Optimal Pro-Biofuel Policies with Land-Use Inertia*

by

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Abstract

Pro-biofuel policies are to cause a large expansion of "semi-perennial" energy crops (e.g. sugarcane, switchgrass, miscanthus...) that exhibit long harvesting cycles (up to 20 years), unlike annual energy crops that need to be replanted every year (e.g. corn). This paper shows that semi-perennials introduce inertia in land conversion to energy crops; although empirically observed, this inertia has never been taken into account in the design of pro-biofuel policies. The scientific debate over the net social benefits of biofuel production is progressing but still unsettled. Thus, I characterize optimal pro-biofuel policies in presence of scientific progress. In this context, inertia in land conversion to semi-perennial crops justifies a departure from the standard Pigovian prescription: biofuels should be subsidized at a lower rate when energy crops are semi-perennial than when they are annual, despite identical returns.

JEL classification: Q12; H23; D81
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I. Introduction

Over the last decade, a growing number of countries implemented pro-biofuel policies. These policies take various forms: large producing countries apply production-supporting policies (e.g. public R&D support and tax incentives in Brazil, protectionist import tariffs in the US); demand-augmenting blend mandates in transportation sectors are increasingly common.[1] In light of current national and international policy discussions on climate change mitigation strategies and energy independence, it is to be anticipated that biofuels will be further promoted as an alternative to regular fuels.

There are two important aspects of biofuel production. On the one hand, the social benefits of biofuel promotion are subject to substantial scientific uncertainty. Recent concerns over indirect land-use changes potentially impacting deforestation (e.g. Searchinger et al., 2008; Andrade de Sá, Palmer and Di Falco, 2013; Horridge and de Souza Ferreira Filho, 2014, among others) and food security in developing countries (e.g. Chakravorty, Hubert and Nostbakken, 2009) have fostered an unsettled but progressing debate over the benefits of biofuel production.

On the other hand, a large – and growing – proportion of energy crops are semi-perennial or perennial; they can sustain several harvests without the need to uproot and replant. Some, like sugarcane, have harvesting cycles of 7 years, while others have much longer ones (10-20 and 15-20 years for switchgrass and giant miscanthus, respectively). In general, these semi-perennial or perennial energy crops have productivity advantages over other (annual) energy crops.[2] This is why, in light of current production projects,

[1] As of early 2014, blend mandates existed in 33 countries, including the US, Brazil, the EU, India and Argentina, among others (REN21, 2014).

[2] According to the Renewable Fuel Standard set in 2007 by the United States, sugarcane ethanol is classified as an advanced biofuel – while corn-based ethanol is not. Following the Brazilian example, countries willing to expand or develop sugarcane-based ethanol production include Zimbabwe, Ghana, Mozambique, South Africa, Angola, Colombia and Peru. They share some of the advantages that Brazil had in developing an ethanol industry: an experience in sugarcane production, suitable climate and land availability, as well as abundant labor supply and low production costs. Cellulosic ethanol obtained from grasses such as switchgrass and giant miscanthus is being investigated as a promising alternative to the

they can be expected to take over most of the increase in energy crops' expansion.

This paper takes a full account of energy crops' semi-perennity. It shows that semi-perennity implies inertia in farmers' land allocation decisions, as observed by Hausman (2012) for the case of sugarcane. Yet, this inertia has never been explicitly taken into account, whether in the literature on land conversion towards energy crops (e.g. Feng and Babcock, 2010; Song, Zhao and Swinton, 2011) or in the literature assessing the effects of biofuel production (e.g. Hochman, Rajagopal and Zilberman, 2010; Khanna and Chen, 2013).

The inertia that arises from crops' semi-perennity differs from the standard land conversion decisions models, in the spirit of Arrow and Fisher (1974) and Dixit and Pindyck (1994). For example, in Schatzki (2003) and Song, Zhao and Swinton (2011) inertia stems from exogenous conversion costs, which are absent here. In fact, semi-perennity gives rise to an opportunity cost of abandoning the benefits of future harvests that do not require replanting investments. These costs are reminiscent of the opportunity cost considered in forestry problems (e.g. Ben Abdallah and Lasserre, 2004), where the growing tree asset may entail a capital gain.

In this context, we revisit optimal pro-biofuel policies when there is a risk over the external value of biofuel production. Scientific progress will *in fine* determine whether biofuel production generates a positive (e.g. replacement of fossil fuels by ethanol) or negative (e.g. if indirect land-use changes drastically deteriorate forests and food security) external effect.[3] We show that the semi-perennity of energy crops requires that pro-biofuel policies be more precautious, in the sense of Gollier and Treich (2003).

We start with a simple setting where a single farmer decides whether to plant an energy crop or an alternative ordinary annual crop (say wheat or beans). To highlight the role

use of coarse grains for ethanol production.

[3]The empirical literature on indirect land-use changes points out that these effects (e.g. on forest conversion) can take several years to materialize (e.g. Andrade de Sá et al., 2013). Their magnitude is thus difficult to quantify (Khanna and Crago, 2012).

of semi-perennity, we consider two types of energy crops. In one case, the energy crop is also an annual crop (corn, say), and on the other it is semi-perennial (e.g. sugarcane or switchgrass). We explicitly model semi-perennity by allowing planting investments to be required on a less regular basis than for annual crops. By comparing the two cases, we show how the possibility of having to abandon semi-perennials entails an opportunity cost that causes inertia. As a result, the policy maker should require higher levels of expected external value of biofuel production to implement a pro-biofuel policy when the energy crop is semi-perennial compared to annual; it is thus optimal to be more "precautious" when it comes to favoring the expansion of semi-perennial energy crops. This is the object of Section 2.

Section 3 considers a Ricardian continuum of farmers that differ by their productivity in the energy crop production. Once more, we compare the case where the energy crop is annual (corn) and the case where it is semi-perennial (sugarcane). We show that in the case of corn, the standard Pigovian prescription applies: pro-biofuel subsidies should be set equal to the expected unitary external value of energy crops production. In contrast, semi-perennity again justifies a more precautious approach: pro-biofuel subsidies should be set equal to a level lower than the usually recommended Pigovian subsidy.

Finally, Section 4 concludes by putting the results into perspective and highlighting their policy implications. First, we discuss the results in the broader context of climate mitigation strategies. The analysis provides a rationale for discriminatory pro-biofuel policies. Hence, we also draw its implications when pro-biofuel policies allow to treat differently various energy crops.

II. The Single-Farmer Model

There are two periods. At each period, a single farmer allocates its unit of land to one of two alternative uses, in such a way as to maximize profits. Possible land uses are an ordinary annual food crop O (e.g. beans, wheat, rice) or an energy crop. The energy crop can either be annual (e.g. Corn) – denoted by C – or semi-perennial (e.g. Sugarcane) – denoted by S. Before harvesting, farmers need to purchase seeds, prepare the land and plant the crops. For the annual crops O and C, the farmer incurs an investment cost I_O and I_C, respectively, at each period. Unlike annual crops, Sugarcane, once planted, can be harvested for the two periods; we assume that I_S is paid only in the first period. The two energy crops C and S only differ by the frequency of initial investments.

One-period revenues from each land use are denoted by π_i, $i = O, C, S$. They are assumed constant over time and are discounted by the factor δ, $0 < \delta < 1$.

As discussed in the Introduction, the production of energy crops generates an externality that may be positive or negative. Policy interventions are required for the farmer to internalize the effect of its land allocation choice. We compare optimal policy for each energy crop C and S.

A. Annual Energy Crop (Corn)

We start with the case where the two alternative land uses are the ordinary annual crop O and the annual energy crop C.

A.1. The Farmer's Behavior

For these single-yield crops, since the investment cost needs to be paid at each period before harvest, the farmer's land allocation choice of the first period does not affect his second-period situation. The farmer's problem is thus static; he faces the same choice at each period. We denote with h_1 and h_2 the crop harvested in periods 1 and 2 respectively. Figure 1 illustrates the farmer's choices over two periods and the associated discounted profits.

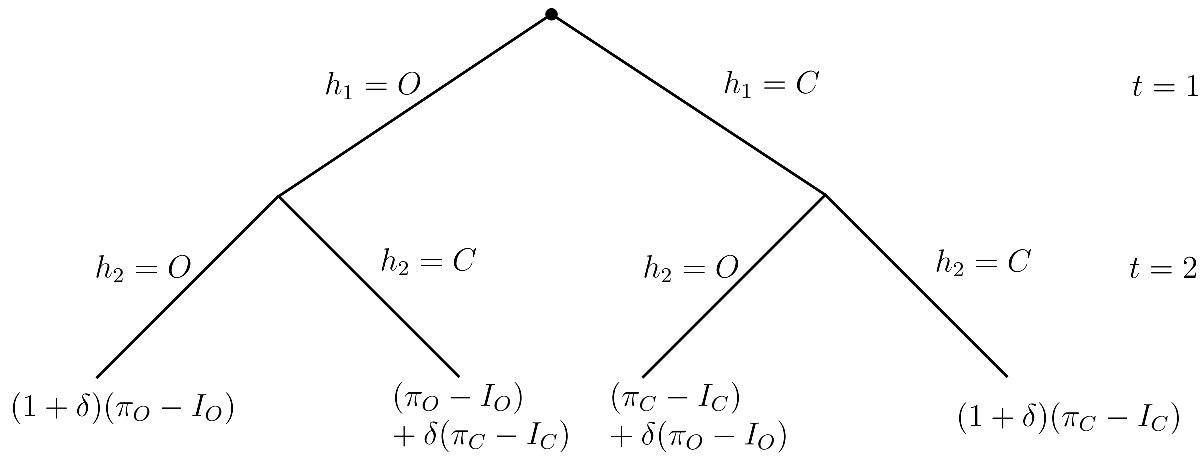

Figure 1: Farmer's decisions between O and C

Absent any intervention, the farmer will allocate land to the ordinary annual crop O if

$$\pi_O - I_O > \pi_C - I_C. \tag{1}$$

Let us assume so, so as to focus on the interesting cases where policy intervention is required for the energy crop to be adopted.

