq \left[W(q^*, x^*) - W_{sta}^{SB}\right] \leq \frac{\delta^2}{2(b+i_0)} e(x^*)^2.$$

- *The welfare loss with an optimal subsidy is bounded as follows:*

$$0 \leq \left[W(q^*, x^*) - W_{sub}^{SB}\right] \leq \frac{\delta^2}{2(b+i_0)} e'^2 \left(\frac{e(x^*)}{e'} - \frac{l(x^*)}{l'}\right)^2.$$

Calculations are provided in Appendix C. The bounds obtained in Proposition 2 allow to distinguish situations in which one of the instruments is welfare superior to the two others. The market size ($1/b$) does not influence welfare comparison, given the absence of scale economies. With all instruments, welfare losses are proportional to the square of the SCC, and to the slope of the emission intensity relative to grass intake (e'). For the standard and the subsidy, the upper bounds correspond to $x = x^*$, either directly or by setting the subsidy adequately ($s = \delta e'/l'$).

We can then compare instruments with each other. The comparison between a meat tax and a technical standard relies mainly on the demand elasticity (through a) and the effectiveness of technical adjustment (e' and γ). The comparison of the bounds found in Proposition 2 gives the following corollary.

Corollary 1 ***Tax versus Standard*** *If demand is sufficiently inelastic (elastic) and technical adjustment cheap (costly), then welfare is higher (lower) with a standard than with a meat tax.*

The efficiency of the subsidy is related to the difference between the x-elasticities of the land-use and emission intensities, that is the relative slope of the land-use and emission intensities, l'/l and e'/e (Proposition 1). If the difference is small enough, the subsidy is welfare superior to the two other instruments.

Proposition 3 *If the difference between the x-elasticities of the land-use and emission intensities is small, then the subsidy is welfare superior to the two other instruments.*

Formally, the subsidy dominates the tax if

$$\left(\frac{e}{e'} - \frac{l}{l'}\right)^2 \leq \frac{1}{\gamma}\left[a - (c_0 + \delta e_0) + \frac{(\delta e')^2}{4\gamma}\right] \tag{15}$$

and it dominates the standard if

$$\left(\frac{e}{e'} - \frac{l}{l'}\right)^2 \leq \left(\frac{e(0)}{e'}\right)^2. \tag{16}$$

The results are derived from the bounds obtained in Proposition 2. It is worth noting that with linear functions, the difference $e/e' - l/l'$ does not depend on x. If that difference is null, GHG emissions are simply proportional to the land requirement. In our baseline numerical calibration, the difference is positive, and in that case, inequality (16) always holds such that the subsidy always dominates the standard.

In the relationship between emissions and land use, $e(x) = e_d(x) + e_c f(x) - \theta_g \alpha_g x - \theta_c \alpha_c f(x) + \theta_n l(x)$, the alignment between the two depends mainly on the carbon sequestration potential of the spontaneous regeneration of natural ecosystems, θ_n, and:

$$\frac{d}{d\theta_n} \left| \frac{e}{e'} - \frac{l}{l'} \right| < 0.$$

We can then derive the following corollary of Proposition 3 .

Corollary 2 *The subsidy for land set aside is more likely to dominate the tax and the standard if the amount of carbon sequestered by natural ecosystem regeneration (θ_n) is large.*

4 Numerical Application

In this section, we conduct numerical simulations to determine the ranking of the policy instruments considered and estimate its sensitivity to parameter values. The model is calibrated with aggregated data from the French beef sector using specification (13). France is a relevant case study since it is the largest beef producer in Europe, most of its antecedent natural vegetation consists of high carbon stock forests, and most of its abandoned agricultural land has become naturally regenerated forest over the last decades.[6] Subsection 4.1 describes the data used for calibration. The second subsection presents the results of the baseline scenario and sensitivity analyses.

4.1 The Data

Table 1 lists the baseline values of the parameters used for calibration and their probability distribution (for details on data and sources, see Appendix E.1).

Demand parameters. The intercept a and slope b of the inverse demand function are calculated from the quantity of beef q_0 (expressed in carcass weight, denoted CW) and price of beef p_0 in the business-as-usual (hereafter BAU) situation (derived from Agreste 2021; Idele and CNE 2021), and the price elasticity of beef demand η (from Gallet 2010).[7]

Supply parameters. Since there is a wide diversity of beef cattle production systems in France, it is challenging to set a representative value of grass intake per unit of meat produced. Based on life-cycle analyses of French beef systems (see Morel et al. 2016; Nguyen et al. 2012; Nguyen et al. 2013), we assume x_0 equals 20 [kg grass].[kg CW]$^{-1}$

6. FAOSTAT data show that the French agricultural area decreased by 2.04 million hectares between 1990 and 2020 while the area of naturally regenerated forest increased by 1.91 million hectares, i.e., 94% of the land taken out of production. This is confirmed by analyses of more disaggregated data (Chakir, Cara, and Vermont 2017).

7. Formally, with η, p_0 and q_0 given, the parameters a and b solves $a - bq_0 = p_0$ and $-p_0/bq_0 = \eta$ so that $b = -\frac{p_0}{\eta q_0}$ and $a = p_0 \frac{\eta - 1}{\eta}$

and γ 0.01 €.[kg CW].[kg grass]$^{-2}$. Parameters f_0 and ϕ of the function $f(.)$ are estimated with a simple OLS regression using the dataset provided in the meta-analysis of Gérard (2023). The intercept c_0 and slope i_0 of the inverse supply curve are calculated from the equilibrium (p_0, q_0) and the price elasticity of beef supply (calibrated from estimates of Marsh 2003; McKendree et al. 2020).

Land use and emission parameters. Values of α_g and α_c are based on the average French national yield for cereals and grasslands (Agreste 2021). The total available land is defined as all the land initially dedicated to beef cattle plus some land set aside, in order to have interior solutions and avoid saturating the land constraint. We find that the land dedicated to beef cattle in France is $q_0 l(x_0) = 3.86$ million hectares, consistent with existing estimates of the French area dedicated to beef cattle farms (Lherm, Agabriel, and Devun 2017). We consider a total land area of 4.5 million hectares. Note that this value does not influence the ranking of instruments.

The linear form of $e_d(x)$ is estimated by OLS with the data from Gérard (2023). We find a positive slope, significant at the 1% level ($R^2 = 0.4$), with an increase of 0.51 kgCO_2eq/kg of meat for each additional kg of grass intake. The emission factors associated with crops, e_c, are set considering the range of emission factors of feeds found in the *ECOALIM Agribalyse* database.[8] The land-related carbon flows (θ_c, θ_g, and θ_n) are calibrated using the values of carbon stocks of Pellerin, Bamière, and al. (2020) for grasslands and cropland and of Efese (2019) for forests. The parameters correspond to these carbon stocks linearly annualized over 80 years, recognized as being reasonably sufficiently long to reach the steady state of carbon stocks after land-use changes for the three land uses considered.[9] The social cost of carbon is set at €50 per ton of CO_2, close to the carbon tax currently applied in France on fossil fuels (€44.6 per ton of CO_2).

4.2 Results

We proceed as follows. We first compare the instruments in the baseline scenario in terms of welfare, emissions, beef production, adopted technique, and land use. Then, we analyze the sensitivity of our results to critical parameters.

Baseline scenario

The results obtained in the baseline scenario are provided in Table 2. The subsidy for land set aside is the best alternative to the Pigouvian policy, achieving welfare gains that are only 7% lower than the first-best ones. The welfare losses with the meat tax and the standard amount to 23% and 66% of the first-best welfare gains, respectively.

The subsidy benefits from its effect on both intensive and extensive margins. Note that the quantity of meat and the technique with the subsidy are intermediate compared to those with the two other alternative policies. The quantity of meat consumed is greater with the subsidy than in the first-best situation but is associated with a lower x (14.78 vs 16.14), leading to similar levels of overall land requirements. The baseline scenario lies in

8. Database in open access at https://www6.inrae.fr/ecoalim/

9. See Cook-Patton et al. (2020) and Lewis et al. (2019) for elements on the time to recover plant carbon accumulation of old-growth forests, and Bárcena et al. (2014) for the dynamic of soil organic carbon stocks after land conversion to a forest. For grasslands and cropland, see Poeplau et al. (2011) for an analysis of the dynamic of soil organic carbon after land-use change.

