Mitigating greenhouse gas emissions from the cattle sector: land-use regulation as an alternative to emissions pricing*

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Abstract

Although the cattle sector is both emissions- and land-intensive, it also represents a great opportunity for mitigation through reforestation. However, implementing a Pigouvian instrument on GHG emissions from this sector faces various barriers. Regulating land use instead of emissions might be a good alternative, as it could simultaneously limit beef production (extensive margin effect) and trigger mitigation through intensification (intensive margin effect) while freeing land for carbon sequestration. To study the efficiency of such land-use regulation, we develop a stylized partial equilibrium model of the beef sector that integrates land use, GHG emissions, and cattle feeding. In the model, farmers choose cattle feeding, which determines the land and emission intensity of meat production. We analyze the first-best emission tax and three second-best instruments: a subsidy to set aside land for natural forest regeneration, a meat tax, and a technical standard on cattle feeding. We then compare the mechanisms and the welfare impacts of these policies. Our analytical results indicate that the subsidy is the best alternative policy, provided that the elasticities of land use and emissions to cattle feeding are close. Interestingly, we show that the optimal meat tax should integrate the carbon opportunity cost of land use. A numerical application of the model to the French beef market shows that the subsidy, which acts at both margins, dominates the meat tax and the technical standard for a large set of parameter values and never induces large welfare losses.

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1 Introduction

Despite a significant contribution to global anthropogenic greenhouse gas (GHG) emissions (IPCC 2022) and a substantial mitigation potential (Frank et al. 2018; Hayek et al. 2021; Theurl et al. 2020), the agricultural sector remains largely outside the scope of existing climate policies. Sector-specific technical and political barriers hinder the enforcement of a first-best carbon pricing policy (Ancev 2011; Grosjean et al. 2016), leaving open the question of the most appropriate regulation to trigger mitigation efforts in agriculture.

Several studies have focused on the design of second-best climate policies addressing GHG emissions from agriculture (e.g., De Cara et al. 2018; Garnache et al. 2017). However, little attention has been paid to interactions between agricultural activities and land use and land use change (LULUC), which are pivotal in the climate impact of agriculture. LULUC contributes to 45% of agricultural emissions (FAO 2020), and the land currently used for agriculture—about one-third of the Earth's ice-free land—has the potential to sequester carbon in soils and above-ground biomass, e.g., through reforestation or afforestation (Hayek et al. 2021; Theurl et al. 2020). It follows that agricultural production entails a *Carbon Opportunity Cost* (COC), corresponding to the potential for carbon sequestration via ecosystem restoration on agricultural land (Hayek et al. 2021; Searchinger et al. 2018). Because what matters is the reduction of *net* GHG emissions, the COC should be accounted for in agricultural climate policies.

This paper investigates the interest and limits of a mitigation policy based on land-use regulation while considering the COC of agricultural production. Our analysis focuses on beef production as one of the most land- and emissions-intensive agricultural activities.[1] We evaluate a subsidy for land set aside for natural ecosystem regeneration and compare this policy to a first-best Pigouvian tax on GHG emissions as well as other second-best policies, namely a tax on meat and a technical standard on cattle feeding. Our analysis also clarifies how the COC should be considered in these policies.

To compare these policies, we develop a partial equilibrium model of the beef sector. The model includes three land uses - grassland, cropland, and land set aside - and accounts for direct emissions from livestock, indirect emissions from feed crops, and carbon sequestration from land. In this model, farmers choose the feed mix of grass and crops per unit of meat that determines the land and emission intensity. Land spared by a decrease in meat output or an intensification of the production decreases net GHG emissions through carbon sequestration. We refer to this alternative land use as 'land set aside'. We then analyze the subsidy for land set aside,[2] the meat tax, and the technical standard on cattle feeding, and assess the economic efficiency of these instruments.

The instruments can act on two levers to mitigate agricultural GHG emissions: (i) a reduction of the quantity of meat and (ii) a technical adjustment of cattle feeding towards

1. Several reasons led us to focus our analysis on the cattle sector. First, cattle alone account for 40% of agricultural GHG emissions (Herrero et al. 2016) and represent a significant part of the mitigation potential in agriculture (Havlík et al. 2014; Hayek et al. 2021; Herrero et al. 2016; Searchinger et al. 2018). Then, they require 27% of agricultural land at the global level (Mottet et al. 2017) and entail, therefore, a substantial carbon opportunity cost (Hayek et al. 2021; Theurl et al. 2020). Third, emissions from cattle are relatively well correlated with land use: extensive grazing systems generate more emissions per unit of meat, not only because of higher LULUC emissions but also because the higher the grass intake, the higher the enteric methane emissions (IPCC 2019; Thomas et al. 2021).

2. Note that in our model, this instrument is equivalent to a zoning policy whereby the social planner would choose the area to devote to the natural regeneration of vegetation.

a less emission-intensive production. These two levers can be interpreted as a volume and a composition effect or the extensive and intensive margins, respectively. At the social optimum, the quantity of meat should be reduced and, under reasonable assumptions, the quantity of grass per unit of meat should be lowered as well.

The optimal meat tax only mitigates agricultural emissions at the extensive margin; it should integrate not only all direct and indirect emissions from beef production but also its COC. However, the meat tax does not induce any technical adjustment. A technical standard favors the intensive margin, with only an indirect effect on the quantity produced. It dominates the meat tax when demand is inelastic and technical adjustment is sufficiently cheap. The subsidy for land set aside activates both margins. By increasing the opportunity cost of land, the subsidy increases the production cost of meat and induces a reduction in the quantity of beef at market equilibrium; it also encourages a reduction in the land intensity (i.e., in the grass intensity) of beef production, which also contributes mitigating GHG emissions. If emissions and land intensities are well 'aligned', the subsidy outperforms the tax and the standard.

A calibration of the model with data representative of the French beef sector provides a quantitative application of our theoretical results. In a realistic range of parameter values, total net emissions increase with the quantity of grass per unit of meat produced. The reduction in direct emissions from livestock (mainly methane from enteric fermentation) and the increased carbon sequestration in land set aside more than compensates for the additional indirect emissions for feed production. The relative land-use emissions, induced by the COC of meat production, accounts for approximately 40% of the optimal meat tax. The tax on meat performs better than the standard except when the technical adjustment of production is very cheap and the demand for beef is inelastic. The subsidy for land set aside is the preferable second-best instrument for a large range of parameter values. Relying on both intensive and extensive margins for GHG mitigation, this instrument also shows the smallest variations in welfare loss when parameters vary.

Our contribution to the literature is threefold. First, we provide new insights into the second-best mitigation policies in agriculture. Several studies have addressed the barriers to implementing a first-best emission tax and proposed alternative policies. Bakam et al. (2012) compare the cost-effectiveness of an emission tax, a fertilizer tax, and a carbon trading scheme for Scottish farms in the presence of transaction costs. Grosjean et al. (2016) review the barriers to agricultural emissions pricing. They argue that partial coverage of a carbon tax is justified to limit monitoring costs of emissions, a trade-off analyzed by De Cara et al. (2018). Garnache et al. (2017) quantify the efficiency costs of several second-best agricultural climate policies and show that using spatially aggregated emission factors may be a good second-best option. Compared to these articles, which tend to focus on the issue of monitoring costs of emissions, we consider a novel land-based policy which indirectly addresses the issue of monitoring costs to the extent that it is easier to monitor land use than emissions. We also explicitly consider the demand side of the market and the COC of agriculture in evaluating second-best policies.

Second, we contribute to the debate on the efficiency of a meat tax. Whereas the above-mentioned articles focus on the supply side (the intensive margin), several articles have analyzed meat taxation to reduce emissions via a diet change (the extensive margin). From a theoretical perspective, Schmutzler and Goulder (1997) show that an output tax can dominate an emission tax under high monitoring costs of emissions, costly mitigation options other than output reduction, and highly elastic demand. Several empirical studies assess the mitigation effect of a tax on meat consumption (see e.g., Bonnet et al. 2018;

Edjabou and Smed 2013; Wirsenius et al. 2011) and show that it has a limited impact because of the low price elasticity of meat demand. More broadly, Funke et al. (2022) advocate using a tax on meat to correct for the multiple externalities from the sector. Katare et al. (2020) analyze a combination between a tax and a green label on meat in the presence of external costs and prosocial consumers. However, a meat tax does not encourage efficiency gains on the production side, which we consider in the present work. We show that the meat tax misses potentially important welfare gains because of this shortcoming.

Last, our work also contributes to debates regarding agricultural intensification's environmental costs and benefits. Despite its local environmental cost, intensive (high-yield) agriculture might benefit the environment by sparing land for nature thanks to its lower land requirement per unit produced (e.g., Waggoner 1996; Borlaug 1997). Green et al. (2005) proposed a simple framework to analyze this trade-off for species abundance. A contentious debate among conservation scientists ensued about the relative merits of 'land-sharing' and 'land-sparing' (Fischer et al. 2014).[3] Some articles in economics have analyzed the issue of land allocation and farming intensity to preserve biodiversity (Desquilbet et al. 2017; Hart et al. 2014; Martinet 2014; Meunier 2020). In their review of the data available to assess the environmental impacts of high-yield farming, Balmford et al. (2018) stress that the environmental impacts of agriculture practices should be assessed per unit produced and not per hectare farmed. Regarding GHG emissions, forgone sequestration should thus be included, which is at the core of our analysis and the notion of COC.[4] Our economic framework allows us to integrate consumer surplus and production costs in the analysis of the trade-offs associated with intensification and to assess the policies available to reduce the GHG emissions from meat production.

The remainder of the paper is organized as follows. The model is presented in section 2. The social optimum is described in section 3 and an analytical comparison of instruments is provided in section 4. Section 5 presents numerical simulations. We discuss the model and the results in section 6 and conclude in section 7.

2 The model

2.1 Framework

The model is kept as simple as possible to highlight the main trade-offs associated with direct (mainly from enteric fermentation) and indirect (from feed production and land-use change) GHG emissions from cattle. We focus on beef cattle, which produce a homogeneous good, and exclude dairy cattle.