Assumption 1 *Absent any policy intervention, the farmer allocates his land to the ordinary annual crop O, i.e. equation (1) holds.*

Farmer's land allocation can be influenced by subsidies γ_O, $\gamma_C \geq 0$ respectively to the ordinary crop and to Corn.[4] It follows from Assumption 1 that a subsidy γ_O need never be used. Thus, it will be ignored.

For notational simplicity and with no consequence on the message, we assume that when the farmer is indifferent between 2 land uses, he produces the most socially desirable one. Hence, any subsidy $\gamma_C \geq \pi_O - I_O - \pi_C + I_C > 0$ induces the farmer to produce Corn instead of the ordinary crop. Further assume that it is more socially desirable to use the

[4]Taxes are ruled out from the analysis. Also, public funds are considered to be available at no cost.

minimum effective subsidy. Therefore,

$$\gamma_C = \pi_O - I_O - \pi_C + I_C > 0. \tag{2}$$

Consider now a risk-neutral policy maker that seeks to maximize social surplus. Surplus is denoted by W and consists of the farmer's profits corrected by the externality generated by the energy crop production. This external value is denoted by v and is drawn from a distribution of density $f(.)$ over $(-\infty, +\infty)$. Scientific progress takes time to resolve uncertainty, especially because the social impacts of energy crops' production are not immediately observable;[5] v is only observed at the end of the first period.

A.2. The Second-Period Optimal Policy

In the second period, the policy maker observes v. Accordingly, he decides to let the farmer continue producing the crop chosen in the first period or to induce a switch.

Regardless of whether the chosen land-use in the first period was O or C, the second-period surplus is

$$\begin{cases} W = \pi_O - I_O \text{ if } i = O \\ W = \pi_C - I_C + v \text{ if } i = C \end{cases}.$$

Hence, there exists a threshold value

$$v^C \equiv \pi_O - I_O - \pi_C + I_C, \tag{3}$$

such that for all $v < v^C$ the policy maker finds it optimal to have the farmer producing the ordinary annual crop O, while for all $v > v^C$ he finds instead optimal to have the farmer producing the energy crop C.

Note that, if $h_1 = C$, as when the minimal effective subsidy γ_C – as defined in (2)

[5] Andrade de Sá et al. (2013) when investigating indirect land-use changes associated with sugarcane production in Brazil and how they affect forest conversion in the Brazilian Amazon show that these effects might take 10 to 15 years to be observable.

– was implemented, inducing the farmer to switch to the ordinary annual crop O in the second period simply requires canceling the first period support to the energy crop. Indeed, by Assumption 1, absent any intervention, the farmer always chooses O.

A.3. The First-Period Optimal Policy

In the first period, the policy maker acts under the veil of ignorance regarding the external value v. However, his problem remains static as there are no consequences on the optimal second-period policy. If $h_1 = O$, as when $\gamma_C = 0$, then $W = \pi_O - I_O$. If instead $h_1 = C$, as when $\gamma_C = \pi_O - I_O + I_C - \pi_C$, then $W = \pi_C - I_c + E(v)$. Hence, implementing γ_C at $t = 1$ is optimal if $\pi_C - I_C + E(v) > \pi_O - I_O$, i.e. if

$$E(v) > E^C \equiv \pi_O - I_O - \pi_C + I_C, \qquad (4)$$

which means that the external value of C more than compensates its private value.

The results obtained in this subsection can be summarized as follows.

Lemma 1 *The minimal effective subsidy $\gamma_C > 0$ to the annual energy crop (Corn) – as defined in (2) – is optimal in the first period if and only if the expected external value of energy crop production $E(v)$ exceeds the threshold given by (4).*

B. Semi-Perennial Energy Crop (Sugarcane)

Consider now that instead of two annual crops the farmer can allocate land either to the ordinary annual O or to a semi-perennial energy crop S. Since S is a multi-yield crop, the corresponding initial investment I_S will be paid only in the first period, while I_O is paid in both periods, as before.

B.1. The Farmer's Behavior

The semi-perennity of Sugarcane introduces a dynamic aspect to the farmer's problem; he faces different choices in the second period, depending on his first period decision.

Indeed, if $h_1 = O$, then in the second period he compares $\pi_O - I_O$ with $\pi_S - \frac{I_S}{1+\delta}$ – where the revenue from producing S only in the second period needs to be adjusted so as to account for the fact it is a two-yield crop planted for just one period. However, if $h_1 = S$, then in the second period the farmer compares $\pi_O - I_O$ with π_S which is greater than $\pi_S - \frac{I_S}{1+\delta}$.

Figure 2 depicts the farmer's choices across periods and the associated discounted profits.

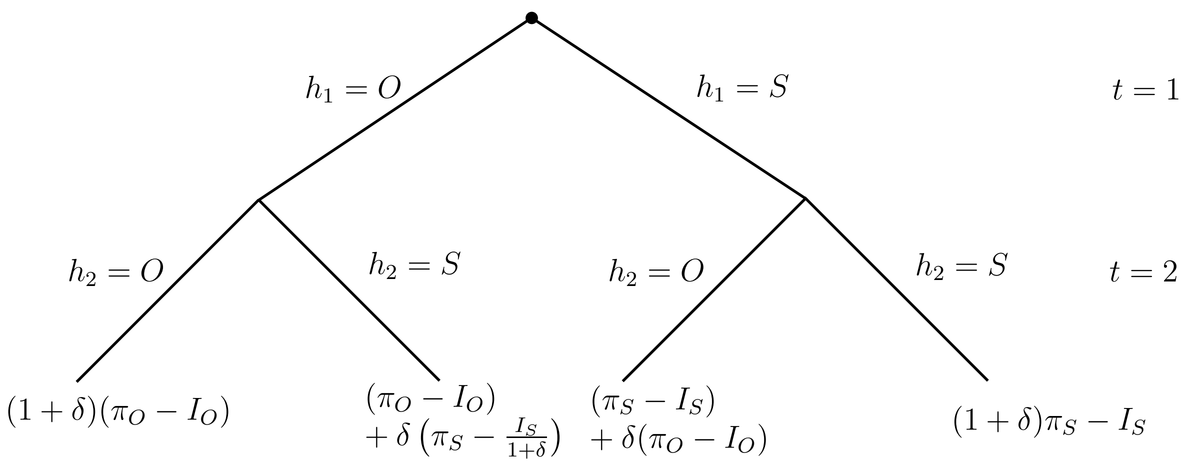

Figure 2: Farmer's decisions between O and S.

The farmer chooses to allocate his land to the ordinary annual crop O at each period if it yields higher revenues over the two periods, i.e. if

$$(\pi_O - I_O)(1+\delta) > \pi_S(1+\delta) - I_S. \tag{5}$$

However, if land is converted to Sugarcane in the first period (because of policy intervention), the farmer can benefit from not paying I_S in the second period. Sugarcane then becomes more attractive than the ordinary annual crop O, i.e.

$$\pi_S \geq \pi_O - I_O. \tag{6}$$

Accordingly, we make the following assumption, that is the counterpart of Assumption 1 with a semi-perennial crop.

Assumption 2 *Absent any policy intervention, the farmer allocates his land to the ordinary annual crop O, i.e. (5) holds. However, if he allocates land to Sugarcane in the first period, he will prefer to remain in the same land use in the second period, i.e. (6) holds.*

Assumption 2 implies that even in absence of a subsidy the farmer chooses S in the second period if he had chosen Sugarcane in the first period. In other words, once land is under sugarcane production, conversion back to the alternative ordinary annual crop entails an opportunity cost of abandonment, which was absent in Subsection A with no semi-perennial.

This abandonment cost will also affect the policy-maker problem, since decisions taken in the first period (e.g. to subsidize or not Sugarcane production) affect the second period optimal choices.