Table 1: Parameter values for calibration

Description	Parameter	Value (baseline scenario)	Probability distribution
Price elasticity of beef demand	η	-0.9	$\mathcal{U}(-0.50, -1.40)$
Intercept of the inverse demand function (€/kg)	a	8.23	
Slope of the inverse demand function (€/kg^2)	b	4.51×10^{-9}	
Cost-minimizing amount of grass (kg/kg CW)	x_0	20	
Cost-minimizing amount of crops (kg/kg CW)	f_0	4.08	$\mathcal{N}(4.08, 0.34)$
Cost of technical change (€.kg CW/kg grass^2)	γ	0.01	$\mathcal{U}(10^{-4}, 0.03)$
Substitution rate between crops and grass (kg crops/kg grass)	ϕ	0.30	$\mathcal{N}(0.30, 0.05)$
BAU market price of beef (€/kg CW)	p_0	3.9	
Price elasticity of beef supply (€/kg CW)	ξ	0.5	$\mathcal{U}(0.25, 1.5)$
Intercept of the inverse supply function (€/kg CW)	c_0	-3.9	
Slope of the inverse supply function (€/kg CW)	i_0	8.13×10^{-9}	
BAU quantity of beef at market equilibrium (kg CW)	q_0	9.60×10^{8}	
Inverse grassland yield (m^2/kg)	α_g	1.67	$\frac{10}{\mathcal{N}(6,1.5)}$
Inverse crop yield (m^2/kg)	α_c	1.67	$\frac{10}{\mathcal{N}(6,1.5)}$
Total available land (m^2)	$\bar{L}$	4.5×10^{10}	
Direct emissions growth rate with the amount of grass (kgCO_2eq/kg grass)	ϵ_d	0.51	$\mathcal{N}(0.51, 0.07)$
Direct emissions of beef when $x = x_0$ (kgCO_2eq/kg CW)	e_{d0}	24.22	$\mathcal{N}(24.22, 0.50)$
Emission factor of crops (kgCO_2eq/kg crops)	e_c	0.50	
Annual carbon sequestration of grasslands* (kgCO_2eq/m^2)	θ_g	0.39	$\mathcal{N}(0.39, 0.03)$
Annual carbon sequestration of crops* (kgCO_2eq/m^2)	θ_c	0.24	$\mathcal{N}(0.24, 0.01)$
Annual carbon sequestration of land set-aside* for forest regeneration (kgCO_2eq/m^2)	θ_n	0.81	$\mathcal{U}(0.36, 0.96)$
Social cost of carbon (€/kgCO_2eq)	δ	0.05	

* These parameters should be interpreted with caution (see Section 6).

the third case of Proposition 1. Indeed, we have $e(x^*) = 41.4$; $e'(x^*) = 0.8$; $l(x^*) = 35.7$; and $l'(x^*) = 1.2$, which gives $l'(x^*)/l(x^*) > e'(x^*)/e(x^*)$.

Table 2: Results in the baseline scenario

	BAU	First-best $\tau = \delta$	Subsidy s^{SB}	Tax t^{SB}	Standard $\bar{x}^{SB}$
$\Delta W = W - W^{BAU}$ (M€)	0	253.25	236.62	194.73	86.23
	(-100%)	(·)	(-7%)	(-23%)	(-66%)
q (kt of carcass)	960	790.34	827.92	784.46	951.48
	(21%)	(·)	(5%)	(-1%)	(20%)
x (kg DM grass/ kg carcass)	20	16.14	14.78	20	15.36
	(24%)	(·)	(-8%)	(24%)	(-5%)
p (€/kg)	3.9	4.67	4.5	4.69	3.94
	(-16%)	(·)	(-4%)	(0%)	(-16%)
E ($MtCO_2eq$)	6.03	-3.84	-3.16	-1.75	2.25
$\frac{E^{BAU}-E}{E^{BAU}-E^{FB}}$	(0%)	(.)	(93%)	(79%)	(38%)
L_n (Mha)	0.64	1.68	1.67	1.35	1.19
	(-62%)	(·)	(-1%)	(-20%)	(-29%)
L_g (Mha)	3.21	2.13	2.04	2.62	2.44
	(51%)	(·)	(-4%)	(23%)	(15%)
L_c (Mha)	0.65	0.69	0.78	0.53	0.87
	(-6%)	(·)	(13%)	(-23%)	(26%)

Notes: Differences relative to the first best are indicated in parenthesis.

The meat tax reduces consumption but does not affect the production technique. It follows that 20% less land is set aside compared to the first-best land allocation, despite a lower quantity of meat. The lack of technical adjustment induces a higher carbon footprint (Table 3).

The technical standard leads to a more intensive production technique than the first-best one, consistently with Lemma 3. The standard also induces the largest quantity of meat because of its relatively small impact on the meat price, which is 16% lower than the first-best price. Overall, despite an important intensification of the production, the area of land set aside for forest regeneration remains 29% lower than in the first-best case.

Regarding total GHG emissions, in the first-best situation, the area of land set aside is sufficiently large to offset the emissions from the beef sector (Table 2, fifth row). The same conclusion holds for the subsidy with which a close level of carbon sequestration is achieved. Carbon sequestration with a meat tax is more limited while the beef sector remains a net GHG emitter with a standard.

Table 3 shows the decomposition of GHG emissions per unit of meat. The carbon footprint of beef can be substantially mitigated by reducing the amount of grass in cattle feeding; it is up to 9% lower with the subsidy than in the BAU situation. Direct emissions represent a bit more than half of the carbon footprint and this share is stable whatever the instrument. COC-induced GHG emissions account for about 40% of the beef carbon footprint and increase with the amount of grass fed to cattle. The share of GHG emissions from crops remains limited, even when the feed ration relies heavily on crops, in line with the literature (Poore and Nemecek 2018).

Table 3: Decomposition of beef carbon footprint

	BAU/ Tax t^{SB}	First-best $\tau = \delta$	Subsidy s^{SB}	Standard $\bar{x}^{SB}$
Carbon footprint ($e(x)$, $kgCO_2eq$)	44.4	41.4	40.3	40.8
Direct emissions ($e_d(x)$)	54.6 %	53.8 %	53.5 %	53.6 %
Crop emissions ($e_c f(x)$)	4.6 %	6.3 %	7.0 %	6.7 %
COC of grasslands ($(\theta_n - \theta_g)\alpha_g x$)	32.0 %	27.7 %	26.0 %	26.7 %
COC of cropland ($(\theta_n - \theta_c)\alpha_c f(x)$)	8.8 %	12.2 %	13.5 %	12.9 %

Sensitivity to supply and demand parameters

We here analyze the sensitivity of the ranking of policies to the cost of technical change, γ, and the price elasticity of meat demand, η.[10] Welfare gains, expressed as a percentage of first-best welfare gains, are shown in Figure 2.

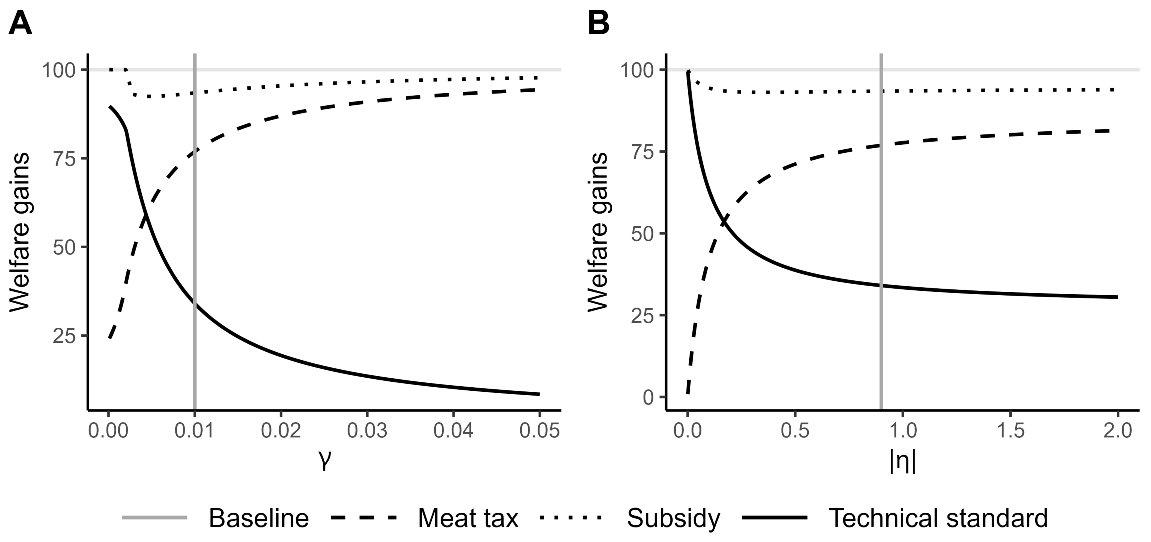

Figure 2: Welfare gains (in % of first-best welfare gains) of second-best policies according to (A) the cost of technical change and (B) the price elasticity of beef demand.