The total quantity of beef produced and consumed is q. On the demand side, the consumer price is denoted p. The gross consumer surplus, $S(q)$, is assumed to be positive, increasing, and concave with respect to q. The net consumer surplus is $S(q) - pq$, and

3. On a given agro-ecological landscape, for a given food production, land-sparing consists in maximizing agricultural yield to minimize land requirement and sparing the remaining land for natural reserves. Land-sharing consists of extensive 'wildlife-friendly' farming covering the whole landscape. Green et al. 2005 show how the shape of the density-yield curve (how local species density relate to agricultural yield) determines the optimal strategy to maximize a species population under a food production constraint.

4. Note that Balmford et al. (2018) compute GHG emissions of different beef production systems and show that GHG emissions decrease together with the land requirement.

the inverse demand function is $P(q) = S'(q)$. The demand for meat at price p is denoted $D(p) = P^{-1}(p)$.

On the producer side, farmers face a technical choice lying in the feeding of animals, composed of grass and crops.[5] Farmers choose the quantity of grass per unit of meat, denoted x. x will be referred to as the *technique*. The associated quantity of crops needed per unit of meat is $f(x)$, with f a positive and decreasing function of x.[6] The production cost per unit of meat is $c(x)$, positive, convex and minimized at $x_0 > 0$, solution of $c'(x) = 0$.[7]

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 natural forest regeneration occurs.[8]

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 :

$$L_n = \bar{L} - (L_g + L_c) = \bar{L} - l(x)q \tag{1}$$

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. With realistic parameters, iit increases with x; that is, the increase in the area of grassland required is greater than the reduction in cropland when increasing the quantity of grass in cattle feeding (see e.g., Mogensen et al. 2015, for an estimate of land intensity of grass-based vs concentrate-based beef production systems).

Assumption A1 *The land needed per unit produced is increasing with x:*

$$l'(x) = \alpha_g + \alpha_c f'(x) > 0, \forall x \geq 0$$

GHG emissions

GHG emissions are decomposed into (i) direct emissions from meat production (including enteric fermentation, manure management, and housing), (ii) indirect emissions from animal 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.[9] Emissions per unit of feed from crops are summarized by the emission factor

5. We summarize the production process to feeding animals because it is one of the main (if not the main) factors that explains the land and emission intensity of beef production.

6. One can interpret $f(.)$ as a zootechnical constraint: the quantity of crops needed together with x to ensure a given weight. The variable x includes grass in all its forms: grazed grass, hay, and silage. The quantity $f(x)$ includes cereals and fodder crops such as corn silage.

7. This cost function includes not only the cost of feeds but also the cost of labor, buildings, machinery, drugs, and all other inputs required.

8. Forest regeneration may be more or less assisted, from natural, spontaneous regeneration to active tree planting. We assume implicitly spontaneous regeneration, though introducing a cost of assisted regeneration would not change our results. Natural forest regeneration on former agricultural land is common in most regions of the world (Chazdon et al. 2020) and, in Europe, about 40% of the regenerated forest area was due to natural regeneration and expansion in 2015 (see Forest Europe 2020, Figure 4.2-2, p 118). Several papers have considered how forest management should be adjusted in response to climate policies to better store carbon (Tahvonen and Rautiainen 2017; Hoel et al. 2014) and produce bioenergy (Favero and Mendelsohn 2014; Hoel and Sletten 2016).

9. 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; Lynch 2019; Mogensen et al. 2015; Thomas et al. 2021).

e_c. And 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. Total emissions are then :

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

Replacing L_g, L_c by their expression and L_n with equation (1) gives:

$$E(q, x) = q \underbrace{[e_d(x) + e_c f(x) + (\theta_n - \theta_g)\alpha_g x + (\theta_n - \theta_c)\alpha_c f(x)]}_{\equiv e(x)} - \theta_n \bar{L} \tag{2}$$

$$= e(x)q - \theta_n \bar{L} \tag{3}$$

In equation (2), land-use emissions are gathered to highlight the COC (θ_n) of land uses.

Total emissions per unit of meat $e(x)$ encompasses 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 5). Therefore, we make the following assumption for the rest of the article.

Assumption A2 *Carbon sequestration is larger in land set aside for natural forest regeneration than in grassland and larger in grassland than in cropland, that is, $\theta_n > \theta_g > \theta_c$.*

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 5) indicates that $e(x)$ is increasing. Non-land-use effects are likely to be positive, i.e., $e'_d(x) > -e_c f'(x)$ (see e.g., Balmford et al. 2018; Capper 2012; Vries et al. 2015), as well as the 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.

Assumption A3 *Total unitary emissions $e(x)$ are increasing with respect to x:*

$$e'_d(x) + (\theta_n - \theta_g)\alpha_g > -f'(x)[e_c + (\theta_n - \theta_c)\alpha_c]$$

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:

$$W(q, x) = S(q) - c(x)q - \delta e(x)q + \theta_n \bar{L} \tag{4}$$

2.2 Regulations

We compare the following policy instruments:

- An exhaustive tax on carbon emissions τ
- A tax on meat t
- A technical standard on cattle feeding $\bar{x}$

- A subsidy to set aside land for natural forest regeneration s. It is equivalent to a zoning policy that would enforce a total area L_n of natural reserves.

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

$$\Pi(x,q,\mathbf{r}) = [p-t-c(x)]q - \tau[e(x)q - \theta_n \bar{L}] + s[\bar{L} - l(x)q] \tag{5}$$
$$\text{subject to } x = \bar{x} \text{ if a standard is used}$$

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. At market equilibrium, the above profit is null.

2.3 Quadratic specifications

Some analytical results and the numerical application will use the following quadratic specifications.

Specification 1

$$S(q) = (a - \frac{b}{2}q)q \tag{6}$$
$$c(x) = c_0 + \frac{\gamma}{2}(x - x_0)^2 \tag{7}$$
$$e_d(x) = e_{d0} + \epsilon_d(x - x_0) \tag{8}$$
$$f(x) = f_0 + \phi(x_0 - x) \tag{9}$$

In specification 1, 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 c_0, e_{d0}, and f_0 correspond to the production cost, direct emissions, and amount of crops per unit of meat, respectively. 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 $e(x)$ (net emissions per unit of meat) and $l(x)$ (net area of land used per unit of meat) are linear functions of x. They are minimized at $x = 0$ if their slope is positive, as will be the case in our simulations.

3 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):

$$S'(q) = c(x) + \delta e(x) \tag{10}$$
$$-c'(x) = \delta e'(x) \tag{11}$$
$$= \delta\left[e_d'(x) + e_c f'(x) + (\theta_n - \theta_g)\alpha_g + (\theta_n - \theta_c)\alpha_c f'(x)\right] \tag{12}$$

The model allows for disentangling the technical choice from the quantity produced. The optimal quantity of meat (equation 10) is such that the marginal utility of meat consumption equalsits marginal social cost. The optimal technique (equation 11) is such that the increase in the production cost is equal to the marginal environmental benefit per unit of meat from this change.

From the first-order conditions of the social optimum (equations (10) et (11)), we get the following effect of the level of the social cost of carbon.

Lemma 1 *An increase in the SCC induces*

- *a reduction in the optimal quantity produced;*
- *a reduction in grass per unit of meat if and only if $e'(x) > 0$ (A3).*

Proof in Appendix A. With an increase in the SCC, the total quantity produced is reduced since $e(x)$ is positive according to Assumption A2. Whether the quantity of grass per unit should decrease depends on its net effect on GHG emissions. As argued, it is likely to be positive.

Given the uncertainty and spatial heterogeneity of the carbon sequestration potential in both grasslands and land set aside, it is interesting to analyze the impact of θ_n and θ_g.

Lemma 2 *An increase in the quantity of carbon sequestered per unit of land set aside (θ_n) induces:*

- *an increase in the area of land set aside;*
- *a reduction in the optimal quantity of meat produced; and*
- *a reduction in the optimal amount of grass per unit of meat if and only if $l'(x) > 0$ (A1)*

An increase in the amount of carbon sequestered by grasslands induces an increase in both the optimal quantity of meat produced and the quantity of grass per unit of meat.

Proof in Appendix A. Increasing the quantity of carbon sequestered in land set aside increases the value of this land use and, thus, its quantity at the social optimum. The quantity of meat and grass per unit of meat should be adjusted. The land requirement per unit of meat, i.e., $l(x) = \alpha_g x + \alpha_c f(x)$, should be reduced, and the variation (reduction or increase) in the amount of grass varies accordingly. It is reduced if Assumption A1 holds.

4 Decentralization and instruments comparison

4.1 First-best and combination of instruments

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

Lemma 3 *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 tax on all emissions, notably the (negative) ones associated with carbon sequestration, the optimum is decentralized. Even though each combination of instruments can decentralize the first best, these combinations do not induce the same transfers between farmers and landowners.

With a subsidy for land set aside and a standard, the optimal subsidy is the ratio between emissions per unit of meat and the area required per unit of meat, times the social cost of carbon, δ.

4.2 Second-best policies and the two levers

The optimal 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 consumed (Lemma 4) and does not allow adjustment at the intensive margin. The technical standard mainly influences the technique and only indirectly affects the quantity consumed (Lemma 5). 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 x-elasticity of the emission intensity of meat relative to that of the land intensity of meat (Proposition 1).

For each instrument, we analyze the second-best allocation obtained by maximizing welfare, given by equation (4), for the given instrument. For each instrument r in $\{sta, sub, tax\}$, the two variables (q, x) at the second-best allocation are denoted q_r^{SB} and x_r^{SB}. 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 social welfare for a given technique* x *is denoted* $q^{\times}(x)$ *and corresponds to*

$$q^{\times}(x) = D(c(x) + \delta e(x)).$$

With a **meat tax** t alone, the technique is kept at x_0, and the quantity produced is $D(c(x_0) + t)$. The optimal tax equals the SCC times total emissions per unit of meat, and the corresponding quantity is $q^{\times}(x_0)$.