B.2. The Second-Period Optimal Policy

In the second period, the policy maker observes v and evaluates whether the farmer should continue producing the crop chosen in the first period or not. If $h_1 = O$ the policy-maker compares $W = \pi_O - I_O$ with $W = \pi_S - \frac{I_S}{1+\delta} + v$. There exists a threshold

$$\overline{v}^S \equiv \pi_O - I_O + \frac{I_S}{1+\delta} - \pi_S > 0, \tag{7}$$

such that for all $v < \overline{v}^S$ the optimal policy is to let the farmer continue producing the annual crop O and for all $v \geq \overline{v}^S$ it is instead optimal to pay the minimal effective subsidy

$$\gamma_{S2} = \pi_O - I_O - \pi_S + \frac{I_S}{1+\delta} \tag{8}$$

that induces land conversion from the ordinary annual to the semi-perennial energy crop.

Conversely, if $h_1 = S$, the policy-maker compares $W = \pi_S + v$ with $W = \pi_O + I_O$. As before, there exists a threshold

$$\underline{v}^S \equiv \pi_O - I_O - \pi_S < 0 \tag{9}$$

such that for all $v \geq \underline{v}^S$ it is optimal to let the farmer continue producing Sugarcane, while for all $v < \underline{v}^S$ the policy-maker finds it optimal to pay the minimal subsidy $\gamma_{O2} = \pi_S - \pi_O + I_O$ that effectively induces a switch from the energy to the ordinary annual crop.

An important property of the model with a semi-perennial crop is that, unlike in Subsection A, there are now two thresholds

$$\underline{v}^S < 0 < \overline{v}^S = v^C. \tag{10}$$

This implies that there are values of v such that the policy maker is indifferent between the status quo land use and inducing land conversion in either direction. This status quo zone stems from the multi-yield character of Sugarcane and the opportunity cost of the farmer abandoning this crop.

B.3. The First-Period Optimal Policy

In the first period, since $\pi_O - I_O > \pi_S - I_S$ by Assumption 2, the policy-maker needs to subsidize Sugarcane production if he wants the farmer to adopt the crop. Subsidy γ_{S1} is effective if it makes the farmer indifferent between the two crops, given that he can perfectly anticipate the second period optimal policies, i.e. it is such that[6]

$$\gamma_{S1} = (\pi_O - I_O - \pi_S)(1 + \delta) + I_S > 0. \tag{11}$$

[6]See Appendix A for details.

The policy maker finds it optimal to implement γ_{S1} if the surplus is higher when farmer chooses S instead of O, given the anticipation of the second-period outcome as functions of the realization of v. Appendix B shows that subsidy γ_{S1} as defined in (11) is optimal if

$$\begin{aligned} E(v) > E^S \quad \equiv \quad & (\pi_O - I_O - \pi_S + I_S) + \delta(\pi_O - I_O - \pi_S + \frac{I_S}{1+\delta})[F(\overline{v}^S) - F(\underline{v}^S)] \\ - \quad & \delta\frac{I_S}{1+\delta}[1 - F(\underline{v}^S)] + \delta E(v \mid_{v>\overline{v}^S}) - \delta E(v \mid_{v>\underline{v}^S}). \qquad (12) \end{aligned}$$

Lemma 2 *Subsidy γ_{S1} to the semi-perennial energy crop (Sugarcane) in the first period is optimal if and only if the expected externality of biofuels production $E(v)$ satisfies (12).*

C. Comparing the Two Cases

Sugarcane and Corn, the two energy crops considered here, differ in that their respective initial investments are made with a different frequency: for Corn, I_C is paid at each period of the two periods, while for Sugarcane, I_S is only paid in the first period. We make the following assumption to further assume that the two crops are otherwise identical.

Assumption 3 *The two energy crops C and S yield the same discounted revenue over two periods, that is $(\pi_C - I_C)(1+\delta) = (1+\delta)\pi_S - I_S$.*

The effects of Sugarcane's semi-perennity appear when comparing conditions (4) and (12), which determine the expected level of social benefits from biofuels production required for γ_C and γ_S to be optimal in the first period.

The following proposition summarizes the result from the single-farmer model.

Proposition 1 *A positive subsidy requires higher levels of the expected externality of biofuel production if the energy crop is semi-perennial.*

See proof in Appendix C.

III. Many Farmers

Farmers' productivity highly differs for various reasons. For instance, farmers' plots are heterogeneous as regards soil quality, slope and distance to markets.[7] Also, farmers may have individual-specific skills that affect their productivity in each crop.

We assume that there exist many farmers, each owning one unit of land. For simplicity, farmers only differ in the profits earned from cultivating the energy crop $i = C, S$. Each type π_i is distributed according to the density $g_i(.)$ over $(\frac{I_s}{1+\delta}, +\infty)$ if $i = S$ or over $(I_c, +\infty)$ if $i = C$. Under Assumption 3, the distributions of the two-period profits from each crop are identical. In both cases, the least productive farmer – respectively $\pi_S = \frac{I_S}{1+\delta}$ and $\pi_C = I_C$ – is assumed to make zero profits from the energy crop production. This is set so as to eliminate situations of limited economic interest where net profits are negative over the two periods. All other assumptions from the previous section hold.

In the following we proceed as before. We first consider the case where the energy crop is annual (Corn) and then the case where it is semi-perennial (Sugarcane). In each case, we first examine farmers' behavior and then characterize optimal policies. Finally, we compare the level of the first-period optimal pro-biofuel policy in the two cases, so as to draw the implications of semi-perennity.

A. Annual Energy Crop (Corn)

A.1. Farmers' Behavior

Absent any policy intervention, a given farmer chooses to produce the ordinary annual crop O as long as $\pi_O - I_O > \pi_C - I_C$ in each period. We define the first-period indifferent farmer π_{C1} as

$$\pi_{C1} \equiv \pi_O - I_O + I_C. \tag{13}$$

All farmers of type $\pi_C < \pi_{C1}$ choose to produce the ordinary crop O, while farmers

[7] The allocation of farmers to plots is out of the scope of this paper.

of type $\pi_C \geq \pi_{C1}$ opt for Corn production. Hence, π_{C1} summarizes the split of total land between each crop O and C.

As before, the policy maker's subsidies can influence farmers' choices. Different farmers however do not react the same way to subsidies, unlike in the single-farmer model.

Since both alternative crops are annual, the first and the second periods are disconnected: for farmers as well as for the policy maker choices are independent across periods. For our purpose, it is thus sufficient to examine the first-period policy.

A.2. The First-Period Optimal Policy

In the first period, absent any policy intervention, the threshold farmer is given by (13). According to the expected external value of producing the energy crop $E(v)$, the policy maker may decide to

1. increase the share of land allocated to the energy crop C with a subsidy $\gamma_{C1} > 0$;
2. increase the share of land allocated to the ordinary annual crop O with a subsidy $\gamma_{O1} > 0$;
3. let the share of each crop unchanged with no subsidy.

Let us focus on the interesting case where the policy maker is increasing the share of land under Corn with a pro-biofuel subsidy $\gamma_{C1} \geq 0$. The indifferent farmer $\pi_{C1}(\gamma_{C1})$ is such as

$$\pi_{C1}(\gamma_{C1}) = \pi_O - I_O + I_C - \gamma_{C1}.$$

The associated first-period surplus is

$$EW_1^C(\gamma_{C1}) = \int_{I_C}^{\pi_{C1}(\gamma_{C1})} (\pi_O - I_O) g_C(\pi_C)\, d\pi_C + \int_{\pi_{C1}(\gamma_{C1})}^{+\infty} [\pi_C - I_C + E(v)] g_C(\pi_C)\, d\pi_C, \tag{14}$$

to be maximized by the choice of $\gamma_{C1} \geq 0$.

It can easily be verified that

$$\frac{dEW_1^C}{d\gamma_{C1}} \geq (equiv. \leq)\ 0 \Longleftrightarrow\ \gamma_{C1} \leq (equiv. \geq)\ E(v), \tag{15}$$

such that the optimal subsidy is the Pigovian one

$$\gamma_{C1}^* = E(v), \tag{16}$$

which should be positive if and only if[8]

$$E(v) > 0 \equiv E^C. \tag{17}$$

The result of this subsection is summarized in the following Lemma.

Lemma 3 *Whenever $E(v)$ is positive, it is optimal to implement the Pigovian first-period subsidy to the annual energy crop (Corn) as defined in (16).*

B. The Semi-Perennial Energy Crop (Sugarcane)

B.1. Farmers' Behavior

When farmers have the choice between the ordinary annual crop O and sugarcane S over two periods, the indifferent farmer – absent any policy intervention – is such that

$$(1+\delta)\pi_S - I_S = (1+\delta)(\pi_O - I_O),$$

that characterizes type

$$\pi_{S1} \equiv \pi_O - I_O + \frac{I_S}{1+\delta}. \tag{18}$$

Hence, all farmers $\pi_S < \pi_{S1}$ choose to produce the ordinary crop O, while those of

[8] The optimal second-period subsidy γ_{C2}^* is computed in the same fashion once $E(v)$ is replaced by the actual realization of the externality, v.

type $\pi_S \geq \pi_{S1}$ allocate their land to Sugarcane production. As for Corn, increasing the share of farmers producing Sugarcane requires subsidies $\gamma_{S1} \geq 0$. As shown in the previous section, the semi-perennity of sugarcane introduces a dynamic aspect to the policy maker's problem. We thus proceed by backward induction and start by analyzing the policy choice in the second period first.