10. The sensitivity of the results to the supply elasticity, ξ, has the same shape as the sensitivity to the demand elasticity, since varying a and b is equivalent to varying c_0 and i_0. Therefore, we only present an analysis of the sensitivity to the demand elasticity.

Cost of technical change Figure 2A shows the sensitivity of our results to γ. The subsidy appears to be the best alternative to the Pigouvian tax regardless of the level of γ. The two other policies and their ranking are very sensitive to this parameter, the standard (tax) being inefficient when γ is large (small), substantiating Corollary 1. The robustness of the subsidy to variations in γ lies in its effect at both margins.

Price elasticity of beef demand Figure 2B shows that the subsidy is welfare-superior to the two other instruments, whatever the elasticity value. When the demand for beef is inelastic, the meat tax is inefficient in mitigating GHG emissions compared to the standard and the subsidy. Conversely, when the demand is price-sensitive, a tax performs well. Mitigation through intensification is still achievable, but its welfare gains become relatively modest, which explains the much lower performance of the standard. Again, because it acts on both margins, the subsidy can reduce the quantity of meat when the demand is elastic and outperforms the other alternative policies.

Sensitivity to the COC of land use

How the different policy instruments studied are sensitive to the COC of land use is analyzed below. We specifically examine the sensitivity to θ_g which determines the COC of grasslands (the main land use), and to θ_n which influences the total COC of beef.

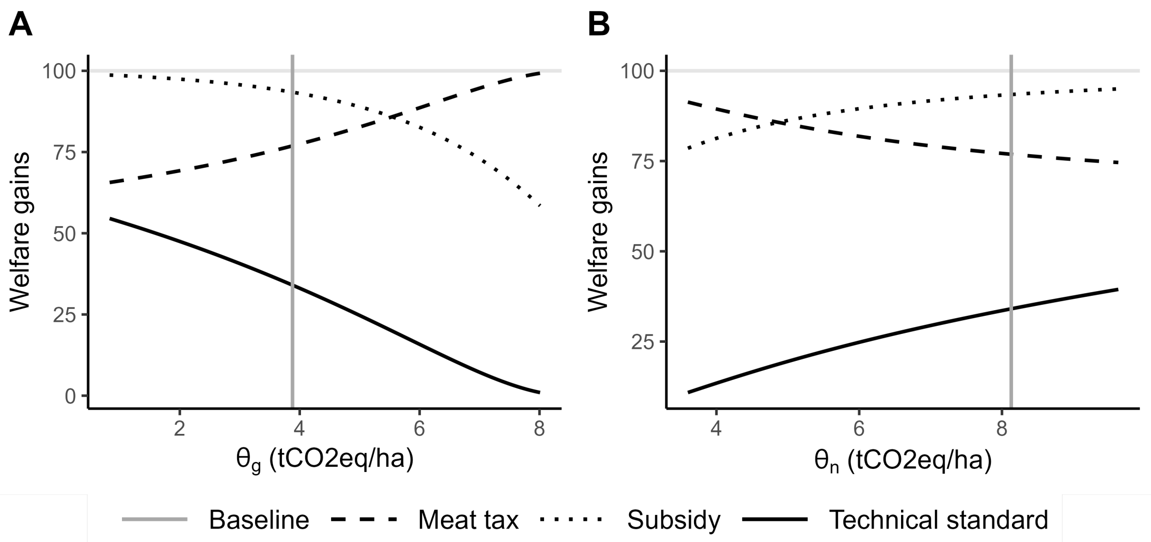

Figure 3: Welfare gains (in % of first-best welfare gains) of second-best policies according to (A) θ_g and (B) θ_n.

COC of grasslands In figure 3A, θ_g takes a range of values derived from the report of Pellerin, Bamière, and al. (2020). When θ_g decreases compared to the baseline, the COC of grasslands ($\theta_n - \theta_g$) increases, *ceteris paribus*. The mitigation potential through land sparing is therefore increasingly important at both margins, which implies lower optimal x and q than in the baseline case. The meat tax misses the higher welfare gains through intensification. The technical standard is penalized by the higher emission burden borne by meat but benefits from a greater intensive margin effect. The subsidy gets closer to the first-best since the alignment between land use and GHG emissions is stronger.

Total COC of meat The efficiency of the subsidy depends strongly on the share of the COC in the carbon footprint of meat and therefore on the value of θ_n. Figure 3B illustrates the results of a sensitivity analysis for possible values of θ_n in France, derived from Efese (2019). For a wide range of values for θ_n, the subsidy remains the best alternative to the Pigouvian tax. As θ_n increases, the subsidy approaches the first best, and is more likely to dominate the meat tax and the standard (Corollary 2). In addition, a higher θ_n increases the efficiency of intensification and thus the performance of the technical standard. However, the meat tax dominates the subsidy for low values of θ_n.

Monte Carlo simulations

For further sensitivity analysis, Monte Carlo simulations are performed. Ten thousand random draws of the parameters are generated according to the probability distributions indicated in Table 1 and justified in Appendix E.2. A truncation of distributions allows accounting for the positivity constraint for concerned parameters. Figure 4 shows the cumulative distribution functions of welfare gains with the three alternative policies to the Pigouvian instrument. The subsidy for land set aside dominates the meat tax and the standard. 76% of the simulations with the subsidy are associated with welfare gains exceeding 90% of the first-best welfare gains. By comparison, 45% of the simulations with the meat tax and only 2% of those with the standard reach welfare gains greater or equal to this level. With the subsidy, the median area of land set aside is 1.1 million ha and the median optimal subsidy is 446€/ha/yr. The median total public spending is 478 million euro , i.e., 5% of the annual European Common Agricultural Policy for France. The median reduction in GHG emissions is 9.4 MtCO_2eq corresponding to a cost of 50.9€/tCO_2eq.

To assess the influence of the various parameters on the performance of the second-best policies, we run a rank regression based on the Monte-Carlo simulations, the results of which are presented in Appendix E.3.

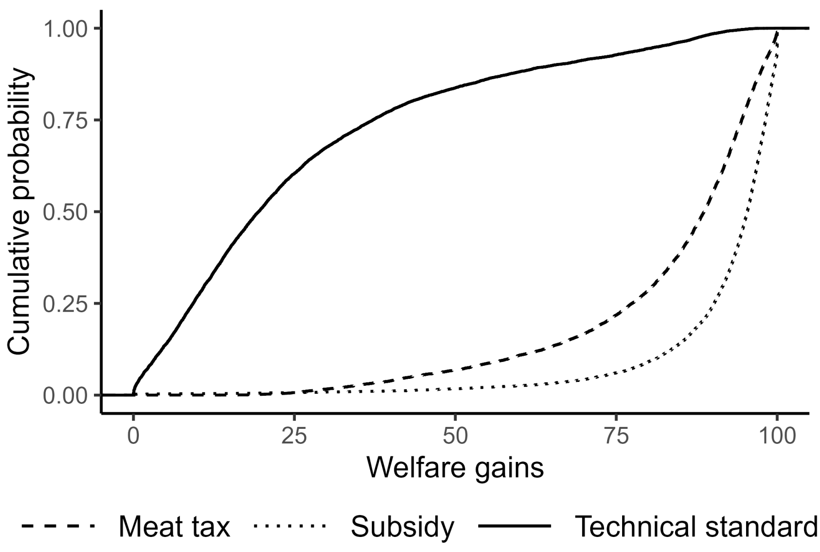

Figure 4: Cumulative distribution of welfare gains (in % of first-best welfare gains) with the second-best policies.

5 International Trade

So far the analysis has been conducted for a closed economy. A recurring concern with a unilateral climate policy is that it may lead to carbon leakage through increased imports. This section presents an extension of the previous analysis to include international trade and associated carbon leakage. The modified analytical framework is briefly presented, followed by a numerical assessment of the impact of carbon leakage on instrument performance.

Let us begin by highlighting important points. First, the analysis remains unchanged with a carbon border adjustment mechanism (CBAM) to address carbon leakage. Second, without CBAM, taxing home emissions is no longer first best. Third, consumption and production taxes are no longer equivalent because they induce different forms of carbon leakage. Fourth, the level of each instrument should be adjusted to integrate its influence on foreign emissions. The welfare comparison of instruments becomes analytically intractable and requires numerical simulations.