Lemma 4 *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 if A3 is satisfied. Formally,*

$$q_{tax}^{SB} \leq q^* \text{ and } x_{tax}^{SB} = x_0 \geq x^*$$

A **technical standard** $\bar{x}$ influences the quantity at equilibrium indirectly through the marginal cost.

Indeed, the cost being minimized at x_0, any change of $\bar{x}$ away from x_0, in one direction, induces an increase in the cost and a reduction in meat production. The optimal second-best standard will be more stringent than the first-best technique because of its effect on the quantity at market equilibrium. If A3 is satisfied, then the optimal technique with a standard is lower than the first best one.

Lemma 5 *The optimal second-best technique with a standard, $\bar{x}^{SB}$, is more stringent than the first-best technique: either $x_0 > x^* \geq \bar{x}^{SB}$ or $x_0 < x^* \leq \bar{x}^{SB}$. If A3 is satisfied, then the former holds.*

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 B.

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

$$S'(q) - c(x) = p - c(x) = sl(x) \tag{13}$$

$$-c'(x) = sl'(x) \tag{14}$$

If the land required per unit of meat is increasing with the amount of grass, i.e., $l'(x) \geq 0$, what is likely, then both the quantity produced and the amount of grass per unit of meat decreases with the subsidy. Both levers move in the right direction relative to the first-best, but not optimally.

The optimal subsidy solves

$$0 = \frac{\partial W}{\partial q}\frac{\partial q}{\partial s} + \frac{\partial W}{\partial x}\frac{\partial x}{\partial s} = [sl(x) - \delta e(x)]\frac{\partial q}{\partial s} + [sl'(x) - \delta e'(x)]\, q\frac{\partial x}{\partial s}. \tag{15}$$

The subsidy affects both the quantity produced and the technique chosen. Equation (15) highlights the trade-off between the two levers as, at the optimum, $\partial W/\partial q$ and $\partial W/\partial x$ have opposite signs. 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 15 gives:

$$s\left[l'(x)q\frac{\partial x}{\partial s} + l(x)\frac{\partial q}{\partial s}\right] - \delta\left[e'(x)q\frac{\partial x}{\partial s} + e(x)\frac{\partial q}{\partial s}\right] = 0 \tag{16}$$

Equation (16) 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 among levers depends on the 'alignment' between the two objectives: saving land and saving emissions. This alignment can be characterized by comparing the x-elasticities of the land and emission intensity of meat production at the optimal technique $x = x^*$.

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

Formally, if A2 and A3 are satisfied, 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* $q_{sub}^{SB} > q^{\times}(x_{sub}^{SB})$*.*

Proof in Appendix C.

The intuition for Proposition 1 is the following. Suppose the land 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 (bottom panel) 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 at the point of tangency between their path and an isoquant (dashed lines).

As the subsidy increases, the quantity consumed and the chosen technique move in the right direction. In Figure 1, (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 cattle feeding 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.

Finally, given our assumptions, welfare is not necessarily quasi-concave with the subsidy. There might be several solutions to the first-order conditions given by equation (15). Notably, a solution with $x > 0$ and another with $x = 0$ (so that $\partial x/\partial s = 0$) are possible. With the quadratic specification, under some conditions on parameter values, welfare is first bell-shaped with respect to s until $x = 0$, and might then increase again (if $q < q^{\times}(0)$ at that point). It is illustrated in Figure 1 with the dashed line. When descending the welfare mount, the subsidy path reaches the q-axis above $q^{\times}(0)$, and ascend the mount again along the q-axis. The top panel depicts welfare along that path.

The possible lack of concavity further illustrates how the misalignment between the actual source of external costs (GHG emissions) and the regulated quantity (land use)

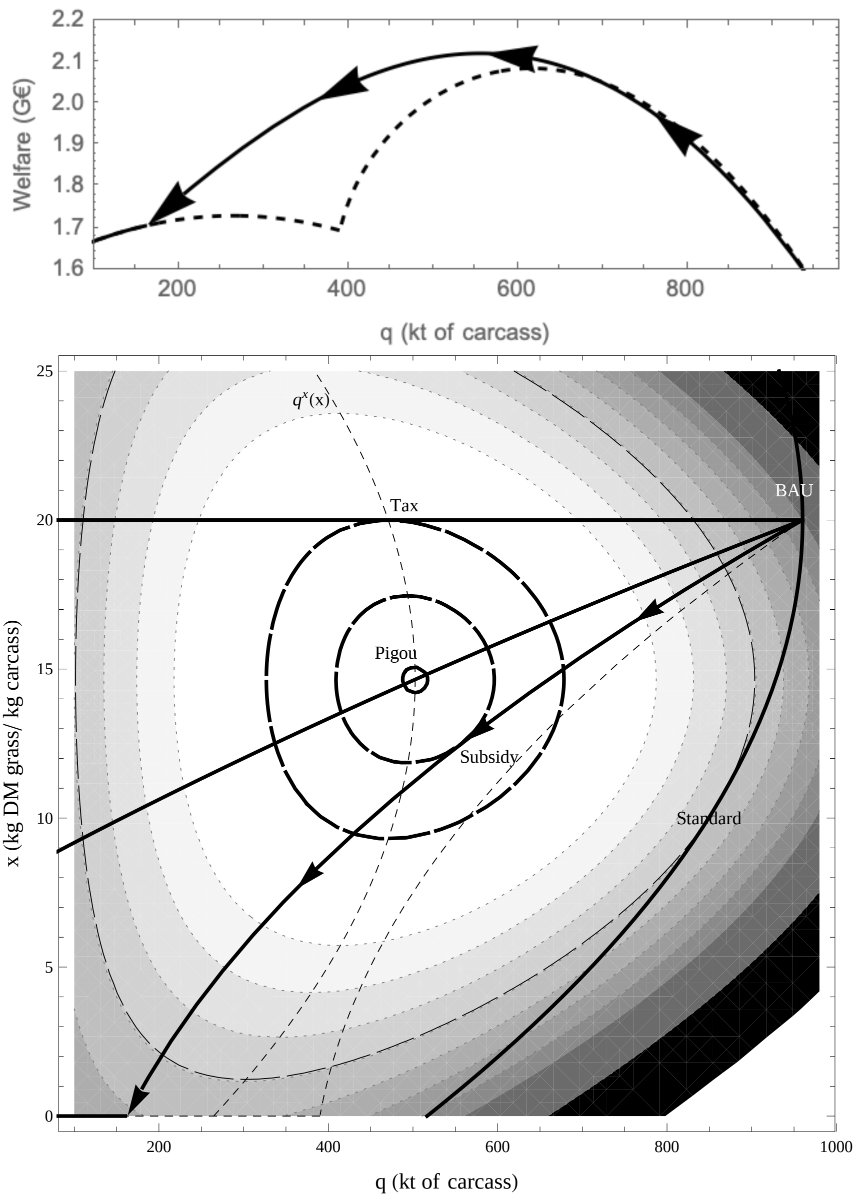

Figure 1: Iso Welfare curves (bottom panel) in the (x, q) plan with paths followed by each instrument. Parameter values are as in the baseline calibration. The top panel shows the welfare along the subsidy path as q moves along the y-axis from q_0 to 0. The dashed line correspond to a larger l'.

can generate complications. However, it is likely a formal issue without deep economic meaning. First, with a cost function such that $c'(0) = -\infty$, the corner maximum would not exist. Second, even with our quadratic specification, the co-existence of the two local maximums holds over a relatively small range of parameters. Third, the quadratic specification does not qualitatively change the result of Proposition 1: in cases where two maximums co-exist they both exhibit an over-reliance on the technical lever.

4.3 Welfare comparison

For each instrument, there are situations in which they perform well. A meat tax is optimal if mitigation at the intensive margin is not possible ($\gamma = +\infty$) or useless ($e'(x) = 0$). A technical standard performs well 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 intensity and the emission intensity of meat production have close x-elasticity ($e'(x)/e(x) = l'(x)/l(x)$). These extreme cases provide intuition on the influence of parameters on the comparison of instruments that we explore below with the quadratic specification (1).

With the quadratic specification, the welfare can be expressed as the difference between the first best and two terms related to each margin:

$$W(q,x) = W(q^*,x^*) - \frac{b}{2}(q-q^*)^2 - \frac{\gamma}{2}(x-x^*)^2 q. \tag{17}$$

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 the quadratic specification, the following properties on welfare losses induced by the second-best instruments compared to the first-best hold.*

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

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

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

$$\frac{\delta^2}{2b}e(0)^2 \leq \left[W(q^*,x^*) - W^{SB}_{sta}\right] \leq \frac{\delta^2}{2b}e(x^*)^2$$

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

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

Calculations are provided in Appendix D. The bounds provided by Proposition 2 indicate situations in which one of the instruments dominates 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 unitary emissions relative to grass intensity (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) as summarized in 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 proof is in Appendix D. The efficiency of the subsidy is related to the difference between the relative slope of land and emission intensities, l'/l and e'/e (Proposition 1). If the difference is small enough, the subsidy dominates both instruments.

Proposition 3 *If the difference between the x-elasticities of land intensity and emission intensity is small, then the subsidy dominates the two other instruments.*

Formally, the subsidy dominates the tax if

$$\left(\frac{e}{e'} - \frac{l}{l'}\right)^2 \leq \frac{1}{\gamma}\left[a - (c_0 + \delta e_0) + \frac{(\delta e')^2}{4\gamma}\right] \tag{18}$$

and it dominates the standard if

$$\left(\frac{e}{e'} - \frac{l}{l'}\right)^2 \leq \left(\frac{e(0)}{e'}\right)^2. \tag{19}$$

The results are derived from the bounds obtained in Proposition 2. It should be noted that with linear functions, the difference $e/e' - l/l'$ does not depend on x. If that difference is null, emissions are simply proportional to the land requirement. In our baseline numerical calibration, the difference is positive, and in that case, equation (19) always holds, ensuring that the subsidy 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 natural forest regeneration θ_n, the latter corresponding more precisely to the weight of land use in GHG emissions from beef.