B.2. The Second-Period Optimal Policy

Assuming that the energy crop S was subsidized in the first period, the indifferent farmer at the end of period 1 is

$$\pi_{S1} \equiv \pi_O - I_O + \frac{I_S}{1+\delta} - \gamma_{S1}.$$

Given the realization of v, the policy maker chooses to increase, maintain or reduce the share of total land allocated to Sugarcane. As will be clear, two cases need to be distinguished. Either the first-period subsidy γ_{S1} was covering the initial investment needed to produce the crop, $\frac{I_S}{1+\delta}$, or it was falling short of it.

Let us analyze the latter first, when $\gamma_{S1} \leq \frac{I_S}{1+\delta}$. Appendix D shows that in the second period the policy maker has three choices:

1. extend the share of farmers producing sugarcane by implementing $\gamma_{S2} > \gamma_{S1}$. This implies that the second-period indifferent farmer is $\pi_{S2} \equiv \pi_O - I_O + \frac{I_S}{1+\delta} - \gamma_{S2} < \pi_{S1}$;

2. extend the share of farmers producing the ordinary annual crop by implementing $\gamma_{O2} > \frac{I_S}{1+\delta} - \gamma_{S1}$. This implies $\pi_{S2} \equiv \pi_O - I_O + \gamma_{O2} > \pi_{S1}$;

3. maintain the shares of land allocated to each crop as determined in the first period with $\gamma_{O2} = \gamma_{S2} = 0$, implying $\pi_{S2} = \pi_{S1}$.

Similarly, if the first-period Sugarcane subsidy was high, i.e. if $\gamma_{S1} > \frac{I_S}{1+\delta}$, the choices of the policy maker are

1. extend the share of farmers producing Sugarcane by implementing $\gamma_{S2} > \gamma_{S1}$, which implies that the new indifferent farmer is $\pi_{S2} \equiv \pi_O - I_O + \frac{I_S}{1+\delta} - \gamma_{S2} < \pi_{S1}$;

2. extend the share of farmers producing the ordinary annual crop by implementing $\gamma_{O2} > 0$ or $0 < \gamma_{S2} < \gamma_{S1} - \frac{I_S}{1+\delta}$. These subsidies result in $\pi_{S2} \equiv \pi_O - I_O + \gamma_{O2} > \pi_{S1}$ or $\pi_{S2} = \pi_O - I_O - \gamma_{S1} > \pi_{S1}$, respectively;

3. maintain the first-period land allocation with $\gamma_{O2} = 0$ or $\gamma_{S1} - \frac{I_S}{1+\delta} < \gamma_{S2} < \gamma_{S1}$, implying $\pi_{S2} = \pi_{S1}$.

Hence, given v and π_{S1}, the policy maker chooses its policy to achieve its objective of maximizing the second-period surplus function. Appendix D solves each of the cases presented above and Figure 3 completely summarizes the results obtained: for each realization of v, it is optimal to either increase, decrease or maintain the share of land allocated to the energy crop; this is achieved by increasing, maintaining or decreasing the pro-biofuel subsidy (γ_{S2}) compared to its first-period level, or by subsidizing the ordinary crop O.

More specifically, Appendix D defines threshold values of v such that

1. for low values of $v < \underline{v}^S$, it is optimal to decrease the share of land allocated to S, which implies $\pi_{S2} > \pi_{S1}$. This is done with γ_{O2} or with a low $\gamma_{S2} < \gamma_{S1}$;

2. for intermediate values of $\underline{v}^S < v < \overline{v}^S$, it is optimal to maintain the first-period land allocation and hence $\pi_{S2} = \pi_{S1}$. This is done with intermediate levels of γ_{S2};

3. for high levels of $v > \overline{v}^S$, it is optimal to increase the share of land allocated to the energy crop and thus implement $\pi_{S2} < \pi_{S1}$. This is done with high levels of $\gamma_{S2} > \gamma_{S1}$.

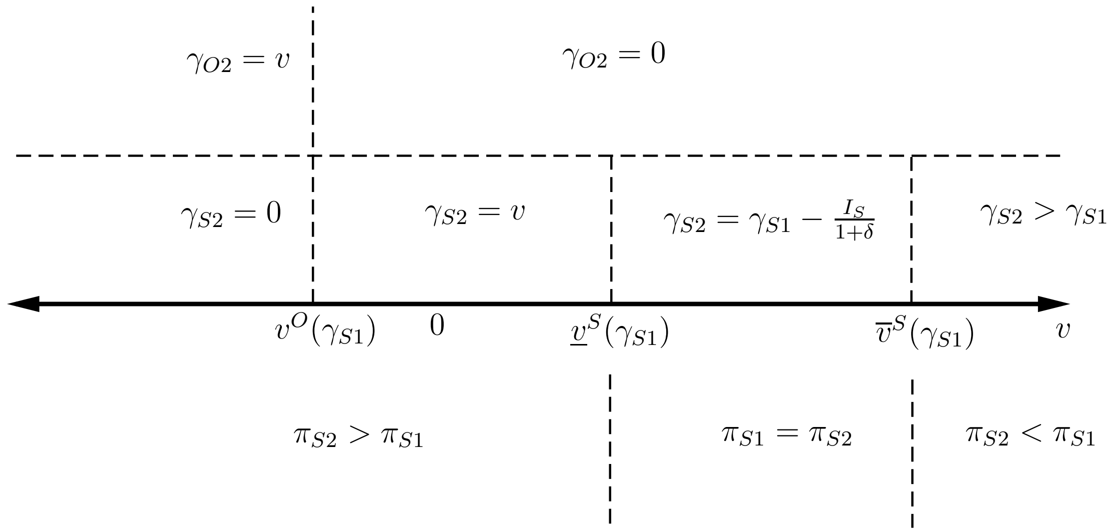

Figure 3: Optimal second-period subsidies γ_{S2} and γ_{O2}

B.3. The First-Period Optimal Policy

Again, we focus on the interesting case where the policy maker finds optimal to implement a pro-biofuel policy, i.e. to subsidize Sugarcane production so as to increase the share of land allocated to this crop further beyond the level that farmers would have chosen absent any policy intervention.

So as to determine the optimal Sugarcane subsidy, the policy maker needs to consider two aspects. First, as noted above, with semi-perennial crops, the farmers' and the policy maker's problem is dynamic: as shown by the solution presented in Figure 3 and as detailed in Appendix D, the second-period problem depends on the first-period subsidy to Sugarcane $\gamma_{S1} \geq 0$, via the thresholds v^O, $\underline{v}^S$ and $\overline{v}^S$; the expected second-period surplus is thus to be expressed as a function of γ_{S1}, i.e. $EW_2^S(\gamma_{S1})$.

Hence, the total surplus that is relevant to the policy maker in the first period is

$$EW^S(\gamma_{S1}) = EW_1^S(\gamma_{S1}) + \delta EW_2^S(\gamma_{S1}). \tag{19}$$

In (19), unlike the problem with Corn where the expected second-period surplus

EW_2^C is independent from γ_{C1}, the total first-period surplus here consists of two terms: $EW_1^S(\gamma_{S1})$, which corresponds to the first-period surplus flow and $\delta EW_2^S(\gamma_{S1})$, which is the discounted expected second-period surplus.

There is a second major difference with the case of an annual energy crop. Here, the effect of γ_{S1} on the first-period surplus differs from the effect of a Corn subsidy, even when the two crops are assumed to yield the same revenues over the two periods, i.e. when $(\pi_C - I_C)(1+\delta) = (1+\delta)\pi_S - I_S$ as per Assumption 3. This is because, when the crop is semi-perennial, all investment costs are sunk in the first period – instead of spread over the two periods for an annual crop. Hence, the same level of subsidy entails a lower first-period surplus when the subsidized crop is Sugarcane. Precisely, the first-period surplus writes

$$EW_1^S(\gamma_{S1}) = \int_{\frac{I_S}{1+\delta}}^{\pi_{S1}(\gamma_{S1})} (\pi_O - I_O) g_S(\pi_S)\, d\pi_S + \int_{\pi_{S1}(\gamma_{S1})}^{+\infty} [\pi_S - I_S + E(v)] g_S(\pi_S)\, d\pi_S, \tag{20}$$

instead of (14) in the case of the annual energy crop, Corn.

Using Assumption 3, (20) can be rewritten as

$$\begin{aligned} EW_1^S(\gamma_{S1}) \ &= \ \int_{\frac{I_S}{1+\delta}}^{\pi_{S1}(\gamma_{S1})} (\pi_O - I_O) g_S(\pi_S)\, d\pi_S + \int_{\pi_{S1}(\gamma_{S1})}^{+\infty} \left[\pi_S - \frac{I_S}{1+\delta} + E(v)\right] g_S(\pi_S)\, d\pi_S \\ &- \ \int_{\pi_{S1}(\gamma_{S1})}^{+\infty} \delta \frac{I_S}{1+\delta} g_S(\pi_S)\, d\pi_S, \end{aligned} \tag{21}$$

where the first two terms correspond to the surplus brought by an otherwise equivalent annual crop, i.e. amount to the surplus relation in (14). The last term, that we denote

$$\Delta(\gamma_{S1}) \equiv \int_{\pi_{S1}(\gamma_{S1})}^{+\infty} \delta \frac{I_S}{1+\delta} g_S(\pi_S)\, d\pi_S \tag{22}$$

represents the positive difference in first-period surplus brought by a pro-biofuel subsidy, for the same expected level of external value of biofuel production $E(v)$, when the energy crop is semi-perennial compared to annual. As explained above, this difference is due to the fact that investment costs are entirely sunk in the first period for the semi-perennial case.