5.1 Analytical Framework

We add international trade in a parsimonious way to focus on the environmental effects of the policies under consideration. The consumer side remains unchanged, with q the quantity consumed domestically and p the consumer price. Exports are denoted z and are possibly negative in the case of imports. Total production is now $q + z$. Trade costs are denoted $d(z)$ a positive and convex function, minimized at $zero$, with $d(z) = d(-z)$. The international price of beef is assumed to be constant and equal to c_f.[11] Without regulation, farmers' profit becomes

$$\pi(q, z, x) = pq + c_f z - c(x)(q + z) - i(q + z) - d(z). \tag{17}$$

Thus, at the market equilibrium, $d'(z) = c_f - p$: farmers export (import) if home price is below (above) the international price. Foreign production depends on exports, it is $\psi(z)$, a positive and decreasing function. Such a function could be microfounded with a model of the world market, but this is irrelevant to the analysis. What only matters is how foreign production varies with exports. Emissions per unit of foreign production are denoted e_f. Welfare is now

$$W(q, x, z) = S(q) + c_f z - c(x)(q + z) - i(q + z) - d(z) - \delta \left[e(x)(q + z) + e_f \psi(z)\right]. \tag{18}$$

We only explain the main changes here. Detailed calculations of the social optimum and the optimal level of policy instruments are presented in Appendix D. At the social optimum, exports z^* are such that

$$d'(z) = c_f - p - \delta\psi'(z)e_f \tag{19}$$

Since foreign emissions are not taxed, there is a positive externality from exports via their effect on these emissions. This externality could be addressed with a CBAM, that

11. The analysis remains unchanged if we model the rest of the world demand and production, as long as we also integrate them into the welfare function. Otherwise, in addition to environmental issues, there would be a "protectionist" incentive to subsidize home production in order to reduce the price of imports.

is, a subsidy $\zeta = -\delta\psi'(z^*)e_f$ per unit exported (or a tax per unit imported). With such a CBAM, the previous analysis remains unchanged. Any instrument can be implemented together with the CBAM and the results are preserved.

Without CBAM, the indirect effect of instruments on foreign emissions influences their optimal level, even for a tax on home emissions. The optimal tax on home emissions is lower, reduced by the SCC times the leakage rate, i.e., the ratio of the change in foreign emissions to the change in home emissions. Similarly, an optimal tax on home production is lower without CBAM in order to preserve exports.

A tax on consumption operates differently than a tax on production since it increases exports (or reduces imports). It should be lower in the absence of CBAM if and only if exports increase world emissions ($e(x_0) > -e_f\psi'(z)$).

Concerning a technical standard, higher production costs reduce both consumption and exports. If there are some gains to export more or to import less, then the optimal technical standard will be closer to x_0 to limit carbon leakage.

Finally, the subsidy for land set aside reduces both consumption and exports. It should be lower without CBAM than with it in order to limit leakage. Again, if land and emissions intensities are perfectly aligned ($l/l' = e/e'$) the subsidy can achieve the same allocation than a tax on home emissions with and without CBAM.

5.2 Numerical Application

In the numerical exercise that follows, we use the same specification as in the closed economy model, together with the following additional functional forms:

$$d(z) = \frac{d_0}{2}z^2 \text{ and } \psi(z) = \psi_0 - \psi_1 z. \tag{20}$$

Values of modified or additional parameters used to calibrate the model are given in Table 4. Other parameters remain as in Table 1. The sources used to calibrate the parameters are specified in Appendix E.4. The quantity consumed q_0 is greater than in the closed economy model since it now includes imports and France is a net importer of beef meat. The quantity z_0 is estimated from data on beef trade from Idele and CNE (2021). We set ψ_0 at zero since we are only interested in variations of the international production. The calculation of b is modified because of the change in the value of q_0. The international price of beef, c_f, is set as the average of the world beef price for the period 2016-2020 (OECD and FAO 2021). The emission intensity of foreign production, e_f, is set at the same level as the domestic one, as most of the beef imported in France comes from European countries using similar production systems (Idele and CNE 2021). The response of international production to exchanges to and from France, ψ_1, is set at 0.5, an intermediate value between a perfectly elastic international supply ($\psi_1 = 1$) and a perfectly elastic international demand ($\psi_1 = 0$).

Table 4: Value of Modified and additional parameters for open economy model calibration

Description	Parameter	Value
BAU quantity of beef at market equilibrium (kg CW)	q_0	9.90×10^8
BAU beef trade balance (kg CW)	z_0	-0.30×10^8
International beef production (kg CW)	ψ_0	0
Slope of the inverse demand function (€/kg^2)	b	4.38×10^{-9}
Slope of the marginal cost of trade (€/kg CW)	d_0	6.67×10^{-9}
World beef price (€/kg CW)	c_f	3.7
Carbon footprint of foreign beef (kg CO_2eq/kg CW)	e_f	44.4
Response of international production to trade	ψ_1	0.5

Table 5 shows the results of simulations under the different policy instruments without CBAM.

Table 5: Results for a Small Open Economy Without CBAM (Except for First-Best)

	BAU	First-best $\tau = \delta$ $\zeta = -\delta\psi_1 e_f$	Emission tax $\tau' < \delta$	Subsidy s^{SB}	Cons. Tax t^{SB}_{cons}	Prod. tax t^{SB}_{prod}	Standard $\bar{x}^{SB}$
$\Delta W = W - W^{BAU}$ (M€)	0	262.00	204.25	197.62	161.07	146.96	84.95
	(-100%)	(·)	(-22%)	(-25%)	(-39%)	(-44%)	(-68%)
q (kt of carcass)	990	793.99	888.46	894.69	789.82	890.26	984.15
	(25%)	(·)	(12%)	(13%)	(-1%)	(12%)	(24%)
z (kt of carcass)	-30	7.70	-96.67	-92.58	79.96	-95.48	-33.84
	(-490%)	(·)	(-1355%)	(-1302%)	(938%)	(-1340%)	(-539%)
x (kg DM grass/ kg carcass)	20	16.14	16.76	14.67	20	20	15.43
	(24%)	(·)	(4%)	(-9%)	(24%)	(24%)	(-4%)
p (€/kg)	3.9	4.76	4.34	4.32	4.78	4.34	3.93
	(-18%)	(·)	(-9%)	(-9%)	(0%)	(-9%)	(-17%)
E ($MtCO_2eq$)	6.7	-3.54	-1.26	-2.21	0.26	0.82	6.36
L_n (Mha)	0.64	1.64	1.61	1.77	1.00	1.30	1.18
	(-61%)	(·)	(-2%)	(8%)	(-39%)	(-21%)	(-28%)
L_g (Mha)	3.21	2.16	2.22	1.97	2.91	2.65	2.45
	(49%)	(·)	(3%)	(-9%)	(35%)	(23%)	(13%)
L_c (Mha)	0.65	0.70	0.67	0.76	0.59	0.54	0.87
	(-7%)	(·)	(-4%)	(9%)	(-16%)	(-23%)	(24%)

Notes: Differences relative to the first best are indicated in parenthesis.

In our baseline scenario, the ranking of instruments remain strikingly similar to that in a closed economy. Interestingly, the subsidy performs almost as well as an emission tax without CBAM, and it outperforms the consumption and production taxes and the standard. A tax on consumption is more efficient than a tax on production because it regulates both domestic and foreign meat. The standard is still the least efficient instrument, despite leakage. The lack of CBAM hampers the performance of all instruments: the welfare gains obtained with the most efficient one (the emission tax) is 22% lower than the gains obtained with the first-best policy. Compared to an emission tax, the subsidy again favors the intensive margin.

Concerning international trade, France imports 3% of its consumption in BAU. Under an optimal (unilateral) regulation with CBAM, France would become a net exporter. With an optimal consumption tax, exports are larger than at the first-best allocation. However, with an emission tax, a production tax, or a subsidy for land set aside, imports increase dramatically, more than threefold relative to the BAU level, or up to 11% of the domestic consumption. The increase is modest with a standard.

Because the different instruments lead to significantly different trade balances (and therefore, carbon leakage), their ranking should heavily depend on how global emissions vary with French trade, i.e, on $\psi_1 e_f$. Figure 5 shows the results of a sensitivity analysis with respect to ψ_1. The emission tax and the subsidy remain close along ψ_1 and they outperform the production tax over the entire range of values considered. This is not surprising since their relative merits are not directly related to international trade. The standard remains the least efficient instrument, although the gap is shrinking when international production is sensitive to French beef exchanges. The main lesson is that a consumption tax is the most efficient instrument for large sensitivities. The results were expected, as it is the only instrument among those considered in the paper to promote exports and reduce foreign emissions and associated external costs.