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

Proof 1

$$\textit{For any given } \theta_n > 0, \ \frac{d}{d\theta_n}\left|\frac{e}{e'} - \frac{l}{l'}\right| < 0$$

5 Numerical Application

In this section, we conduct numerical simulations to determine the ranking of the second-best instruments in a realistic context and estimate its sensitivity to parameter values. The model is calibrated with aggregated data from the French beef sector using specification (1). Subsection 5.1 describes the data used for calibration. The second subsection presents the results of the baseline scenario and sensitivity analysis.

5.1 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).

Demand parameters. The intercept a and slope b of the inverse demand function are computed from the quantity of beef q_0 (expressed in carcass weight, denoted CW) and price of beef p_0 in the BAU situation (derived from Agreste 2021; Idele and CNE 2021), and the price elasticity of beef demand η (Gallet 2010).[10].

Supply parameters. Since there is a wide diversity of cattle beef systems in France, it is not easy to set a value of grass intake per unit of meat produced that can be considered representative. Based on the 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]$^{-1}$. Parameters f_0 and ϕ of the function $f(.)$ have been estimated using the dataset provided in the meta-analysis of Gérard (2023). The baseline cost c_0 is equal to the initial price of beef p_0. γ is assumed to be 0.01 and has been chosen such that the production cost of beef does not exceed 105% of its minimum value (reached at $x = x_0$) when x varies within the range [15,25].

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: $\overline{L} = q_0(\alpha_g x_0 + \alpha_c f_0)$. $\overline{L}$ is 3.84 million hectares, consistent with existing estimates of the French area dedicated to beef cattle farms (Lherm et al. 2017).

The linear form of $e_d(x)$ is estimated by OLS with data from Gérard (2023). We find a significant and positive slope, with an increase of 0.57 kgCO_2eq/kg of meat for each additional kg of grass intake. The model explains more than 60% of the variance, indicating that grass intake is a good predictor of direct emissions. The emission factors associated with crops, e_c, has been set considering the range of emission factors of feeds found in the *ECOALIM Agribalyse* database.[11] The emission factors related to land use (θ_c, θ_g, and θ_n) have been evaluated using the values of carbon stocks of Pellerin et 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.[12] The social cost of carbon is set at €50.tCO_2eq^{-1}, close to the carbon tax currently applied in France on fossil fuels (€44.6 .tCO_2eq^{-1}).

5.2 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.

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

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

12. For forest regeneration on land set aside, 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	3.98	$\mathcal{N}(3.98, 0.42)$
Technical flexibility of beef production (€.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	0.14	$\mathcal{N}(0.14, 0.04)$
BAU production cost/ market price of beef (€/kg CW)	c_0, p_0	3.9	
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)	$\bar{L}$	$3.84 * 10^{10}$	
Emission growth rate with the amount of grass (kgCO_2eq/kg grass)	ϵ_d	0.57	$\mathcal{N}(0.57, 0.05)$
Direct emissions of beef when $x = x_0$ (kgCO_2eq/kg CW)	e_{d0}	24.17	$\mathcal{N}(24.17, 0.51)$
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	$\frac{44\times\mathcal{N}(84.1,35.0)}{12\times10\times80}$
Annual carbon sequestration of crops (kgCO_2eq/m^2)	θ_c	0.24	$\frac{44\times\mathcal{N}(51.6,16.2)}{12\times10\times80}$
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	

Table 2: Results in the baseline scenario (in brackets are differences with the first-best)

	BAU	First-best $\tau = \delta$	Subsidy s^{SB}	Tax t^{SB}	Standard $\bar{x}^{SB}$
$\Delta W = W - W^{BAU}$ (M€)	0 (-100%)	609.75 ($\cdot$)	589.65 (-3%)	540.62 (-11%)	245.84 (-60%)
q (kt of carcass)	960.00 (+91%)	502.07 ($\cdot$)	556.82 (+11%)	470.58 (-6%)	860.03 (+71%)
x (kg DM grass/ kg carcass)	20.00 (+36%)	14.67 ($\cdot$)	12.48 (-15%)	20.00 (+36%)	10.50 (-28%)
p (€/kg)	3.90 (-35%)	5.97 ($\cdot$)	5.72 (-4%)	6.11 (+2%)	4.35 (-27%)
E ($MtCO_2eq$)	11.18	-11.91	-11.10	-10.45	-1.95
L_n (Mha)	0.00 (-100%)	2.22 ($\cdot$)	2.21 (=)	1.96 (-12%)	1.57 (-29%)
L_g (Mha)	3.21 (+161%)	1.23 ($\cdot$)	1.16 (-6%)	1.57 (+28%)	1.51 (+23%)
L_c (Mha)	0.64 (+61%)	0.40 ($\cdot$)	0.47 (+18%)	0.31 (-21%)	0.77 (+93%)

5.2.1 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 tax, achieving 97% of the first-best welfare gains. The meat tax induces 11% less welfare gains than the first-best while the standard is much less efficient, missing 60% of the potential welfare gains.

The interest of the subsidy lies in its ability to activate both mitigation levers. Note that the quantity of meat and the technique with the subsidy are intermediate compared to those with the two other second-best policies. The quantity of meat consumed is greater with the subsidy than in the first-best situation but is associated with a lower x (12.48 vs 14.67), leading to similar levels of overall land requirements. The baseline scenario lies in the third case of Proposition 1. Indeed, we have $e(x^*) = 38.5$; $e'(x^*) = 1.1$; $l(x^*) = 32.4$; and $l'(x^*) = 1.4$, which gives $l'(x^*)/l(x^*) > e'(x^*)/e(x^*)$.

The meat tax reduces consumption but does not affect the production technique. It follows that about 12% less land is set aside compared to the first-best land allocation, despite a lower quantity of meat (the latter is consistent with Lemma 4). The lack of technical adjustment induces a higher carbon footprint (Table 3) and a higher price (6.11 vs. 5.97 in the first-best case) than in the first-best.

The technical standard leads to the most intensive production technique (lowest x), notably more intensive than the first-best technique. This is consistent with the analytical results of Lemma 5. The standard also induces the largest quantity of meat because of its relatively small impact on the meat price, which is 27% 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.

Table 3: Decomposition of beef carbon footprint.

	BAU/ Tax t^{SB}	First-best τ^*	Subsidy s^{SB}	Standard $\bar{x}^{SB}$
Carbon footprint ($e(x)$, $kgCO_2eq$)	44.2	38.5	36.2	34.0
Direct emissions ($e_d(x)$)	54.7%	55.0%	55.1%	55.2%
Crop emissions ($e_c f(x)$)	4.5%	6.2%	7.0%	7.8%
Relative emissions of grasslands ($(\theta_n - \theta_g)\alpha_g x$)	32.1%	27.0%	24.5%	21.9%
Relative emissions of crops ($(\theta_n - \theta_c)\alpha_c f(x)$)	8.7%	11.8%	13.4%	15.1%

Regarding total GHG emissions, in the first-best situation, the area of land set aside is sufficiently large to more than compensate for the emissions from the beef sector (Table 2, fifth row). The same conclusion holds for the subsidy and the meat tax, for which similar levels of carbon sequestration are found. With the technical standard, even though the quantity produced decreases only by around 10% compared to the BAU, net sectoral emissions are negative, indicating that GHG mitigation at the intensive margin may be substantial.

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 23% lower with the standard than in the BAU situation, i.e., when halving cows' grass intake. Direct emissions represent a bit more than half of the carbon footprint and this share is stable whatever the instrument. The relative emissions from land use induced by the COC are responsible for about 40% of beef carbon footprint and increase with the amount of grass in cattle feeding; this means that the increased need for land to feed cattle with grass rather than with crops more than compensates the higher sequestration potential per unit area of grasslands compared to cropland ($\theta_g \geq \theta_c$). The share of GHG emissions from crops remains limited, even when feeding relies importantly on crops, in line with the literature (see Poore and Nemecek 2018).

5.2.2 Sensitivity to supply and demand parameters

We here analyze the sensitivity of the ranking of second-best policies to the key parameters of production and consumption: the technical flexibility of beef production (that can also be interpreted as the cost of technical change), γ, and the price elasticity of meat demand, η.

Technical flexibility of beef production Figure 2A shows the sensitivity of our results to the technical flexibility of production, γ. The welfare gains on the y-axis are

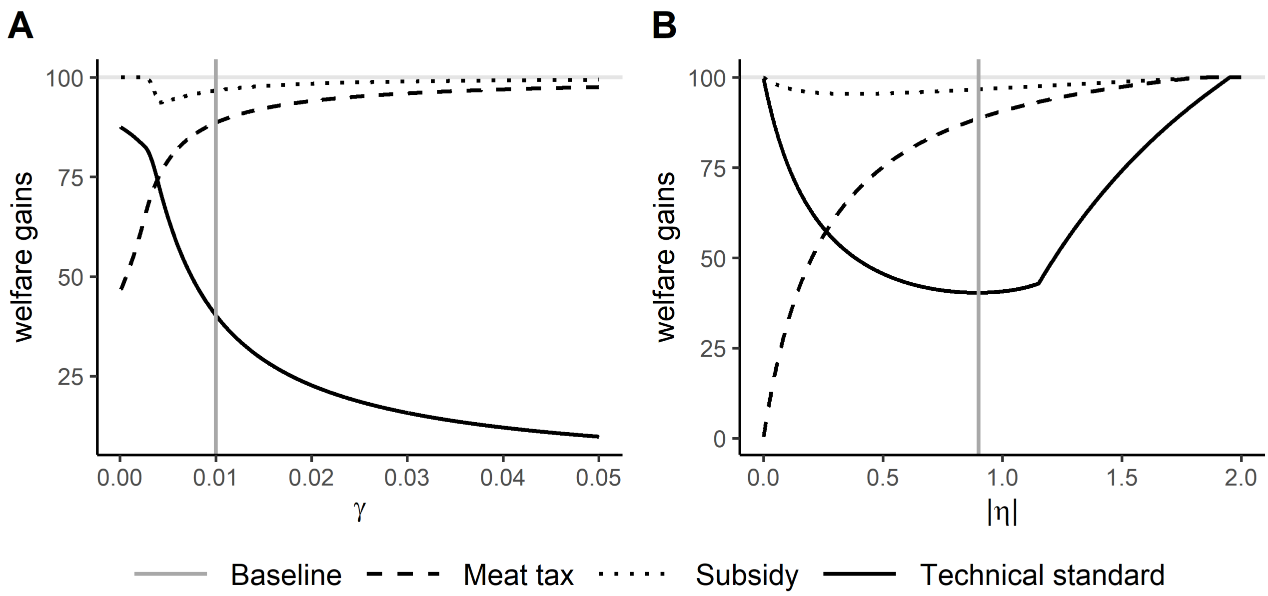

Figure 2: Welfare gains (in % of first-best welfare gains) of second-best policies according to (A) the technical flexibility of beef production and (B) the price elasticity of beef demand.

percentages of first-best welfare gains.[13]

Note that the lower γ, the more flexible the production of beef is, i.e., the cheaper the technical change. The subsidy appears to be the best alternative to the Pigouvian tax since it reaches the highest percentage of the first-best welfare gains, regardless of the level of γ. Conversely, the two other policies are very sensitive to this parameter, the standard being inefficient when γ is high and the tax when γ is low. The robustness of the subsidy to variations in γ lies in its effect at both margins. Unlike the subsidy, the meat tax misses important welfare gains at the intensive margin when technical change is cheap. The standard cannot substantially reduce the quantity of meat and has almost no effect when this is the only cost-effective mitigation lever.