To summarize, in the first period the policy maker considers total surplus

$$EW_1^S(\gamma_{S1}) = EW_1^C(\gamma_{S1}) - \Delta(\gamma_{S1}) + \delta EW_2^S(\gamma_{S1}), \tag{23}$$

which is maximized by the choice of γ_{S1}. Hence, as explained in Appendix E, the optimal first-period subsidy γ_{S1}^* is characterized by the following first-order condition:

$$\left(\frac{dEW_1^C}{d\gamma_{S1}} - \frac{d\Delta}{d\gamma_{S1}} + \delta \frac{dEW_2^S}{d\gamma_{S1}} \right) \bigg|_{\gamma_{S1}^*} = 0. \tag{24}$$

C. Comparing the Two Cases

To highlight the role played by Sugarcane's semi-perennity in this Ricardian setting, we again compare the annual and the semi-perennial energy crop cases. We are interested in comparing the level of the optimal first-period pro-biofuel policy in the two cases.

We have seen above that a given Sugarcane subsidy γ_{S1} not only affects the second-period surplus, but also yields a lower first-period surplus. Although these two effects (on the first and second-period surpluses) go in opposite directions, Appendix E shows that the combined effect is always negative, i.e. $-\frac{d\Delta}{d\gamma_{S1}} + \delta \frac{dEW_2^S}{d\gamma_{S1}} < 0$. Then, (24) implies that the optimal subsidy to the semi-perennial energy crop satisfies

$$\frac{dEW_1^C}{d\gamma_{S1}} \bigg|_{\gamma_{S1}^*} > 0. \tag{25}$$

Hence, the policy maker is always willing to subsidize less a semi-perennial energy crop than an annual one, for the same expected external value of biofuel production $E(v)$. This is illustrated in Figure 4.

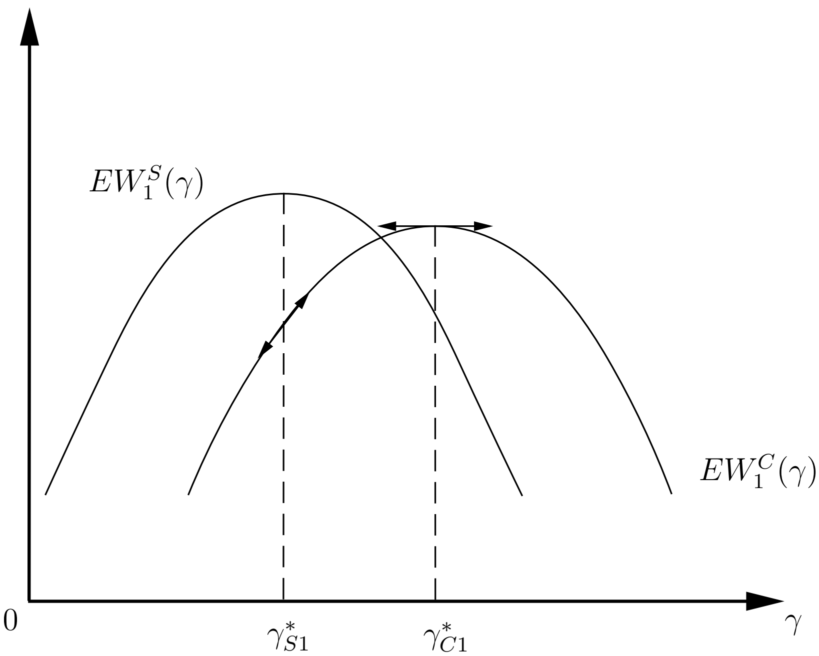

Figure 4: Optimal first-period subsidies γ^*_{S1} and γ^*_{C1}

The result is summarized in the following proposition.

Proposition 2 *For a given positive level of expected external value $E(v)$, the optimal first-period subsidy is lower for the semi-perennial energy crop (Sugarcane) than for the annual one (Corn).*

Since, by (16), $\gamma^*_{C1} = E(v)$, Propostion 2 implies that the optimal first-period Sugarcane subsidy γ^*_{S1} is lower than the Pigovian prescription.

IV. Concluding Remarks

This paper characterizes optimal biofuel-promoting policies in presence of semi-perennial energy crops and scientific progress over biofuels' external benefits. In the single-farmer model of Section 2, which is based on a discrete unit of investment, the policy maker requires higher expected external value from biofuel production to implement the biofuel subsidy when the energy crop is semi-perennial.

The many-farmer setting of Section 3 is closer to the incremental investment model of Dixit and Pindyck (1994, Chap. 11). In this framework, the policy maker not only chooses which crop to subsidize but also the level of the subsidy. Hence, he ultimately determines the share of the land resource allocated to the energy crop. Despite identical social returns, biofuels should be less supported when energy crops are semi-perennial than when they are annual. Semi-perennity indeed provokes inertia in land allocation which justifies a departure from the Pigovian prescription that biofuels should be subsidized at their expected marginal external benefits.

A. *Pro-Biofuel Policies in Climate Mitigation Strategies*

Concerns over irreversible consequences of climate change call for higher investments in alternative (non-fossil) fuels such as biofuels, as a measure of precaution. The analysis developed here highlights that there exist other forms of irreversibility associated with biofuel production. In particular, the fact that a growing fraction of energy crops are semi-perennial requires that biofuel-promoting policies be precautions. Precaution should be maintained until scientific uncertainty over potential negative effects (e.g. indirect-land use changes affecting deforestation) is resolved.

Our results are in line with interpretations of a precautionary measure, i.e. "a temporary and flexible decision that is taken in face of lack of current scientific evidence" (Gollier and Treich, 2003, p. 86). Indeed, given the land-use inertia they entail, semi-perennial energy crops can be interpreted as a less flexible option than annual energy crops. Uncertainty over the external value of biofuel production should lead policies to favor more the flexible option than the less flexible one.

B. *Discriminatory Pro-biofuel Policies*

The above recommendation is particularly relevant in light of the fact that most blending mandates do not distinguish amongst the different energy crops used for biofuel production. Interestingly, there was a recent shift towards more discriminatory policies at the European Union level[9]. Indeed, if policies can target annual energy crops, which represent the more flexible option, this would be a precautious decision in the spirit of Gollier and Treich (2003).

Nevertheless, the possibility of differentiating implies another trade-off linked to the differences in energy performances of energy crops. Throughout the paper, in order to compare the annual and semi-perennial energy crop cases, we assumed that both energy crops yielded the return. However, as mentioned in the introduction, semi-perennial energy crops such as sugarcane are more energy-efficient, i.e. they yield more energy output per hectare cultivated. Hence, policies willing to treat differently various energy crops, face a choice between more flexible but less efficient annual crops and more efficient but less flexible semi-perennials. This highly practical question is the object of my ongoing research.

[9] http://ec.europa.eu/energy/renewables/biofuels/sustainability_criteria_en.htm.

APPENDIX

A Optimal First-Period Sugarcane Subsidy in the Single-Farmer Model

Under the assumptions of Section 2, the optimal subsidy makes the farmer indifferent between the ordinary annual crop O and the semi-perennial sugarcane crop S. The farmer rationally formulates anticipations over the second-period policies; depending on the realization of the external value v of the energy crop, the policy maker may find it optimal to make the farmer switch to another crop in the second period. According to the analysis of Subsection 2.B.2, if $h_1 = S$, the policy maker will let the farmer continue producing S if $v \geq \underline{v}^S$ – no subsidy is needed for that by Assumption 2 – or will otherwise implement the minimal effective subsidy $\gamma_{O2} = \pi_S - \pi_O + I_O$ to induce the farmer to abandon S for O; these two cases occur with probabilities $1 - F(\underline{v}^S)$ and $F(\underline{v}^S)$ respectively. If $h_1 = O$, the minimal effective subsidy $\gamma_{S2} = \pi_O - I_O - \pi_S + \frac{I_S}{1+\delta}$ will be implemented if $v \geq \overline{v}^S$ to induce the farmer to start producing S, or no subsidy will be implemented so that he will continue producing O by Assumption 1; these two cases occur with probabilities $1 - F(\overline{v}^S)$ and $F(\overline{v}^S)$ respectively.