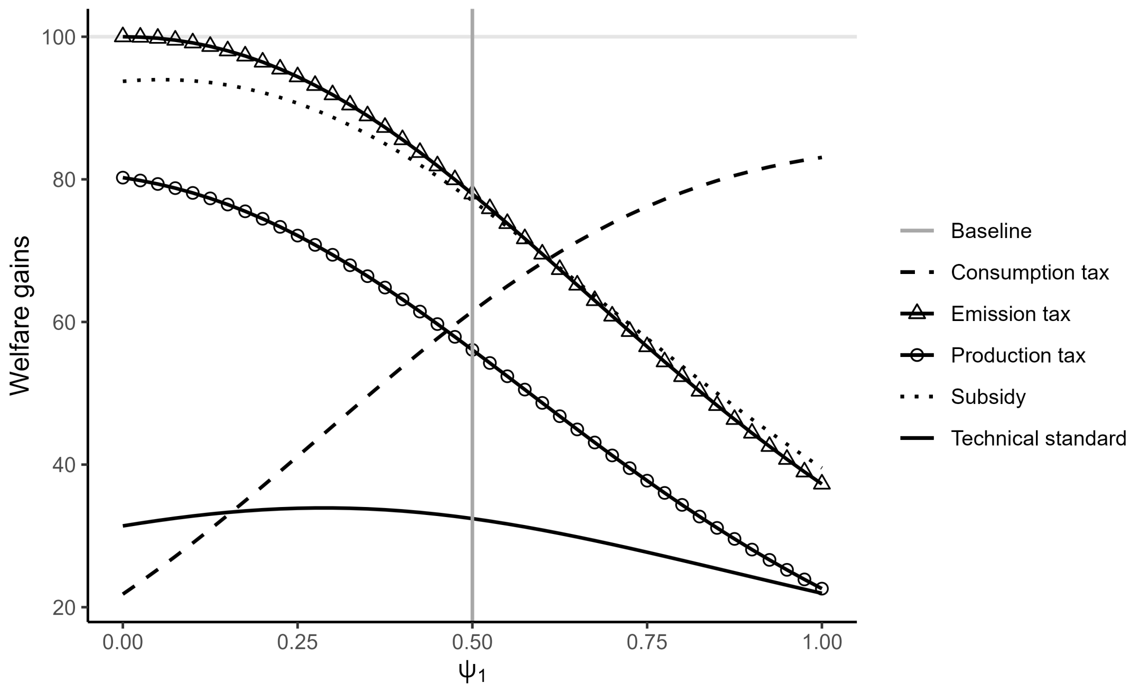

Figure 5: Welfare gains (in % of first-best welfare gains) of second-best policies according to the adjustment of international production to French beef exchanges.

6 Discussion

6.1 Discussion of the Model

The model has been kept as simple as possible and many characteristics of the cattle sector have been ignored.

On the demand side First, we consider a single homogeneous good and therefore ignore the different qualities of beef products. Second, while the reduction of beef consumption would likely be offset by an increase in the consumption of plant-based foods or other meat products, such substitutions are not modeled. It raises the issue of coordinating the regulation of the beef market with that of its protein-rich food substitutes, which would require broadening the range of regulatory instruments. In our model, a tax on feed crops or grass combined with the meat tax could have been considered among the regulatory options available. Finally, this paper does not consider consumer preferences for some production methods, such as extensive grass-based beef production, due to animal welfare concerns. Including such preferences would alter the optimal technique x and could change the relative efficiency of the policy instruments studied.

On the production side Technical options for mitigating GHG emissions other than intensification are not considered, although they can have a significant impact (Crosson et al. 2011; Herron et al. 2021; Nguyen et al. 2013).[12] The synergy between meat and dairy

12. Such levers include cow breed, age at first calving, replacement rate of suckler cows, type of bedding, manure management and fertilization practices.

production is also ignored, although there are important opportunities for mitigation through better integration of the two sectors (Faverdin et al. 2022; Selm et al. 2021; Zehetmeier et al. 2012). We also do not account for heterogeneity in land quality in terms of productivity and carbon sequestration. With land heterogeneity, there would be an issue of land allocation among the three land uses, in addition to the choice of intensification. Finally, it should be noted that the assumption of natural ecosystem regeneration on all land taken out of beef production is conservative. While the subsidy specifically targets land set aside for ecosystem regeneration, it is likely that a substantial portion of the land made available through a meat tax or a standard will not be preserved for vegetation regrowth and may be partially urbanized.

On the dynamics of carbon sequestration The most critical point to address is the absence of land carbon sequestration dynamics in our static framework. In practice, for any given land-use change, there is a dynamic profile of carbon removal until a steady state is reached (see Poeplau et al. 2011; Cook-Patton et al. 2020); at that steady state, a fixed carbon stock is sequestered, and net carbon flows are null. Conceptually, in our static model, the parameters θ_i are the annual carbon flows associated with the land uses, and properly taking into account the dynamic of sequestration would not only require that they vary over time but also that they depend on the history of each land plot.

Our calibration of the parameters is consistent with an interpretation of the model as a long-run equilibrium, and the θ_i the average removal over the horizon: if a land use i is associated with Θ_i tCO_2eq stored at steady state, then, the total amount of carbon stored is $\Theta_c L_c + \Theta_g L_g + \Theta_n L_n$. The amount of CO_2 removed from the atmosphere over the period is the difference between the latter and the initial carbon stock. With the proposed interpretation, $\theta_i = \Theta_i/n$, with n the duration of the period. It should be emphasized that the results do not depend on the initial state, and that all arbitrages considered involve differences between the θ_i and not absolute values. Our calibration closely follows the IPCC *stock-difference method* and *approach 1* for the representation of land (IPCC 2006, chap. 2, p. 10 and chap. 3, pp. 10-12)

On other land-use related ecosystem services Consistent with the literature (Balmford et al. 2018; Blaustein-Rejto, Soltis, and Blomqvist 2023), we find that intensive, land-efficient beef production systems produce less GHG emissions. As a consequence, intensification is welfare-improving in our model. However, this result might no longer hold with a more comprehensive welfare function that would include other environmental impacts. The effect on biodiversity of intensification combined with land set aside depends on whether the separation of conservation and agricultural production is a better strategy than their integration on the same land. This refers to a highly debated question among conservation scientists known as the 'land-sharing' *vs.* 'land-sparing' controversy (Fischer et al. 2014; Meunier 2020). Regarding acidification and eutrophication of soil and water through nutrient runoff, studies' results are nuanced but tend to show that more concentrate-based systems are less polluting per unit of product (Balmford et al. 2018; McDowell et al. 2022; Vries, Middelaar, and Boer 2015).

Finally, our assumption of **spontaneous ecosystem regeneration** on land spared could be relaxed. The type of regenerated ecosystem depends on the land's antecedent natural vegetation. In most regions of the world, spontaneous forest regeneration on former agricultural land has been observed (Chazdon et al. 2020). However, regeneration could be assisted and forest managed so as to enhance carbon sequestration. Analytically, it could be considered by adding a cost $c_n(\theta_n)L_n$, with θ_n chosen by the regulator, such that $\delta = c'(\theta_n)$. The analysis would remain similar as long as we assume that the management of the land spared does not depend on the instrument chosen. A more comprehensive analysis would relax this assumption, which would pave the way to integrate our work with articles specifically dealing with the influence of climate policies on forest management (e.g., Lintunen and Uusivuori 2016; Li, Sohngen, and Tian 2022).

6.2 Policy Implications

Although cattle farming is currently the most subsidized agricultural activity in France (Cour des Comptes 2023), political support for the sector may change in the future. To reach carbon neutrality in 2050, the French national low-carbon strategy foresees a reduction by one-third of the French beef cattle herd and an increase of the terrestrial carbon sink to compensate for the remaining (primarily agricultural) emissions (Ecological and Transition 2020). To date, no convincing policies have been proposed to achieve these two objectives in a consistent manner.

Our initial inspiration stems from the intuition that advocating for the expansion of natural reserves or protected areas may find greater political support compared to a meat tax or a Pigouvian tax.[13] However, there are some pitfalls with the implementation of such a policy which relates to leakage, additionality, permanence, perverse incentives, and equity. These issues are common to afforestation programs, which have been extensively studied (e.g., Austin et al. 2020; Richards and Stokes 2004) but without systematically addressing those issues.

It is first important to keep in mind that, in our framework, the subsidy for land set aside is equivalent to a tax on agricultural land or to a zoning policy reducing agricultural land while promoting the expansion of natural areas. The implementation could consist in subsidizing the conversion of agricultural land to natural ecosystem together with a zoning policy preventing the reverse conversion (via restrictions or taxes). Such combination would address both leakage (within the country, not the international one) and non-permanence. It would reinforce a decades-long trend in Europe of agricultural decline and forest expansion(see Mather, Fairbairn, and Needle 1999, for the French case).

To overcome additionality issues, some authors have proposed nonlinear payments to farmers (Bourgeon, Jayet, and Picard 1995; Mason and Plantinga 2013). How such scheme should be modified to take into account the intensive margin of farmers is a topic for further research. Concerning perverse incentives, farmers anticipating the implementation of the policy are incentivized to deforest in order to get paid to reforest. This is an issue common to many environmental policy from emissions trading scheme to fisheries management (Costello and Grainger 2022). A possible solution would be to use a historical land use situation as a baseline and only pay for additional land set aside compared to that baseline.