For low values of γ, the curve discontinuities observable for the subsidy and the standard corresponds to the situation at which x reaches 0: the cost of intensification is sufficiently low to lead to no grass in cattle feeding.

Price elasticity of beef demand Figure 2B shows that the subsidy does better than the two other instruments, whatever the elasticity value. When the demand for beef is inelastic, a price variation has a small effect on the demand. In this case, the meat tax is not efficient in mitigating GHG emissions. [14] The only efficient instruments are the standard and the subsidy, equivalent to the first-best with a perfectly inelastic demand. Conversely, when the demand is price-sensitive, a tax may have a significant impact on the quantity of meat consumed and be economically efficient to mitigate GHG emissions. Elastic demand means that the marginal utility of meat consumption is stable, even for the first units of meat consumed. Therefore the welfare impact of reducing meat

13. Formally they are computed as $\frac{W_r^{SB}-W^{BAU}}{W^{*}-W^{BAU}}$, with $r \in \{sub, sta, tax\}$.

14. In the case of a perfectly inelastic demand, all the welfare gains are due to technical adjustment, and the meat tax corresponds to the BAU.

consumption is limited, while the social cost of carbon remains the same. Mitigation through intensification is still achievable, but its welfare gains become relatively modest, explaining the much lower performance of the standard.[15] Again, because it acts on both margins, the subsidy can reduce the quantity of meat when demand is elastic and outperforms the other instruments.

5.2.3 Sensitivity to land carbon sequestration parameters

How the second-best policies studied are sensitive to the carbon sequestration potential of grasslands, θ_g, and land set aside, θ_n, is analyzed below.

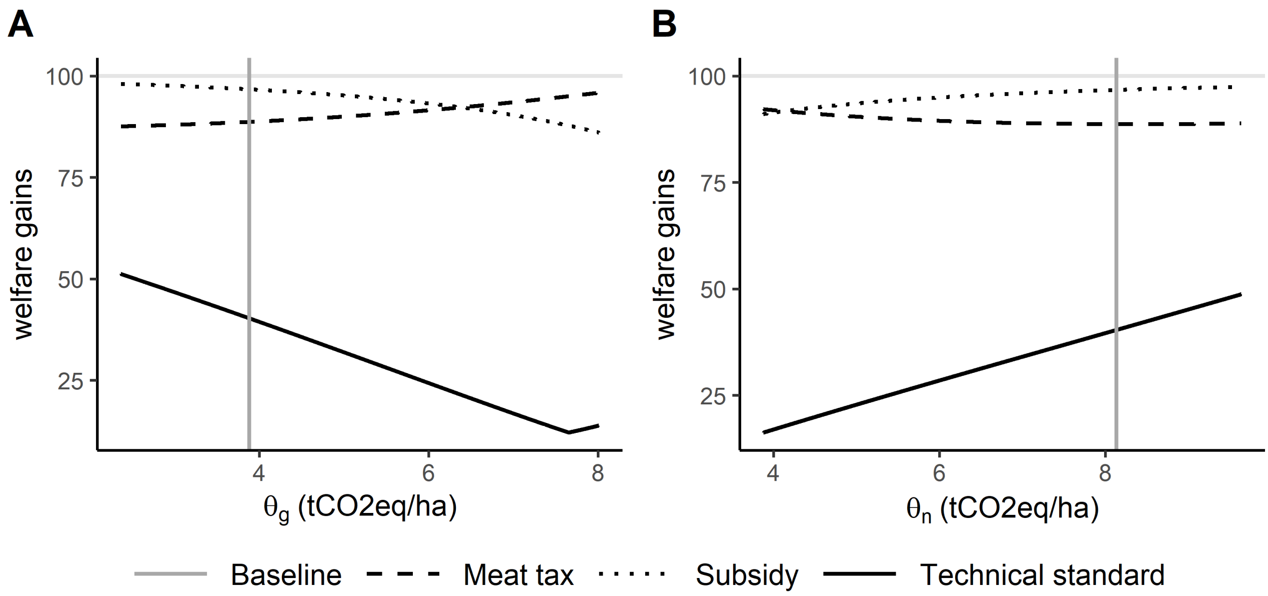

Figure 3: welfare gains (in % of first-best welfare gains) of second-best policies according to (A) the carbon sequestration potential of grasslands and (B) the carbon sequestration potential of land set aside.

Carbon sequestration potential of grasslands In figure 3A, θ_g takes a range of values derived from the report of Pellerin et al. (2020), the minimum being equal to θ_c to satisfy Assumption A2. When the carbon sequestration potential of grasslands decreases compared to the baseline, the relative emissions of grasslands due to the COC of land use increase, *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 increase in the relative emissions of grasslands improves the alignment between land use and GHG emissions.

When θ_g increases, the relative emissions of grasslands decreases and the gains from intensification become limited. The GHG mitigation potential then lies increasingly on

15. Note that for high values of elasticity, the convergence of instruments is due to a first-best quantity that is zero.

direct and crop emissions. The lower weight of the intensive margin effect improves the economic efficiency of the meat tax, which even do better than the subsidy. The efficiency of the subsidy decreases because of the reduction of the alignment between land use and GHG emissions. With the standard, the welfare gains decrease because of the reduced mitigation effect of intensification.[16]

Carbon sequestration potential of forest regeneration on land set aside Subsidizing land set aside for natural forest regeneration relies on the assumption that forest regrowth will actually occur with a significant carbon sequestration level. Therefore, it is crucial to know to what extent the subsidy for land set aside depends on the ability of renatured land to sequester carbon. Figure 3B illustrates the results of a sensitivity analysis for values of θ_n between 3.9 tCO_2eq/ha/yr (the value of θ_g, to stay within the scope of A2), and 9.6 tCO_2eq/ha/yr (equivalent to a closed coniferous forest of the continental region), derived from Efese (2019). For almost all the range of values for θ_n, the subsidy is the best alternative to the Pigouvian tax. In particular, the higher θ_n, the closer the subsidy is to the first-best. Indeed, the higher θ_n, the larger the COC and the relative emissions of both grasslands and cropland and the better the alignment between land use and GHG emissions. Conversely, any increase in θ_n decreases the relative welfare obtained with the meat tax, because it does not trigger mitigation at the intensive margin while the welfare gains related to this margin increases. The higher efficiency of intensification due to higher θ_n makes the technical standard a better instrument.

5.2.4 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. A truncation of distributions allows accounting for the positivity constraint for concerned parameters. The rejection sampling method ensures that Assumptions A2 and A3 are met for all the simulations. Figure 4 shows the cumulative distribution functions of welfare gains with the three second-best policies. The subsidy for land set aside clearly dominates the meat tax and the standard. 96% of the simulations with the subsidy are associated with welfare gains exceeding 90% of the first-best welfare gains. By comparison, 63% of the simulations with the meat tax and only 4% of those with the standard reach welfare gains greater or equal to this level. The median welfare gains are 97.8%, 92.7%, and 36.4% for the subsidy, the meat tax, and the standard, respectively. With the subsidy, the median area of land set aside is 2.16 million ha, and the median optimal subsidy is 488€/ha/yr. Those figures correspond to 1.0 billion euro of public spending, i.e., 10% of the annual CAP budget for France. The median reduction in GHG emissions is 18.8 $MtCO_2eq$ corresponding to a cost of 51.7€/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 results of the Monte-Carlo simulations. It 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. Results are presented in table 4. All parameters are significant at the 5% level, except for the

16. For high values of θ_g, close to θ_n, the welfare gains obtained with the standard increases on fig. 3A. As the gains from intensification are reduced (although positive), it becomes more optimal to have a standard higher than the BAU technique x_0, so that the standard increases land requirements per unit of meat and can limit the meat quantity by playing on the saturation of the total land constraint.