With such anticipations, the subsidy γ_{S1} makes the farmer indifferent in the first period if and only if

$$\pi_S - I_S + \gamma_{S1} + \delta(\pi_O - I_O + \gamma_{O2})F(\underline{v}^S) + \delta\pi_S 1 - F(\underline{v}^S)\,]$$

$$=$$

$$\pi_O - I_O + \delta(\pi_O - I_O)F(\overline{v}^S) + \delta\left(\pi_S - \frac{I_S}{1+\delta} + \gamma_{S2}\right)1 - F(\overline{v}^S)\,],$$

where $\overline{v}^S$ and $\underline{v}^S$ are characterized by (7) and (9) respectively, and where γ_{O2} and γ_{S2} should be replaced by their values given above. Replacing and rearranging give the first-period minimal effective Sugarcane subsidy (11)

B Computing E^S in the Single-Farmer Model

In the first period, given $E(v)$, the policy maker decides whether to subsidize the energy crop (Sugarcane). He implements the minimal effective subsidy γ_{S1} defined in (11) if this yields a higher surplus, taking into account his anticipations of the optimal second-period policies. These anticipations depend on the realization of v in the way described in the previous appendix. Social surplus comprises the farmer's profit, the external value of the crop he produces, and is reduced by the subsidy accruing the farmer but covered by the rest of society. Thus inducing the farmer to produce Sugarcane in the first period ($h_1 = S$) yields a greater surplus than letting him produce the ordinary crop if and only if

$$\pi_S - I_S + E(v) + \delta(\pi_O - I_O)F(\underline{v}) + \delta\pi_S \left[1 - F(\underline{v}^S)\right] + \delta E(v \mid_{v>\underline{v}^S})$$
$$\geq$$
$$\pi_O - I_O + \delta(\pi_O - I_O)F(\overline{v}^S) + \delta\left(\pi_S - \frac{I_S}{1+\delta}\right)\left[1 - F(\overline{v}^S)\right] + \delta E(v \mid_{v>\overline{v}^S}),$$

which holds if and only if $E(v)$ satisfies

$$\begin{aligned} E(v) &\geq (\pi_O - I_O - \pi_S + I_S) + \delta(\pi_O - I_O)\left[F(\overline{v}^S) - F(\underline{v}^S)\right] \\ &+ \delta\left(\pi_S - \frac{I_S}{1+\delta}\right)\left[1 - F(\overline{v}^S)\right] - \delta\pi_S\left[1 - F(\underline{v}^S)\right] \\ &+ \delta E(v \mid_{v>\overline{v}^S}) - \delta E(v \mid_{v>\underline{v}^S}). \end{aligned}$$

Adding and subtracting $\delta\frac{I_S}{1+\delta}\left[F(\overline{v}^S) - F(\underline{v}^S)\right]$ on the left-hand side, and rearranging, give (12).

C Proof of Proposition 1

Proposition 1 means that (12) defines a smaller set of $E(v)$ values than (4), or equivalently that

$$E^S > E^C.$$

By Assumption 3, the threshold E^C defined in (4) may be rewritten

$$E^C = \pi_O - I - O - \pi_S + \frac{I_S}{1+\delta}.$$

Using the definition of E^S given by (12), $E^S > E^C$ is equivalent to

$$\begin{aligned} (\pi_O - I_O - \pi_S + I_S) &+ \delta\left(\pi_O - I_O - \pi_S + \frac{I_S}{1+\delta}\right)\left[F(\overline{v}^S) - F(\underline{v}^S)\right] \\ &- \delta\frac{I_S}{1+\delta}\left[1 - F(\underline{v}^S)\right] + \delta\left[E(v \mid_{v>\overline{v}^S}) - E(v \mid_{v>\underline{v}^S})\right] \\ &> \left(\pi_O - I_O - \pi_S + \frac{I_S}{1+\delta}\right). \end{aligned}$$

Subtracting $(\pi_O - I_O - \pi_S + I_S)$ from both sides, that is also equivalent to

$$\begin{aligned} \delta(\pi_O - I_O - \pi_S + \frac{I_S}{1+\delta}) \left[F(\overline{v}^S) - F(\underline{v}^S)\right] \\ -\delta \frac{I_S}{1+\delta}\left[1 - F(\underline{v}^S)\right] + \delta\left[E(v \mid_{v>\overline{v}^S}) - E(v \mid_{v>\underline{v}^S})\right] \\ > -\delta \frac{I_S}{1+\delta}, \end{aligned}$$

which reduces to the following condition after rearranging:

$$\delta\left(\pi_O - I_O - \pi_S + \frac{I_S}{1+\delta}\right)\left[F(\overline{v}^S) - F(\underline{v}^S)\right] + \delta\frac{I_S}{1+\delta}\left[F(\underline{v}^S)\right] + \delta\left[E(v \mid_{v>\overline{v}^S}) - E(v \mid_{v>\underline{v}^S})\right] > 0;$$

this condition turns out to be satisfied since all terms in the right-hand side are positive. This proves that $E^S > E^C$, and thus Proposition 1.

D Many Farmers - Optimal Second-Period Policy when the Energy Crop is Sugarcane

Assuming that Sugarcane was subsidized in the first period with $\gamma_{S1} \geq 0$, farmers producing this crop in the first period are characterized by

$$\pi_S \geq \pi_{S1} \equiv \pi_O - I_O + \frac{I_S}{1+\delta} - \gamma_{S1}. \tag{26}$$

In the second period, their profits, if they continue producing Sugarcane, are π_S as they do not need to pay the investment cost I_S. Hence, the second-period policies maintain the share of farmers producing Sugarcane if

$$\pi_{S1} + \gamma_{S2} \geq \pi_O - I_O + \gamma_{O2}. \tag{27}$$

Replacing π_{S1} by $\pi_O - I_O + \frac{I_S}{1+\delta} - \gamma_{S1}$, the share of Sugarcane is maintained if

$$\gamma_{S2} \geq \gamma_{S1} - \frac{I_S}{1+\delta}$$

or

$$\gamma_{O2} \leq \frac{I_S}{1+\delta} - \gamma_{S1}.$$

Conversely, farmers producing the ordinary annual crop O in the first period, $\pi_S \leq \pi_{S1}$

with π_{S1} defined in (26), continue doing so in the second period if

$$\pi_{S1} - \frac{I_S}{1+\delta} + \gamma_{S2} < \pi_O - I_O + \gamma_{O2}, \tag{28}$$

that is if

$$\gamma_{O2} > \gamma_{S2} - \gamma_{S1}$$

or

$$\gamma_{S2} < \gamma_{O2} - \gamma_{S1}.$$

Then, depending on the initial level of subsidies to Sugarcane in the first period, two cases arise.

A. *Case 1:* $\gamma_{S1} < \frac{I_S}{1+\delta}$

Since we rule out taxes, there are 4 possibilities for the policy maker. He can

- maintain the share of farmers producing Sugarcane with $\gamma_{S2} > 0$ or with $0 < \gamma_{C2} \leq \frac{I_S}{1+\delta} - \gamma_{S1}$;
- maintain the share of farmers producing O with $\gamma_{O2} > 0$ or with $0 < \gamma_{S2} < \gamma_{S1}$.

All subsidy values that maintain both farmers in O and farmers in S imply the status quo: $\pi_{S2} = \pi_{S1}$. In all those cases, the outcome is the same as with no policy intervention, which is more desirable by assumption. We can thus reduce the policy maker choice set to three distinct alternatives:

- Extending the share of land under S with $\gamma_{S2} > \gamma_{S1}$. In this case, the new indifferent farmer π_{S2} is $\pi_{S2} = \pi_O - I_O + \frac{I_S}{1+\delta} - \gamma_{S2} < \pi_{S1}$.
- Extending the share of land under O with $\gamma_{O2} > \frac{I_S}{1+\delta} - \gamma_{S1}$. This implies $\pi_{S2} = \pi_O - I_O + \gamma_{O2} > \pi_{S1}$.
- The status quo $\pi_{S2} = \pi_{S1}$ with $0 < \gamma_{S2} < \gamma_{S1}$ or with $0 < \gamma_{O2} < \frac{I_S}{1+\delta}$, which are dominated by $\gamma_{S2} = \gamma_{O2} = 0$.

In the following we examine the surplus functions associated to each of these alternatives, and derive the conditions under which each instrument becomes optimal. Also, this exercise allows to investigate how the second-period maximized surplus is affected by a given marginal change in the first-period subsidyγ_{S1}.