13. Indeed, climate policies actually implemented depart from the textbook Pigouvian solution and consist in a mix bag of taxes, subsidies, mandates, and various combinations thereof. The aversion to Pigouvian taxes has been analyzed in experiments (e.g. Kallbekken, Kroll, and Cherry 2011) and surveys (see Douenne and Fabre 2020, and references therein).

7 Conclusion

We develop a partial equilibrium model of the cattle sector to examine the efficiency of a land-use regulation rewarding farmers for setting aside land for natural ecosystem regeneration as a second-best mitigation policy. We compare this policy not only to the first-best Pigouvian instrument but also to two alternative policies: a meat tax and a technical standard on animal feeding.

The interest of the subsidy lies mainly in its effect on both the production technique (intensive margin) and the quantity of meat (extensive margin): it does not only incentivize farmers to intensify their production but also induces an opportunity cost of land that acts as an implicit tax on meat. The meat tax only reduces the quantity of meat but does not trigger a technical adjustment, while the technical standard specifically targets mitigation at the intensive margin with a modest effect on quantity. We show analytically that a sufficient alignment of land use and GHG emissions is required for the subsidy to be more efficient than the two other instruments. The meat tax is preferable when the demand for meat is sufficiently elastic and technical change is costly. The technical standard requires a cheap technical change and an inelastic demand to be the most efficient alternative policy.

Calibration of the model with French data indicates that the subsidy for land set aside is likely the best alternative to the Pigouvian tax on emissions in our framework. Sensitivity analyses show this result holds for a wide range of parameter values. The welfare loss with this instrument remains small and stable regardless of the parameters, in contrast to the meat tax and the standard, which can induce significant losses in some cases. However, the performance of the subsidy is sensitive to carbon leakage when the economy is open to trade, and a consumption tax may be a better policy under high leakage rates.

Implementing a subsidy for land set aside raises several questions to be addressed in future research. The willingness of farmers to reforest their agricultural land may depend on other factors not accounted for in this paper (Claytor et al. 2018). Furthermore, the analysis focused on GHG emissions, and it would be worth integrating animal welfare and biodiversity. Intensification may be detrimental to the welfare of beef cattle, whereas their current husbandry conditions in France appear to be satisfactory (Espinosa and Treich 2024). As for biodiversity, reforestation of spared grasslands in Europe may remove the habitat of various species in some locations (Burrascano et al. 2016). A more comprehensive analytical framework should consider the potential trade-offs and synergies between GHG emissions reduction, animal welfare, and biodiversity.

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A Proof of Lemma 3

Let us define $Q(.)$ the equilibrium quantity as a function of the marginal cost of the first unit produced. For a given cost c (which could include taxes), it solves $S'(Q) = i'(Q) + c$, that is:

$$Q(c) = [S' - i']^{-1}(c). \tag{21}$$

For a standard $\bar{x}$, the equilibrium quantity of meat is $q(\bar{x}) = Q(c(\bar{x}))$, and its derivative is $\partial q/\partial \bar{x} = Q'.c'(\bar{x})$. Differentiating welfare $W(q(\bar{x}), \bar{x})$, given by eq. (4), with respect to x gives:

$$\begin{aligned}\frac{dW}{d\bar{x}} &= -[c'(\bar{x}) + \delta e'(\bar{x})]q + [S'(q) - c(\bar{x}) - i'(q) - \delta e(\bar{x})]\frac{\partial q}{\partial \bar{x}} \\ &= -[c'(\bar{x}) + \delta e'(\bar{x})]q - \delta e(\bar{x})Q'c'(\bar{x})\end{aligned}$$

Therefore, at x^*, the derivative is $-\delta e Q'c'(x^*) = Q'\delta^2 ee'(x^*)$, and it is negative if $e'(x^*) > 0$, implying that $\bar{x}^{SB} < x^* < x_0$ in that case (by quasi concavity of W with respect to $\bar{x}$). Otherwise, if $e'(x^*) \leq 0$, then $\bar{x}^{SB} \geq x^* \geq x_0$.

Given $e > 0$ and $Q' < 0$, it follows immediately that $Q(c(\bar{x})) > Q(c(\bar{x}) + \delta e(\bar{x}))$, and therefore $q(\bar{x}^{SB}) > q^{\times}(\bar{x}^{SB})$.

The comparison of $q(\bar{x}^{SB})$ with q^* is not trivial and depends on whether $c(\bar{x}^{SB})$ is smaller or greater than $c(x^*) + \delta e(x^*)$.

B Proof of Proposition 1

We assume that $l'(x) > 0$ and $e'(x) > 0$. The optimal s solves

$$[sl(x) - \delta e(x)]\frac{\partial q}{\partial s} + [sl'(x) - \delta e'(x)]q\frac{\partial x}{\partial s} = 0 \tag{22}$$

With $l(x) > 0$ and $l'(x) > 0$, both q and x are decreasing with respect to s. Then, from equation (22), the derivatives of welfare with respect to q and with respect to x have opposite signs at the optimal subsidy.

Let us denote $\tilde{s}$ the subsidy at which $x(s) = x^*$:

$$\tilde{s} = \frac{\delta e'(x^*)}{l'(x^*)}$$

The derivative of welfare with respect to s at $\tilde{s}$ is then (since $\partial W/\partial x = 0$ at $x = x^*$ for all q).

$$\frac{dW}{ds} = \frac{\partial W}{\partial q}\frac{\partial q}{\partial s} = (\tilde{s}l(x^*) - \delta e(x^*))\frac{\partial q}{\partial s} = \delta e'(x^*)\left[\frac{l(x^*)}{l'(x^*)} - \frac{e(x^*)}{e'(x^*)}\right]\frac{\partial q}{\partial s}$$

- if $l/l' = e/e'$ at x^*, then welfare is maximized for $s = \tilde{s}$ and this corresponds exactly to the first-best.

- If $l/l' > e/e'$ at x^*: welfare is decreasing at $\tilde{s}$ ($\partial q/\partial s \leq 0$). Therefore, s^{SB} is smaller than $\tilde{s}$ and $x^{SB}_{sub} > x^*$. The latter implies $\partial W/\partial x < 0$ and $\partial W/\partial q > 0$ (from (22)). So $S'(q^{SB}_{sub}) \geq c(x^{SB}_{sub}) + \delta e(x^{SB}_{sub}) + i'(q^{SB}_{sub})$, that is, $q^{SB}_{sub} < q^{\times}(x^{SB}_{sub})$,

  and the latter is lower than q^* (the cost $c(x) + \delta e(x)$ being minimized at $x = x^*$).

- If $l/l' < e/e'$ at x^*: welfare is increasing at $\tilde{s}$. Therefore, s^{SB} is larger than $\tilde{s}$ and $x^{SB}_s < x^*$. The latter implies $\partial W/\partial x > 0$. Thus, $\partial W/\partial q < 0$ so $q^{SB}_{sub} > q^{\times}(x^{SB}_{sub})$.

C Proof of Proposition 2

With specification (13), we have

$$c(x) + \delta e(x) = c(x^*) + \delta e(x^*) + \frac{\gamma}{2}(x - x^*)^2 \tag{23}$$

Using eq. (23) and specification (13) in the expression of welfare (4) gives

$$\begin{aligned} W(q, x) &= \big(a - \frac{b}{2}q\big)q - \frac{i_0}{2}q^2 - \left(c(x^*) + \delta e(x^*)\right) q - \frac{\gamma}{2}(x - x^*)^2 q + \delta\theta_n \bar{L} \\ &= W(q^*, x^*) - \frac{b + i_0}{2}(q - q^*)^2 - \frac{\gamma}{2}(x - x^*)^2 q \end{aligned}$$

Welfare losses with the second-best instruments:

- With the meat tax, the welfare loss is obtained by plugging $x = x_0$ and $q = q^{\times}(x_0) = (a - c_0 - \delta e(x_0))/(b + i_0)$ into expression (14).

- For the standard: the quantity as a function of the standard is $q(\bar{x}) = (a - c(\bar{x}))/(b + i_0) = q^{\times}(\bar{x}) + \delta e(\bar{x})/(b + i_0)$.