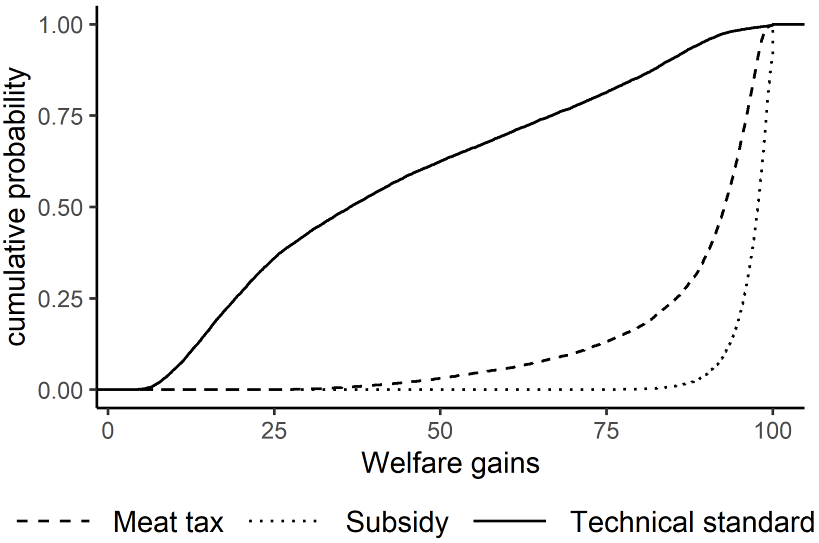

Figure 4: Distribution of welfare gains (in % of first-best welfare gains) with the second-best policies.

regression on the standard's performance. With the subsidy, θ_n has the strongest effect, which is positive, and is associated with a large and negative effect of θ_g. As expected, this indicates that the relative emissions of grasslands induced by the COC, $\theta_n - \theta_g$, plays a major role in the efficiency of the subsidy, determining the benefit from land sparing. Conversely, θ_c has a positive effect as the lower the relative emissions of cropland, the better is the intensive margin effect. The γ and η parameters influence the meat tax's performance the most - and positively. Last, the efficiency of the standard is mostly impacted by γ, θ_n, and θ_g. Intensification must be cheap (negative effect of γ) and allows an important reduction in *net* emissions through the reduction of the grassland area. Although the elasticity of demand is particularly critical for the meat tax, it remains a leading factor for all second-best instruments including the standard.

6 Discussion of the model

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

On the demand side First, we consider a single homogeneous good and therefore disregard the various qualities of beef products and possible transformations. Second, while the reduction of beef consumption would likely be compensated 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 to enlarge 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. In addition, this paper does not consider consumers' preferences for some production methods, such as those for extensive grass-based farming, due to animal welfare concerns. Including such

Table 4: Rank regression results

	Subsidy	Tax	Standard
Int.	80,03	-2156.92 ***	3780.76 ***
	(124.33)	(53.53)	(101.43)
rank(γ)	0.17 ***	0.73 ***	-0.48 ***
	(0.01)	(0.00)	(0.01)
rank($\|\eta\|$)	0.30 ***	0.54 ***	0.31 ***
	(0.01)	(0.00)	(0.01)
rank(θ_n)	0.40 ***	0,00	0.46 ***
	(0.01)	(0.00)	(0.01)
rank(θ_g)	-0.30 ***	0.08 ***	-0.24 ***
	(0.01)	(0.00)	(0.01)
rank(θ_c)	0.06 ***	-0.05 ***	0,00
	(0.01)	(0.00)	(0.01)
rank(ϵ)	0.18 ***	-0.12 ***	0.09 ***
	(0.01)	(0.00)	(0.01)
rank(e_{d0})	-0.04 ***	0.03 ***	0,01
	(0.01)	(0.00)	(0.01)
rank(ϕ)	0.03 ***	0.12 ***	-0.10 ***
	(0.01)	(0.00)	(0.01)
rank(f_0)	0.04 ***	0.04 ***	0,00
	(0.01)	(0.00)	(0.01)
rank(α_g)	-0.10 ***	-0.07 ***	0.23 ***
	(0.01)	(0.00)	(0.01)
rank(α_c)	0.23 ***	0.12 ***	-0.04 ***
	(0.01)	(0.00)	(0.01)
N	10,000	10,000	10,000
R^2	0.42	0.89	0.61

*** p <0.001; ** p <0.01; * p <0.05.

preferences would modify the optimal technique x and could change the relative efficiency of the policy instruments studied.

On the production side Technical possibilities for mitigating GHG emissions other than intensification are not considered while they can have significant effects (Crosson et al. 2011; Herron et al. 2021; Nguyen et al. 2013).[17] Then, the synergy between meat and dairy production is not considered either, despite important mitigation opportunities through better integration of both sectors (Faverdin et al. 2022; Selm et al. 2021; Zehetmeier et al. 2012). We also ignore the heterogeneity of 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, on top of the choice of intensifying. In addition, international trade is not considered and would introduce a form of carbon leakage through the trade of beef (for an estimate, see Zech and Schneider 2019). Leakage would call for border adjustment mechanism, or other second-best approaches extensively studied in the literature, and would not add theoretical insights. Finally, it should be noted that the assumption of forest regeneration on all the land no longer dedicated to beef production is 'conservative' and disadvantages the subsidy when comparing instruments. Indeed, while the subsidy targets specifically the setting aside of land for forest regeneration, a substantial share of land made available with a meat tax or a standard is likely not to be preserved for vegetation regrowth but rather urbanized.

On the dynamics of carbon sequestration The absence of the dynamics of land carbon sequestration in our static framework is probably the most critical point to address. In practice, for any given land-use change, there is a dynamic profile of carbon removal until a steady state is reached (for dynamics of soil organic carbon after different land-use changes and of plant carbon after natural forest regrowth, see respectively Poeplau et al. 2011; Cook-Patton et al. 2020); at that steady state, a fixed stock of carbon is sequestered and net carbon flows are null. Conceptually, in our static model, the parameters θ_i are the annualized 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.[18] The model may also be interpreted as a long-run equilibrium, and the θ_i the average removal over the horizon. [19]

Our calibration of the θ_i is consistent with that interpretation. The calculation is

17. Such levers include the cow breed, age at first calving, slaughter age and weight, replacement rate for suckler cows, type of bedding, manure management and fertilization practices.

18. Ragot and Schubert 2008 analyze the optimal policy of carbon sequestration in agricultural soils modeling the (asymmetric) dynamic of sequestration, with two land uses. They show that ignoring the asymmetry of carbon sequestration can have important consequences. Indeed, there is an heterogeneity among land plots due to the heterogeneity in land-use changes.

19. Formally, if a land use i is associated with Θ_i tC stored (in the soil and above-ground biomass) 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 all the carbon initially stored in land. With the proposed interpretation of the model $\theta_i = \Theta_i/n$, with n the length of the period. We thus implicitly assume that the carbon stock is zero in the reference land allocation, the counterfactual land carbon sequestration being $\theta_n \bar{L}$ (equation 2). Any alternative reference land allocation could be used without impacting our analytical results and the instruments' comparison in the simulations. Only the welfare and global GHG emissions in absolute values would be modified.

based on the IPCC *stock-difference method*[20] and *approach 1* for the representation of lands.[21] *Approach 1* allows to represent lands based on total land-use area when there is no information on conversions between land uses, which is suitable for our static framework in which plots are not tracked over time. With these assumptions on land carbon sequestration, it is important to note that the initial land use does not matter in the calculation of the θ_i parameters; a hectare of grassland should have the same θ_g whether it was initially dedicated to cropland, grassland or forest. This is related to the fact that all arbitrages considered in the paper involve differences between the θ_i and not absolute values.

7 Conclusion

While a large body of literature indicates an important GHG mitigation potential in the livestock sector—mainly through land use and its carbon opportunity cost—few studies have focused on optimal policies to mobilize this potential. Several papers have highlighted the barriers to pricing agricultural emissions and have proposed second-best policies to overcome them. However, land use has remained largely overlooked in the literature. With this study, we provide a micro-founded analytical framework to analyze land-use regulation as a second-best mitigation policy in agriculture. Focusing on the beef sector, we propose a partial equilibrium setting where the quantity of meat and cattle feeding as production technique are endogenous. We compare a policy that rewards the setting aside of land for natural forest regeneration, a tax on meat, and a technical standard on cattle feeding, vis-à-vis the first-best.

The interest of the subsidy lies mainly in its effect on both the production technique (intensive margin) and the quantity of meat (extensive margin). Conversely, the meat tax only decreases the quantity of meat by raising prices, but does not trigger any technical adjustment, missing potential welfare gains. The technical standard targets specifically mitigation at the intensive margin by constraining the intensification of the production.

The relative economic efficiency of these second-best instruments is variable and depends on consumers' behavior, the cost of technical change, the distribution of emissions between the different sources, and the sensitivity of emissions to the production technique. The analytical study of the model shows that a sufficient alignment of land use and GHG emissions is required for the subsidy to be economically efficient relatively to the two other instruments. The meat tax is preferable when the demand for meat is elastic and the technical change of production is costly, while the technical standard requires a cheap technical change and an inelastic demand to be the most efficient alternative policy.

The 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 shows that this result holds for an extensive range of parameter values. The welfare loss with this instrument remains low and stable whatever the parameters, unlike the meat tax and the standard that can induce significant losses in some cases.

20. IPCC (2006), volume 4 'Agriculture, Forestry and Other Land Use', chapter 2 'Generic Methodologies Applicable to Multiple Land-Use Categories', page 10, equation 2.5.

21. IPCC (2006), volume 4 'Agriculture, Forestry and Other Land Use', chapter 3 'Consistent representation of lands', pages 10-12.

Implementing a subsidy for land set aside raises, however, 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 helps reduce GHG emissions but may be detrimental to animal welfare, while the reforestation of spared grasslands may remove the habitat of various species in some locations (Burrascano et al. 2016). A more comprehensive analytical framework should consider these trade-offs between GHG emissions reduction, animal welfare, and biodiversity.

References

Agreste. 2021. *Statistique agricole annuelle 2020, chiffres définitifs.* Technical report. Ministère de l'agriculture et de l'alimentation. Accessed January 27, 2022. https://agreste.agriculture.gouv.fr/agreste-web/disaron/Chd2114/detail/.

Ancev, T. 2011. Policy Considerations for Mandating Agriculture in a Greenhouse Gas Emissions Trading Scheme. *Applied Economic Perspectives and Policy* 33 (1): 99–115.

Bakam, I., B. B. Balana, and R. Matthews. 2012. Cost-effectiveness analysis of policy instruments for greenhouse gas emission mitigation in the agricultural sector. *Journal of Environmental Management* 112:33–44.

Balmford, A., T. Amano, H. Bartlett, D. Chadwick, A. Collins, D. Edwards, R. Field, P. Garnsworthy, R. Green, P. Smith, et al. 2018. The environmental costs and benefits of high-yield farming. *Nature sustainability* 1 (9): 477–485.