A.1. *Extending the Share of* S *with* $\gamma_{S2} \geq \gamma_{S1}$

In this sub-case, given $\gamma S1$ (thus π_{S1}) and given v, the second-period surplus is

$$\begin{aligned} W_2^S(\gamma_{S1}, v) &= \max_{\gamma_{S2} > \gamma_{S1}} W_{S2}^S(\gamma_{S1}, \gamma_{S2}, v) \\ &= \max_{\gamma_{S2} > \gamma_{S1}} \int_{I_S/(1+\delta)}^{\pi_{S2}(\gamma_{S2})} (\pi_O - I_O) g(\pi_S)\ d\pi_S \\ &+ \int_{\pi_{S2}(\gamma_{S2})}^{\pi_{S1}(\gamma_{S1})} \left(\pi_S - \frac{I_S}{1+\delta} + v\right) g(\pi_S)\ d\pi_S \\ &+ \int_{\pi_{S1}(\gamma_{S1})}^{+\infty} (\pi_S + v) g(\pi_S)\ d\pi_S. \end{aligned} \tag{29}$$

The first-order condition associated with the choice of γ_{S2} is $\frac{dW_{S2}^S}{d\gamma_{S2}} = 0$, which implies

$$g(\pi_{S2})(\pi_O - I_O)\frac{d\pi_{S2}}{d\gamma_{S2}} - g(\pi_{S2})\left(\pi_{S2} - \frac{I_S}{1+\delta} + v\right)\frac{d\pi_{S2}}{d\gamma_{S2}} = 0.$$

In this sub-case, $\pi_{S2} = \pi_O - I_O + \frac{I_S}{1+\delta} - \gamma_{S2}$ implies $\frac{d\pi_{S2}}{d\gamma_{S2}} = -1$. Replacing and rearranging give

$$\gamma_{S2} = v. \tag{30}$$

Setting γ_{S2} equal to its lower boundary in this sub-case, i.e. $\gamma_{S2} = \gamma_{S1}$, one can define the threshold level

$$\overline{v}^S \equiv \gamma_{S1}, \tag{31}$$

which is such that

$$\begin{cases} \forall v > \overline{v}^S, \gamma_{S2} > \gamma_{S1} \text{ as per (30)} \\ \forall v \leq \overline{v}^S, 0 < \gamma_{S2} \leq \gamma_{S1} \end{cases}. \tag{32}$$

Finally, in this sub-case, for all $v > \overline{v}^S$, the effect of the first-period subsidy on W_2^S is

$$\frac{\partial W_2^S}{\partial \gamma_{S1}} = g(\pi_{S1})\left(\pi_{S1} - \frac{I_S}{1+\delta} + v\right)\frac{d\pi_{S1}}{d\gamma_{S1}} - g(\pi_{S1})(\pi_{S1} + v)\frac{d\pi_{S1}}{d\gamma_{S1}} = g(\pi_{S1})\left(\frac{I_S}{1+\delta}\right) > 0. \tag{33}$$

A.2. Extending the Share of O with $\gamma_{O2} > \frac{I_S}{1+\delta} - \gamma_{S1}$

In this sub-case, the second-period surplus is

$$
\begin{aligned}
W_2^S(\gamma_{S1}, v) &= \max_{\gamma_{O2} > \frac{I_S}{1+\delta} - \gamma_{S1}} W_{O2}^S(\gamma_{S1}, \gamma_{O2}, v) \\
&= \max_{\gamma_{O2} > \frac{I_S}{1+\delta} - \gamma_{S1}} \int_{I_S/(1+\delta)}^{\pi_{S2}(\gamma_{O2})} (\pi_O - I_O) g(\pi_S)\ d\pi_S \\
&+ \int_{\pi_{S2}(\gamma_{O2})}^{+\infty} (\pi_S + v) g(\pi_S)\ d\pi_S. \qquad (34)
\end{aligned}
$$

The first-order condition associated with the choice of γ_{O2}, $\frac{dW_{O2}^S}{d\gamma_{O2}} = 0$, implies

$$
g(\pi_{S2})(\pi_O - I_O)\frac{d\pi_{S2}}{d\gamma_{O2}} - g(\pi_{S2})(\pi_{S2} + v)\frac{d\pi_{S2}}{d\gamma_{O2}} = 0.
$$

In this sub-case $\pi_{S2} = \pi_O - I_O + \gamma_{O2}$ implies $\frac{d\pi_{S2}}{d\gamma_{O2}} = 1$. Substituting and rearranging give

$$
\gamma_{O2} = -v. \qquad (35)
$$

Setting γ_{O2} equal to its lower boundary in this sub-case, i.e. $\gamma_{O2} = \frac{I_S}{1+\delta} - \gamma_{S1}$, one can define the threshold level

$$
v^O \equiv -\left(\frac{I_S}{1+\delta} - \gamma_{S1}\right), \qquad (36)
$$

such that

$$
\begin{cases}
\forall v < v^O, \gamma_{O2} > 0 \text{ as per (35)} \\
\forall v \geq v^O, \gamma_{O2} = 0
\end{cases}. \qquad (37)
$$

Finally, by the envelope theorem, we also have that for all $v < v^O$,

$$
\frac{\partial W_2^S}{\partial \gamma_{S1}} = 0. \qquad (38)
$$

A.3. Status Quo

In this sub-case, since $\gamma_{S2} = \gamma_{O2} = 0$, the second-period surplus is

$$
W_2^S(\gamma_{S1}) = \int_{I_S/(1+\delta)}^{\pi_{S1}(\gamma_{S1})} (\pi_O - I_O) g(\pi_S)\ d\pi_S + \int_{\pi_{S1}(\gamma_{S1})}^{+\infty} (\pi_S + v) g(\pi_S)\ d\pi_S. \qquad (39)
$$

How the second-period surplus is affected by γ_{S1} is given by

$$\frac{\partial W_2^S}{\partial \gamma_{S1}} = g(\pi_{S1})(\pi_O - I_O)\frac{d\pi_{S1}}{d\gamma_{S1}} - g(\pi_{S1})(\pi_{S1} + v)\frac{d\pi_{S1}}{d\gamma_{S1}}.$$

In this sub-case, $\pi_{S1} = \pi_O - I_O + \frac{I_S}{1+\delta} - \gamma_{S1}$ implies $\frac{d\pi_{S1}}{d\gamma_{S1}} = -1$. Replacing and rearranging give

$$\frac{\partial W_2^S}{\partial \gamma_{S1}} = g(\pi_{S1})\left[\frac{I_S}{1+\delta} - \gamma_{S1} + v\right], \tag{40}$$

continuously increasing in v.

One can easily verify that when v tends to $\overline{v}^S \equiv \gamma_{S1}$, then $\frac{\partial W_2^S}{\partial \gamma_{S1}}$ tends towards $\frac{I_S}{1+\delta}g(\pi_{S1})$, which implies that $\frac{\partial W_{S2}}{\partial \gamma_{S1}} > 0$. However, when v tends to $v^O \equiv -\left(\frac{I_S}{1+\delta} - \gamma_{S1}\right)$, then $\frac{\partial W_2^S}{\partial \gamma_{S1}}$ tends towards 0. Therefore,

$$\frac{\partial W_2^S}{\partial \gamma_{S1}} > 0 \text{ over } v \in (v^O, \overline{v}^S). \tag{41}$$

B. *Case 2:* $\gamma_{S1} > \frac{I_S}{1+\delta}$

Following the same reasoning as before, the policy choices in this case are

- Conserving the share of farmers producing Sugarcane with $\gamma_{S2} > \gamma_{S1} - \frac{I_S}{1+\delta}$ or with $\gamma_{C2} = 0$.
- Conserving the share of farmers producing O with $\gamma_{O2} \geq 0$ or with $0 < \gamma_{S2} < \gamma_{S1}$.

Again, since the values $\gamma_{S1} - \frac{I_S}{1+\delta} \leq \gamma_{S2} \leq \gamma_{S1}$ and $\gamma_{O2} = 0$ conserve both the share of O and of S, they implement the status quo. Hence, the policy maker's choices can be reduced to

- Extending the share of land under S with $\gamma_{S2} > \gamma_{S1}$. In this case, the new indifferent farmer is $\pi_{S2} = \pi_O - I_O - \frac{I_S}{1+\delta} + \gamma_{S2} < \pi_{S1}$.
- Extending the share of land under O with $\gamma_{O2} > O$ or $0 < \gamma_{S2} < \gamma_{S1} - \frac{I_S}{1+\delta}$. This implies $\pi_{S2} = \pi_O - I_O - \gamma_{S2} > \pi_{S1}$.
- The status quo $\pi_{S2} = \pi_{S1}$ with $0 < \gamma_{O2} = 0$ or $\gamma_{S1} - \frac{I_S}{1+\delta} < \gamma_{S2} < \gamma_{S1}$, which are dominated by $\gamma_{S2} = \gamma_{O2} = 0$.

B.1. *Extending the Share of S with* $\gamma_{S2} \geq \gamma_{S1}$

In this sub-case, the second-period surplus is

$$
\begin{aligned}
W_2^S(\gamma_{S1}, v) &= \max_{\gamma_{S2} > \gamma_{S1}} W_{S2}^S(\gamma_{S1}, \gamma_{S2}, v) \\
&= \max_{\gamma_{S2} > \gamma_{S1}} \int_{I_S/(1+\delta)}^{\pi_{S2}(\gamma_{S2})} (\pi_O - I_O) g(\pi_S)\ d\pi_S \\
&+ \int_{\pi_{S2}(\gamma_{S2})}^{\pi_{S1}(\gamma_{S1})} (\pi_S - \frac{I_S}{1+\delta} + v) g(\pi_S)\ d\pi_S \\
&+ \int_{\pi_{S1}(\gamma_{S1})}^{+\infty} (\pi_S + v) g(\pi_S)\ d\pi_S, \qquad (42)
\end{aligned}
$$

which is exactly the same surplus function as in $A.1$. Hence, the same threshold level $\overline{v}^S$ defined by (30) applies, such that $\gamma_{S2} > \gamma_{S1}$ for all $v > \overline{v}^S$ and

$$
\frac{\partial W_2^S}{\partial \gamma_{S1}} = g(\pi_{S1})(\frac{I_S}{1+\delta}) > 0, \qquad (43)
$$

as before.