  Upper bound: Welfare at $\bar{x} = \bar{x}^{SB}$ is larger than at $\bar{x} = x^*$. Therefore

$$\begin{aligned} W^{FB} - W^{SB}_{sta} &= \frac{b + i_0}{2}(q(\bar{x}^{SB}) - q^*)^2 + \frac{\gamma}{2}(\bar{x}^{SB} - x^*)^2 q(\bar{x}^{SB}) \\ &\leq \frac{b + i_0}{2}(q(x^*) - q^*)^2 = \frac{\delta^2}{2(b + i_0)} e(x^*)^2 \end{aligned}$$

  Lower bound: write $q - q^* = q - q^{\times} + q^{\times} - q^*$ and $q^{\times} - q^* = -\frac{\gamma}{2(b+i_0)}(x - x^*)^2$, plugging this into eq. (14) gives

$$\begin{aligned} W^{FB} - W &= \frac{\gamma^2}{8(b + i_0)}(x - x^*)^4 + \frac{\gamma}{2}q^*(x - x^*)^2 + \frac{b + i_0}{2}\left(q - q^{\times}(x)\right)^2 \\ &\geq \frac{b + i_0}{2}\left(q - q^{\times}(x)\right)^2 \end{aligned}$$

  and, with a standard $q - q^{\times} = \delta e(\bar{x})/(b + i_0)$ which is positive and greater than $e(x_0)$. The lower bound follows.

- For the subsidy: the quantity produced is $q = (a - c(x) - sl(x))/(b + i_0)$, so $q - q^* = (\delta e(x) - sl(x))/(b + i_0)$. With the subsidy $s = \delta e'(x^*)/l'(x^*)$ the technique is the first-best one, $x = x^*$, and

$$W^{FB} - W^{SB}_{sub} \leq \frac{1}{2(b + i_0)}\left(sl(x^*) - \delta e(x^*)\right)^2 = \frac{\delta^2 e'^2}{2(b + i_0)}\left(\frac{l(x^*)}{l'} - \frac{e(x^*)}{e'}\right)^2$$

D Analytical results with international trade

The welfare function is given by eq. (18). The social optimum (q^*, x^*, z^*) is characterized by the first-order conditions :

(24a) $$S'(q) = c(x) + i'(q+z) + \delta e(x)$$

(24b) $$-c'(x) = \delta e'(x)$$

(24c) $$c_f = c(x) + i'(q+z) + d'(z) + \delta[e(x) + \psi'(z)e_f].$$

With a tax τ on home emissions and a CBAM ζ farmers profit is

$$\pi = pq + (c_f + \zeta)z - [(c(x) + \tau e(x))(q+z) + i(q+z)]$$

So that the market equilibrium is described by the equations

(25a) $$S'(q) = p = c(x) + i'(q+z) + \tau e(x)$$

(25b) $$-c'(x) = \tau e'(x)$$

(25c) $$c_f + \zeta = c(x) + i'(q+z) + d'(z) + \tau e(x)$$

Setting $\tau = \delta$ together with $\zeta = -\delta e_f \psi'(z^*)$ decentralizes the optimal allocation. Because a CBAM addresses the effect of exports on world emissions, the instrument used to regulate home emissions is set independently of its effect on exports.

For each instrument $r \in \{\tau, t_p, t_c, \bar{x}\}$, where t_p and t_c denote a production and a consumption tax, respectively, the effect on welfare is

(26) $$\frac{\partial W}{\partial q}\frac{\partial q}{\partial r} + \frac{\partial W}{\partial r}\frac{\partial x}{\partial r} + \frac{\partial W}{\partial z}\frac{\partial z}{\partial r}$$

Injecting the market equilibrium equations associated to the instrument considered will give the expression of the optimal second-best instrument.

With a **domestic tax on emissions** τ, farmers trade beef such that $c_f = c(x) + i'(q+z) + \tau e(x) + d'(z)$ instead of (19). An optimal tax τ^{SB} is such that (injecting market equilibrium equations into eq. (26) and regrouping terms related to total production $z+q$):

(27) $$(\tau - \delta)\Big[e(x)\frac{\partial(q+z)}{\partial\tau} + e'(x)(q+z)\frac{\partial x}{\partial\tau}\Big] - \delta e_f \psi'(z)\frac{\partial z}{\partial\tau} = 0$$

The bracketed factor correspond to the effect on home emissions of the tax. The optimal second-best tax is then

$$\tau^{SB} = \delta + \delta\frac{e_f\psi'(z)\frac{\partial z}{\partial\tau}}{\partial[e(x)(q+z)]/\partial\tau}$$

The denominator is negative, home emissions decrease with the tax. The numerator is positive since $\frac{\partial z}{\partial\tau} < 0$ and $\psi' < 0$. The optimal emission tax is lower without CBAM than with it.

Expressions for the derivatives could be obtained from market equilibrium equations (25) with $\zeta = 0$:

$$\frac{\partial q}{\partial\tau} = -e(x)\frac{d''}{i''d'' - S''(i''+d'')};\ \frac{\partial z}{\partial\tau} = -e(x)\frac{-S''}{i''d'' - S''(i''+d'')};\ \frac{\partial x}{\partial\tau} = \frac{-e'(x)}{c'' + \tau e''}.$$

An optimal **production tax** satisfies

$$[t_p - \delta e(x)]\frac{\partial(q+z)}{\partial t_p} - \delta e_f \psi'(z)\frac{\partial z}{\partial t_p} = 0$$

The ratio between the change of foreign production and the change of total production $q+z$ is obtained from the market equilibrium equation $c_f - S'(q) = d'(z)$, which gives:

$$t_p^{SB} = \delta e(x_0) + \delta\psi'(z)e_f\frac{S''}{S''-d''}$$

The second term being negative ($\psi' < 0$), the optimal production tax is lower in an open economy than in a closed economy.

An optimal **consumption tax** satisfies:

$$[t_c - \delta e(x)]\frac{\partial q}{\partial t_c} - \delta\Big[e(x) + e_f\psi'(z)\Big]\frac{\partial z}{\partial t_c}$$

The ratio between the change of export and the change of home consumption is obtained from the market equilibrium equation $c_f = c(x_0) + i'(q+z) + d'(z)$ so that

$$t_c^{SB} = \delta e(x_0) - \frac{\delta i''}{i''+d''}\left[e(x_0) + \psi'(z)e_f\right]$$

In a closed economy, we have $t_c^{SB} = \delta e(x_0)$. The optimal meat tax is lower in an open economy than in a closed economy if and only if $e(x) > -\psi'(x)e_f$.

An optimal **technical standard** satisfies

$$\frac{\partial W}{\partial \bar{x}} + \frac{\partial W}{\partial q}\frac{\partial q}{\partial \bar{x}} + \frac{\partial W}{\partial z}\frac{\partial z}{\partial \bar{x}} = 0 \tag{28}$$

$$-\Big[c'(x) + \delta e'(x)\Big](q+z) - \delta e(x)\frac{\partial q + z}{\partial x} - \delta e_f\psi'(z)\frac{\partial z}{\partial x} = 0 \tag{29}$$

The full derivatives of the market equilibrium equations give the expression of the derivatives of quantities so that

$$-[c'(x) + \delta e'(x)](q+z) + \delta c'(x)\frac{e(x)(d''-S'') + e_f\psi'(z)(-S'')}{i''d'' - S''(i''+d'')} = 0$$

At $x = x^*$, the bracketed term is null and, if $e'(x^*) > 0$, then $c'(x^*) < 0$, and the second term is negative if and only if $e(x)(d''-S'') > -e_f\psi'S''$, which is likely the case. The standard will then be tighter than the optimal technique. With CBAM, the welfare effect of the standard on foreign emissions would be cancelled, and the standard would be even tighter.

Finally, an optimal **subsidy for land set aside** solves:

$$[sl'(x) - \delta e'(x)]\,q\frac{\partial x}{\partial s} + [sl(x) - \delta e(x)]\,\frac{\partial(q+z)}{\partial s} - \delta e_f\psi'(z)\frac{\partial z}{\partial s} = 0 \tag{30}$$

Expressions for the derivatives are obtained from market equilibrium equations.

$$\frac{\partial q}{\partial s} = -l(x)\frac{d''}{i''d'' - S''(i''+d'')};\ \frac{\partial z}{\partial s} = -l(x)\frac{-S''}{i''d'' - S''(i''+d'')};\ \frac{\partial x}{\partial s} = \frac{-l'(x)}{c''+sl''}$$

An increase in the subsidy leads to a reduction in the quantities consumed and exported. Its effect on the technique depends on the monotony of $l(x)$; if $l(x)$ is increasing in x, then x decreases with respect to s. The last term in equation (30) is negative suggesting that the subsidy should be lower without CBAM than with it in order to limit leakage. Indeed, if $l/l' = e/e'$, the subsidy can achieve the same allocation as the emission tax with and without CBAM.