Bárcena, T. G., L. P. Kiær, L. Vesterdal, H. M. Stefánsdóttir, P. Gundersen, and B. D. Sigurdsson. 2014. Soil carbon stock change following afforestation in Northern Europe: a meta-analysis. *Global Change Biology* 20 (8): 2393–2405.

Bonnet, C., Z. Bouamra-Mechemache, and T. Corre. 2018. An Environmental Tax Towards More Sustainable Food: Empirical Evidence of the Consumption of Animal Products in France. *Ecological Economics* 147:48–61.

Borlaug, N. E. 1997. Feeding a world of 10 billion people: the miracle ahead. *Biotechnology & Biotechnological Equipment* 11 (3-4): 3–13.

Burrascano, S., M. Chytrý, T. Kuemmerle, E. Giarrizzo, S. Luyssaert, F. M. Sabatini, and C. Blasi. 2016. Current European policies are unlikely to jointly foster carbon sequestration and protect biodiversity. *Biological Conservation* 201:370–376.

Capper, J. L. 2012. Is the Grass Always Greener? Comparing the Environmental Impact of Conventional, Natural and Grass-Fed Beef Production Systems. *Animals* 2 (2): 127–143.

Chazdon, R. L., D. Lindenmayer, M. R. Guariguata, R. Crouzeilles, J. M. R. Benayas, and E. L. Chavero. 2020. Fostering natural forest regeneration on former agricultural land through economic and policy interventions. *Environmental Research Letters* 15 (4): 043002.

Claytor, H. S., C. D. Clark, D. M. Lambert, and K. L. Jensen. 2018. Cattle producer willingness to afforest pastureland and sequester carbon. *Forest Policy and Economics* 92:43–54.

Cook-Patton, S. C., S. M. Leavitt, D. Gibbs, N. L. Harris, K. Lister, K. J. Anderson-Teixeira, R. D. Briggs, et al. 2020. Mapping carbon accumulation potential from global natural forest regrowth. *Nature* 585 (7826): 545–550.

Crosson, P., L. Shalloo, D. O'Brien, G. J. Lanigan, P. A. Foley, T. M. Boland, and D. A. Kenny. 2011. A review of whole farm systems models of greenhouse gas emissions from beef and dairy cattle production systems. *Animal Feed Science and Technology* 166-167:29–45.

De Cara, S., L. Henry, and P.-A. Jayet. 2018. Optimal coverage of an emission tax in the presence of monitoring, reporting, and verification costs. *Journal of Environmental Economics and Management* 89:71–93.

Desquilbet, M., B. Dorin, and D. Couvet. 2017. Land Sharing vs Land Sparing to Conserve Biodiversity: How Agricultural Markets Make the Difference. *Environmental Modeling & Assessment* 22 (3): 185–200.

Edjabou, L. D., and S. Smed. 2013. The effect of using consumption taxes on foods to promote climate friendly diets – The case of Denmark. *Food Policy* 39:84–96.

Efese. 2019. *La séquestration de carbone par les écosystèmes en France.* Technical report. Commissariat général au développement durable. Accessed January 27, 2022. https://ree.developpement-durable.gouv.fr/donnees-et-ressources/ressources/publications/article/efese-la-sequestration-de-carbone-par-les-ecosystemes-en-france.

FAO. 2020. The share of agriculture in total GHG emissions. Global, regional and country trends 1990-2017. *FAOSTAT Analytical Brief Series No 1.*

Faverdin, P., H. Guyomard, L. Puillet, and A. Forslund. 2022. Animal board invited review: Specialising and intensifying cattle production for better efficiency and less global warming: contrasting results for milk and meat co-production at different scales. *Animal* 16 (1): 100431.

Favero, A., and R. Mendelsohn. 2014. Using markets for woody biomass energy to sequester carbon in forests. *Journal of the Association of Environmental and Resource Economists* 1 (1/2): 75–95.

Fischer, J., D. J. Abson, V. Butsic, M. J. Chappell, J. Ekroos, J. Hanspach, T. Kuemmerle, H. G. Smith, and H. von Wehrden. 2014. Land sparing versus land sharing: moving forward. *Conservation Letters* 7 (3): 149–157.

Forest Europe. 2020. *State of Europe's forests 2020.* Technical report. Ministerial Conference on the Protection of Forests in Europe - FOREST EUROPE. Accessed June 10, 2022. https://foresteurope.org/state-of-europes-forests/.

Frank, S., R. Beach, P. Havlık, H. Valin, M. Herrero, A. Mosnier, T. Hasegawa, J. Creason, S. Ragnauth, and M. Obersteiner. 2018. Structural change as a key component for agricultural non-CO2 mitigation efforts. *Nature Communications* 9 (1).

Funke, F., L. Mattauch, I. v. d. Bijgaart, H. C. J. Godfray, C. Hepburn, D. Klenert, M. Springmann, and N. Treich. 2022. Toward Optimal Meat Pricing: Is It Time to Tax Meat Consumption? *Review of Environmental Economics and Policy* 16 (2): 219–240.

Gallet, C. A. 2010. Meat Meets Meta: A Quantitative Review of the Price Elasticity of Meat. *American Journal of Agricultural Economics* 92 (1): 258–272.

Garnache, C., P. R. Mérel, J. Lee, and J. Six. 2017. The social costs of second-best policies: Evidence from agricultural GHG mitigation. *Journal of Environmental Economics and Management* 82:39–73.

Gérard, M. 2023. Are grass-fed beef systems more climate friendly? New insights from a meta-analysis of life-cycle assessments of beef systems. *Mimeo.*

Green, R. E., S. J. Cornell, J. P. W. Scharlemann, and A. Balmford. 2005. Farming and the Fate of Wild Nature. *Science* 307 (5709): 550–555.

Grosjean, G., S. Fuss, N. Koch, B. L. Bodirsky, S. De Cara, and W. Acworth. 2016. Options to overcome the barriers to pricing European agricultural emissions. *Climate Policy* 18 (2): 151–169.

Hart, R., M. Brady, and O. Olsson. 2014. Joint Production of Food and Wildlife: Uniform Measures or Nature Oases? *Environmental and Resource Economics* 59 (2): 187–205.

Havlík, P., H. Valin, M. Herrero, M. Obersteiner, E. Schmid, M. C. Rufino, A. Mosnier, et al. 2014. Climate change mitigation through livestock system transitions. *Proceedings of the National Academy of Sciences* 111 (10): 3709–3714.

Hayek, M. N., H. Harwatt, W. J. Ripple, and N. D. Mueller. 2021. The carbon opportunity cost of animal-sourced food production on land. *Nature Sustainability* 4 (1): 21–24.

Herrero, M., B. Henderson, P. Havlík, P. K. Thornton, R. T. Conant, P. Smith, S. Wirsenius, et al. 2016. Greenhouse gas mitigation potentials in the livestock sector. *Nature Climate Change* 6 (5): 452–461.

Herron, J., T. P. Curran, A. P. Moloney, M. McGee, E. G. O'Riordan, and D. O'Brien. 2021. Life cycle assessment of pasture-based suckler steer weanling-to-beef production systems: Effect of breed and slaughter age. *Animal* 15 (7): 100247.

Hoel, M., B. Holtsmark, and K. Holtsmark. 2014. Faustmann and the climate. *Journal of forest economics* 20 (2): 192–210.

Hoel, M., and T. M. Sletten. 2016. Climate and forests: the tradeoff between forests as a source for producing bioenergy and as a carbon sink. *Resource and Energy Economics* 43:112–129.

Idele and CNE. 2021. *Les chiffres clés du GEB - Bovins 2021 : Production lait et viande.* Technical report. Institut de l'Elevage, Confédération Nationale de l'Elevage. Accessed December 15, 2021. https://idele.fr/detail-article/les-chiffres-cles-du-geb-bovins-2021.

IPCC. 2006. *IPCC Guidelines for National Greenhouse Gas Inventories.* Technical report. IPCC. Accessed January 10, 2023. https://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html.

IPCC. 2019. *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.* Technical report. IPCC. Accessed June 10, 2022. https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html.

———. 2022. *Summary for Policymakers. In:Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Technical report. Accessed June 6, 2022. https://www.ipcc.ch/report/ar6/wg3/.

Katare, B., H. H. Wang, J. Lawing, N. Hao, T. Park, and M. Wetzstein. 2020. Toward Optimal Meat Consumption. *American Journal of Agricultural Economics* 102 (2): 662–680.

Lewis, S. L., C. E. Wheeler, E. T. A. Mitchard, and A. Koch. 2019. Restoring natural forests is the best way to remove atmospheric carbon. *Nature* 568 (7750): 25–28.

Lherm, M., J. Agabriel, and J. Devun. 2017. État des lieux et évolutions de la production bovine allaitante en France et dans trois pays européens. *INRAE Productions Animales* 30 (2): 93–106.

Lynch, J. 2019. Availability of disaggregated greenhouse gas emissions from beef cattle production: A systematic review. *Environmental Impact Assessment Review* 76:69–78.

Martinet, V. 2014. The Economics of the Food Versus Biodiversity Debate. In *EAAE 2014 Congress "Agri-Food and Rural Innovations for Healthier Societies", August, 26-29, Ljubljana, Slovenia.* Accessed December 6, 2021. https://ageconsearch.umn.edu/record/182800/.

Meunier, G. 2020. Land-sparing vs land-sharing with incomplete policies. *European Review of Agricultural Economics* 47 (2): 438–466.

Mogensen, L., T. Kristensen, N. I. Nielsen, P. Spleth, M. Henriksson, C. Swensson, A. Hessle, and M. Vestergaard. 2015. Greenhouse gas emissions from beef production systems in Denmark and Sweden. *Livestock Science* 174:126–143.

Morel, K., J.-P. Farrié, J. Renon, V. Manneville, J. Agabriel, and J. Devun. 2016. Environmental impacts of cow-calf beef systems with contrasted grassland management and animal production strategies in the Massif Central, France. *Agricultural Systems* 144:133–143.