B.2. Extending the Share of O with $\gamma_{O2} > 0$ or with $0 < \gamma_{S2} < \gamma_{S1} - \frac{I_S}{1+\delta}$

When the policy maker opts for implementing $\gamma_{O2} > 0$, the same results as in $A.2$ apply, i.e. equations (35)-(38) hold.

If instead the policy maker implements $0 < \gamma_{S2} < \gamma_{S1} - \frac{I_S}{1+\delta}$, the second-period surplus becomes

$$
\begin{aligned}
W_2^S(\gamma_{S1}, v) &= \max_{0 < \gamma_{S2} < \gamma_{S1} - \frac{I_S}{1+\delta}} W_{O2}^S(\gamma_{S1}, \gamma_{O2}, v) \\
&= \max_{0 < \gamma_{S2} < \gamma_{S1} - \frac{I_S}{1+\delta}} \int_{I_S/(1+\delta)}^{\pi_{S2}(\gamma_{S2})} (\pi_O - I_O) g(\pi_S) d\pi_S \\
&+ \int_{\pi_{S2}(\gamma_{S2})}^{+\infty} (\pi_S + v) g(\pi_S) d\pi_S. \qquad (44)
\end{aligned}
$$

The first-order condition associated with the choice of γ_{O2}, $\frac{dW_{O2}^S}{d\gamma_{S2}} = 0$, implies

$$
g(\pi_{S2})(\pi_O - I_O)\frac{d\pi_{S2}}{d\gamma_{S2}} - g(\pi_{S2})(\pi_{S2} + v)\frac{d\pi_{S2}}{d\gamma_{S2}} = 0.
$$

Since, in this sub-case, $\pi_{S2} = \pi_O - I_O - \gamma_{S2}$, it follows that $\frac{d\pi_{S2}}{d\gamma_{S2}} = -1$. Replacing and rearranging we have

$$\gamma_{S2} = v. \tag{45}$$

Setting γ_{S2} equal to its upper boundary in this sub-case, $\gamma_{S1} - \frac{I_S}{1+\delta}$, defines the threshold

$$\underline{v}^S \equiv \gamma_{S1} - \frac{I_S}{1+\delta} \tag{46}$$

such that

$$\begin{cases} \forall v < \underline{v}^S, 0 < \gamma_{S2} < \gamma_{S1} - \frac{I_S}{1+\delta} \text{ as per (45)} \\ \forall v > \underline{v}^S, \gamma_{S2} = \gamma_{S1} - \frac{I_S}{1+\delta} \end{cases}. \tag{47}$$

Finally, in both sub-cases, the surplus function is not directly affected by γ_{S1}. Hence, by the envelope theorem we have that for all $v < \underline{v}^S$

$$\frac{\partial W_2^S}{\partial \gamma_{S1}} = 0. \tag{48}$$

B.3. Status Quo

In this sub-case, since $\gamma_{S2} = \gamma_{O2} = 0$, the second-period surplus is

$$W_2^S(\gamma_{S1}) = \int_{I_S/(1+\delta)}^{\pi_{S1}(\gamma_{S1})} (\pi_O - I_O) g(\pi_S)\ d\pi_S + \int_{\pi_{S1}(\gamma_{S1})}^{+\infty} (\pi_S + v) g(\pi_S)\ d\pi_S. \tag{49}$$

How the second-period surplus function is affected by the first-period subsidy γ_{S1} is given by

$$\frac{\partial W_2^S}{\partial \gamma_{S1}} = g(\pi_{S1})(\pi_O - I_O)\frac{d\pi_{S1}}{d\gamma_{S1}} - g(\pi_{S1})(\pi_{S1} + v)\frac{d\pi_{S1}}{d\gamma_{S1}}.$$

Here, $\pi_{S1} = \pi_O - I_O + \frac{I_S}{1+\delta} - \gamma_{S1}$ implies $\frac{d\pi_{S1}}{d\gamma_{S1}} = -1$. Replacing and rearranging give

$$\frac{\partial W_2^S}{\partial \gamma_{S1}} = g(\pi_{S1})\left[\frac{I_S}{1+\delta} - \gamma_{S1} + v\right]. \tag{50}$$

This sub-case holds if $\underline{v}^S \leq v \leq \overline{v}^S$, where $\underline{v}^S = \gamma_{S1} - \frac{I_S}{1+\delta}$ and $\overline{v}^S = \gamma_{S1}$. Thus, it turns out that

$$\frac{\partial W_2^S}{\partial \gamma_{S1}} \geq 0. \tag{51}$$

E Proof of Proposition 2

The total surplus when Sugarcane is subsidized can be expressed as the expected first-period surplus flow in the case where the energy crop is annual (Corn), minus the cost of subsidizing Sugarcane compared to the annual energy crop Corn, $\Delta(\gamma_{S1})$, plus the discounted second-period surplus flow when the energy crop is Sugarcane, i.e.,

$$EW_1^S(\gamma_{S1}) = EW_1^C(\gamma_{S1}) - \Delta(\gamma_{S1}) + \delta EW_2^S(\gamma_{S1}), \tag{52}$$

which is (23) in the main text. One can easily verify that there is exists a γ_{S1}^* such that $\frac{dEW_1^S}{d\gamma_{S1}} \geq (\leq) 0 \iff \gamma_{S1} \leq (\geq) \gamma_{S1}^*$. γ_{S1}^* is characterized by maximizing $EW_1^S(\gamma_{S1})$ with respect to γ_{S1}, which yields the following first-order condition:

$$\frac{dEW_1^C}{d\gamma_{S1}} - \frac{d\Delta}{d\gamma_{S1}} + \delta \frac{dEW_2^S}{d\gamma_{S1}} = 0. \tag{53}$$

If the sum of the last two terms is negative, it would imply that $\frac{dEW_1^C}{d\gamma_{S1}} > 0$. Since γ_{C1} is such that $\frac{dEW_1^C}{d\gamma_{C1}} = 0$, this would imply that the policy maker would always want to subsidize more an annual energy crop that a semi-perennial one, thus proving Proposition 2. So, let us determine the sign of these terms. On the one hand, since $\frac{d\pi_{S1}}{d\gamma_{S1}} = -1$, we have

$$\frac{d\Delta}{d\gamma_{S1}} = -g(\pi_{S1})\delta \frac{I_S}{1+\delta} \frac{d\pi_{S1}}{d\gamma_{S1}} = \delta \frac{I_S}{1+\delta} g(\pi_{S1}) > 0.$$

On the other hand, the sign of $\delta \frac{\partial EW_2^S}{\partial \gamma_{S1}}$ may take different values depending on the realization of the external value of energy crops production v, as described in Appendix D. We thus need to distinguish several cases.

A. Low values $v < \underline{v}^S$

Using equations (38) and (48), we know that for all $v < \underline{v}^S$, $\frac{\partial W_2^S}{\partial \gamma_{S1}} = 0$. Thus, in this case

$$-\frac{d\Delta}{d\gamma_{S1}} + \delta \frac{\partial W_2^S}{\partial \gamma_{S1}} < 0. \tag{54}$$

B. Intermediate values $\underline{v}^S < v < \overline{v}^S$

Using equations (41) and (51) we know that $\frac{\partial W_2^S}{\partial \gamma_{S1}}$ is continuously increasing in v and that when v tends to $\overline{v}^S$ then $\frac{\partial W_2^S}{\partial \gamma_{S1}}$ tends towards $\frac{I_s}{1+\delta} g(\pi_{S1}) > 0$, while when v tends to $\underline{v}^S$ then $\frac{\partial W_2^S}{\partial \gamma_{S1}}$ tends towards 0.

Hence, for these intermediate values of v we have that $0 < \delta \frac{\partial W_2^S}{\partial \gamma_{S1}} < \delta \frac{I_s}{1+\delta} g(\pi_{S1}) = \frac{d\Delta}{d\gamma_{S1}}$. Thus, inequality (54) also holds in this case.

C. High values $v > \overline{v}^S$

Using equation (33), we know that for all $v > \overline{v}^S$, $\frac{\partial W_2^S}{\partial \gamma_{S1}} = \frac{I_s}{1+\delta} g(\pi_{S1})$. Hence,

$$-\frac{d\Delta}{d\gamma_{S1}} + \delta \frac{\partial W_2^S}{\partial \gamma_{S1}} = 0. \tag{55}$$

Thus, combining (54) and (55), we have that for any value $v \in (-\infty, +\infty)$

$$-\frac{d\Delta}{d\gamma_{S1}} + \delta \frac{\partial W_2^S}{\partial \gamma_{S1}} \leq 0. \tag{56}$$

Taking the expectation of W_2^S over $v \in (-\infty, +\infty)$ we have

$$-\frac{d\Delta}{d\gamma_{S1}} + \delta \frac{\partial E(W_2^S)}{\partial \gamma_{S1}} < 0. \tag{57}$$

Therefore,

$$\left. \frac{dEW_1^C}{d\gamma_{S1}} \right|_{\gamma_{S1}^*} > 0 \tag{58}$$

which proves Proposition 2.

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