E Numerical application

E.1 Description and source of parameters used for model calibration

Parameter	Description (unit)	Value	Source
η	Price elasticity of beef demand	-0.9	Gallet (2010)
a	Intercept of the inverse demand function (€/kg)	8.23	Authors' calculations from the price elasticity of demand
b	Slope of the inverse demand function (€/kg^2)	$4.51 * 10^{-9}$	Authors' calculations from the price elasticity of demand
x_0	Cost-minimizing amount of grass (kg/kg CW)	20	Assumption (justified in the main text)
f_0	Cost-minimizing amount of crops (kg/kg CW)	4.08	Authors' calculations from the value taken by x_0 and f function
γ	Cost of technical change (€.kg CW/kg grass^2)	0.01	Assumption (justified in the main text)
ϕ	Substitution rate between crops and grass (kg crops/ kg grass)	0.30	Author's calculations from the meta-analysis of (Gérard 2023)
p_0	BAU market price of beef (€/kg CW)	3.9	Assumption based on data from Idele and CNE (2021)
ξ	Price elasticity of beef supply	0.5	Assumption based on data from Idele and CNE (2021)
c_0	Intercept of the inverse supply function	-3.9	Assumption based on data from Idele and CNE (2021)
i_0	Slope of the inverse supply function	8.13×10^-9	Authors' calculations from the price elasticity of supply
q_0	BAU quantity of beef at market equilibrium (kg CW)	$9.60 * 10^8$	Authors' calculations with data from Idele and CNE (2021) and Agreste (2021)
α_g	Inverse grassland yield (m^2/kg)	1.67	Assumption based on data from Agreste (2021)
α_c	Inverse crop yield (m^2/kg)	1.67	Assumption based on data from Agreste (2021)
$\overline{L}$	Total available land (m^2)	4.5×10^{10}	Assumption (justified in the main text)
ϵ_d	Direct emission growth rate with respect to the amount of grass (kgCO_2eq/kg grass)	0.51	Authors' calculations from the meta-analysis of Gérard (2023)
e_{d0}	Direct emissions of beef when $x = x_0$ (kgCO_2eq/kg CW)	24.22	Authors' calculations from the meta-analysis of Gérard (2023)
e_c	Emission factor of crops (kgCO_2eq/kg crops)	0.50	Assumption based on the Agribalyse - ECOALIM database
θ_g	Annual carbon sequestration of grasslands (kgCO_2eq/m^2)	0.39	Authors' calculations based on data from Pellerin, Bamière, and al. (2020)
θ_c	Annual carbon sequestration of crops (kgCO_2eq/m^2)	0.24	Authors' calculations based on data from Pellerin, Bamière, and al. (2020)
θ_n	Annual carbon sequestration of land set aside for forest regeneration (kgCO_2eq/m^2)	0.81	Authors' calculations based on data from Efese (2019)
δ	Social cost of carbon (€/kgCO_2eq)	0.05	Level of the French carbon tax

Concerning the estimation of functions f and e_d, we use the database built by (Gérard 2023) but have removed observations from an old paper (Casey and Holden 2006). The reason is that the observations from this paper associate very low values for crop intakes, grass intakes, and the carbon footprint of beef, which substantially increases the estimated slope of functions e_d and f. As a result, the slope of function e is high, and emissions are unrealistically reduced by intensification.

E.2 Parameter distribution functions for Monte Carlo simulations

η: A meta-analysis by Gallet (2010) indicates that the price elasticity is around -0.9 worldwide. At the European scale, Wirsenius, Hedenus, and Mohlin (2011) estimates the elasticity of meat demand at -1.30. Gren, Höglind, and Jansson (2021) and Säll (2018) find much lower values for Sweden, around -0.5. The estimate of Roosen, Staudigel, and Rahbauer (2022) is around -0.9 for Germany. At the French level, calculations vary between -1.11 (Caillavet, Fadhuile, and Nichèle 2019) and -1.34 (Bonnet, Bouamra-Mechemache, and Corre 2018). Therefore, the price elasticity of demand for beef seems to be in the interval $[-1.4; -0.5]$. Without any additional information on the distribution, we assume that the price elasticity is uniformly distributed over this interval.

$f_0, \phi, \epsilon_d, e_{d0}$: Those parameters are estimated with an OLS regression. Their normal distributions are derived directly from the regression results.

γ: Based on the sensitivity analysis to gamma, we have chosen to focus on the range of values where the major changes in the ranking of policy instruments occur. To give the same weight to all values within the range, we assume a uniform distribution.

ξ : This distribution is based on the lower and upper bounds of estimates of the price elasticity of beef supply from the literature (McKendree et al. 2020; Marsh 2003)

α_g, α_c**:** Those distributions are based on the average yield in France for grasslands and major crops for beef cattle (wheat and barley grains), respectively, and on standard deviation set to cover most of the French territory.

θ_c, θ_g**:** We use the distribution of French carbon stocks of soils under grassland and cropland provided in (Pellerin, Bamière, and al. 2020), p. 32. Those distributions are then multiplied by 44/12 to convert the stocks in CO_2eq, divided by the time horizon considered, i.e., 80 years here, and adjusted to get values in kgCO_2eq/m^2.

θ_n**:** The distribution is based on the upper and lower bounds of the carbon stocks of natural ecosystems in the French regions where most of the beef cattle production takes place. In particular, the drier Mediterranean region is not included in the definition of the lower limit because there are almost no cattle farms there.

E.3 Rank analysis

The rank analysis of the results of the Monte-Carlo simulations is a simple non-parametric method that consists in regressing the rank of the welfare gains on the rank of the parameters over the simulations for the three instruments. It allows to identify the parameters that are quantitatively the most influential. Results are presented in Table 6. Most of the parameters are significant at the 5% level. Key parameters in the ranking of instruments are the cost of technical change, γ, and the effect of technical adjustment on emissions, ϵ. Grassland and cropland yields, α_g and α_c, as well as the COC of grasslands, $\theta_n - \theta_g$, are also important parameters for the performance of the subsidy. The market elasticity, $|\eta| + \xi$, has a key role in the efficiency of the meat tax.

Table 6: Rank regression results

	Dependent variable:		
	Subsidy	Tax	Standard
	(1)	(2)	(3)
rank(γ)	0.09***	0.59***	−0.59***
	(0.01)	(0.004)	(0.004)
rank($\lvert\eta\rvert$)	0.07***	0.14***	−0.07***
	(0.01)	(0.004)	(0.004)
rank($\lvert\xi\rvert$)	0.11***	0.25***	−0.13***
	(0.01)	(0.004)	(0.004)
rank(θ_n)	0.06**	0.12***	−0.07***
	(0.01)	(0.01)	(0.01)
rank(θ_g)	−0.31***	−0.03***	0.003
	(0.01)	(0.01)	(0.01)
rank(θ_c)	0.11***	−0.06***	0.05***
	(0.01)	(0.004)	(0.004)
rank(ϵ)	0.48***	−0.67***	0.71***
	(0.02)	(0.01)	(0.01)
rank(e_{d0})	−0.02***	0.02***	−0.01***
	(0.01)	(0.004)	(0.004)
rank(ϕ)	0.08***	0.05***	−0.04***
	(0.01)	(0.004)	(0.004)
rank(f_0)	0.02***	0.03***	−0.02***
	(0.01)	(0.004)	(0.004)
rank(α_g)	−0.31***	0.03***	−0.005
	(0.01)	(0.01)	(0.005)
rank(α_c)	0.32***	0.08***	−0.06***
	(0.01)	(0.004)	(0.004)
Constant	1,486.94***	2,227.28***	6,155.31***
	(138.90)	(91.10)	(82.52)
Observations	10,000	10,000	10,000
R^2	0.64	0.85	0.87
Note:	*p<0.1; **p<0.05; ***p<0.01		

E.4 Description and source of parameters for model calibration with international trade extension

Domestic consumption q_0 and exports z_0: Since France is a net importer of beef, the domestic consumption is the sum of domestic production plus net imports. The domestic production for the national market $(q_0 + z_0)$ is the same as in the closed economy model, derived from Idele and CNE (2021)(9.60×10^8). The net trade balance for beef (z_0) is also calibrated from Idele and CNE (2021) (-0.30×10^8). This gives $q_0 = 9.90 \times 10^8$.

International beef production ψ_0: See main text.

Slope of the inverse demand function b: With η the price elasticity of beef demand, we get $b = -p_0/(\eta q_0)$. This is the same calculation than in the closed economy model, but the change in q_0 changes the value of b.

Slope of the marginal cost of trade d_0: It derives directly from the first-order condition $d_0 z_0 = c_f - p_0$.

International price of beef c_f: It is calculated as the 2016-2020 average of the world reference price for beef from the OECD-FAO agricultural outlook 2021-2030 report (OECD and FAO 2021). Prices are converted into euros using the exchange rates from the OECD.

Carbon footprint of foreign beef e_f: See main text.

Response of international production to trade ψ_1: See main text.