Mottet, A., C. de Haan, A. Falcucci, G. Tempio, C. Opio, and P. Gerber. 2017. Livestock: On our plates or eating at our table? A new analysis of the feed/food debate. *Global Food Security* 14:1–8.

Nguyen, T. T. H., M. Doreau, M. Eugène, M. S. Corson, F. Garcia-Launay, G. Chesneau, and H. M. G. v. d. Werf. 2013. Effect of farming practices for greenhouse gas mitigation and subsequent alternative land use on environmental impacts of beef cattle production systems. *Animal* 7 (5): 860–869.

Nguyen, T. T. H., H. M. G. van der Werf, M. Eugène, P. Veysset, J. Devun, G. Chesneau, and M. Doreau. 2012. Effects of type of ration and allocation methods on the environmental impacts of beef-production systems. *Livestock Science* 145 (1): 239–251.

Pellerin, S., L. Bamière, and al. 2020. *Stocker du carbone dans les sols français, quel potentiel au regard de l'objectif 4 pour 1000 et à quel coût ? Synthèse du rapport d'étude.* Technical report. INRA. Accessed January 27, 2022. https://www.inrae.fr/actualites/stocker-4-1000-carbone-sols-potentiel-france.

Poeplau, C., A. Don, L. Vesterdal, J. Leifeld, B. Van Wesemael, J. Schumacher, and A. Gensior. 2011. Temporal dynamics of soil organic carbon after land-use change in the temperate zone – carbon response functions as a model approach. *Global Change Biology* 17 (7): 2415–2427.

Poore, J., and T. Nemecek. 2018. Reducing food's environmental impacts through producers and consumers. *Science* 360 (6392): 987–992.

Ragot, L., and K. Schubert. 2008. The optimal carbon sequestration in agricultural soils: do the dynamics of the physical process matter? *Journal of Economic Dynamics and Control* 32 (12): 3847–3865.

Schmutzler, A., and L. H. Goulder. 1997. The Choice between Emission Taxes and Output Taxes under Imperfect Monitoring. *Journal of Environmental Economics and Management* 32 (1): 51–64.

Searchinger, T. D., S. Wirsenius, T. Beringer, and P. Dumas. 2018. Assessing the efficiency of changes in land use for mitigating climate change. *Nature* 564 (7735): 249–253.

Selm, B. van, I. J. M. de Boer, S. F. Ledgard, and C. E. van Middelaar. 2021. Reducing greenhouse gas emissions of New Zealand beef through better integration of dairy and beef production. *Agricultural Systems* 186:102936.

Tahvonen, O., and A. Rautiainen. 2017. Economics of forest carbon storage and the additionality principle. *Resource and Energy Economics* 50:124–134.

Theurl, M. C., C. Lauk, G. Kalt, A. Mayer, K. Kaltenegger, T. G. Morais, R. F. M. Teixeira, T. Domingos, W. Winiwarter, and K.-H. Erb. 2020. Food systems in a zero-deforestation world: Dietary change is more important than intensification for climate targets in 2050. *Science of The Total Environment* 735:139353.

Thomas, D. T., Y. G. Beletse, S. Dominik, and S. A. Lehnert. 2021. Net protein contribution and enteric methane production of pasture and grain-finished beef cattle supply chains. *Animal* 15 (12): 100392.

Vries, M. de, C. E. van Middelaar, and I. J. M. de Boer. 2015. Comparing environmental impacts of beef production systems: A review of life cycle assessments. *Livestock Science* 178:279–288.

Waggoner, P. E. 1996. How much land can ten billion people spare for nature? *Daedalus* 125 (3): 73–93.

Wirsenius, S., F. Hedenus, and K. Mohlin. 2011. Greenhouse gas taxes on animal food products: rationale, tax scheme and climate mitigation effects. *Climatic Change* 108 (1): 159–184.

Zech, K. M., and U. A. Schneider. 2019. Carbon leakage and limited efficiency of greenhouse gas taxes on food products. *Journal of Cleaner Production* 213:99–103.

Zehetmeier, M., J. Baudracco, H. Hoffmann, and A. Heißenhuber. 2012. Does increasing milk yield per cow reduce greenhouse gas emissions? A system approach. *Animal* 6 (1): 154–166.

A Proof of Lemma 1 and 2

Proof of Lemma 1:

The total cost $c(x^*) + \delta e(x^*)$ is increasing with respect to δ since $e(x^*) > 0$ by Assumption A2. Therefore, $q^* = D(c(x^*) + \delta e(x^*))$ is decreasing with respect to δ.

The derivative of x^* with respect to δ satisfies (differentiating eq. (11)):

$$\frac{\partial x^*}{\partial \delta} = -\frac{e'}{c'' + \delta e''}.$$

Both $c(x)$ and $e(x)$ being convex, x^* is decreasing with respect to δ iff $e' > 0$.

Proof of Lemma 2:

For any parameters z that influences emissions and not cost, differentiating the two first order conditions (10) and (11) gives (we keep the notation e' for $\partial e/\partial x$)

$$\frac{\partial q^*}{\partial z} = \delta D' \frac{\partial e}{\partial z} \text{ and } \frac{\partial x^*}{\partial z} = -\frac{\delta}{c'' + \delta e''}\frac{\partial e'}{\partial z} \tag{20}$$

Let us write $e(x) = e_d(x) + e_c f(x) - \theta_g \alpha_g x - \theta_c \alpha_c f(x) + \theta_n l(x)$.

• For θ_n:

$$\frac{\partial e}{\partial \theta_n} = l(x) \text{ and } \frac{\partial e'}{\partial \theta_n} = l'(x)$$

Plugging these into eq. (20) gives that q^* is decreasing with respect to θ_n, and, x^* is decreasing with respect to θ_n if and only if $l'(x^*) > 0$. Furthermore, the land intensity $l(x^*)$ is decreasing with respect to θ_n whatever the sign of l'. Therefore, land set aside $L_n = \bar{L} - l(x)q$ is increasing with respect to θ_n.

• And for θ_g: both e and e' are decreasing with respect to θ_g, so both q^* and x^* are increasing with respect to θ_g (from eq. (20)).

B Proof of Lemma 5

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

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

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

Given $e > 0$ and $D' < 0$, it follows immediately that $D(c(\bar{x})) > D(c(\bar{x}) + \delta e(\bar{x}))$, 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 $c(x^*) + \delta e(x^*)$.

C Proof of Proposition 1

The optimal s solves

$$[sl(x) - \delta e(x)]\frac{\partial q}{\partial s} + [sl'(x) - \delta e'(x)]q\frac{\partial x}{\partial s} = 0 \tag{21}$$

Under A2 and A3, $l'(x) > 0$ and both q and x are decreasing with respect to s. Then, from equation (21), the derivatives of welfare with respect to q and with respect to x have opposite sign 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 $x_{sub}^{SB} > x^*$. The latter implies $\partial W/\partial x < 0$ and $\partial W/\partial q > 0$ (from (21)). So $S'(q_{sub}^{SB}) \geq c(x_{sub}^{SB}) + \delta e(x_{sub}^{SB})$, that is, $q_{sub}^{SB} < q^{\times}(x_{sub}^{SB})$,

  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 $x_s^{SB} < x^*$. The latter implies $\partial W/\partial x > 0$. Thus, $\partial W/\partial q < 0$ so $q_{sub}^{SB} > q^{\times}(x_{sub}^{SB})$.

D Proof of Proposition 2

With Specification 1, the social cost of meat is

$$c(x) + \delta e(x) = c(x^*) + \delta e(x^*) + \frac{\gamma}{2}(x - x^*)^2 \tag{22}$$

Using eq. (22) and Specification (1) in the expression of welfare (eq. (4)) gives

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

Welfare losses with the second-best instruments:

- With the meat tax, the welfare loss is obtained by plugging $x = x_0$ and $q = q^{\times}(x_0) = (a - c_0 - \delta e(x_0))/b$ into expression (17).

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

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

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

  Lower bound: write $q - q^* = q - q^{\times} + q^{\times} - q^*$ and $q^{\times} - q^* = -\gamma/(2b)(x - x^*)^2$, plugging this into eq. (17) gives

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

  and, with a standard $q - q^{\times} = \delta e(x)/b$ which is positive and greater than $e(0)$. The lower bound follows.

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

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

E Set of parameters for the baseline

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
b	Slope of the inverse demand function (€/kg^2)	$4.51 * 10^{-9}$	Authors' calculations
x_0	Cost-minimizing amount of grass (kg/kg CW)	20	hypothesis based on data from representative farms
f_0	Cost-minimizing amount of crops (kg/kg CW)	3.98	Authors' calculations from the value taken by x_0 and f function
γ	Technical flexibility of beef production (€.kg CW/kg grass^2)	0.01	Hypothesis
ϕ	Substitution rate between feed crops and grass (kg crops/ kg grass)	0.14	Author's calculations from the meta-analysis of (Gérard 2023)
c_0, p_0	BAU production cost/ market price of beef (€/kg CW)	3.9	hypothesis based on data from Idele and CNE (2021)
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	hypothesis based on data from Agreste (2021)
α_c	Inverse crop yield (m^2/kg)	1.67	hypothesis based on data from Agreste (2021)
$\overline{L}$	Total available land (m^2)	$3.84 * 10^{10}$	authors' calculations
ϵ_d	Direct emission growth rate with respect to the amount of grass (kgCO_2eq/kg grass)	0.57	Authors' calculations from the meta-analysis of Gérard (2023)
e_{d0}	Direct emissions of beef when $x = x_0$ (kgCO_2eq/kg CW)	24.17	Authors' calculations from the meta-analysis of Gérard (2023)
e_c	Emission factor of crops (kgCO_2eq/kg crops)	0.5	Assumption based on ECOALIM, database of the Agribalyse program
θ_g	Annual carbon sequestration of grasslands (kgCO_2eq/m^2)	0.39	Authors' calculations based on data from Pellerin et al. (2020)
θ_c	Annual carbon sequestration of crops (kgCO_2eq/m^2)	0.24	Authors' calculations based on data from Pellerin et 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