The land use change time-accounting failure*

Marion Dupoux†

Abstract

This paper deals with the economic evaluation of projects involving land use change (LUC) emissions. I bring together two contradicting observations in the LUC literature. On the one hand, natural scientists observe that LUC emissions have a decreasing time profile. On the other hand, European energy policy relies on a steady time profile of LUC emissions. I investigate the effect of using the improper time distribution of LUC emissions on the net present value of LUC-related projects. I show that utilisation of a constant time profile distorts direct LUC emissions costs by approximately 20% upward (downward) when carbon prices grow slower (faster) than the discount rate. I propose two tools to aid in decision-making and address the decision error. Contextual policy recommendations are provided.

Keywords: land use change, time distribution, cost-benefit analysis, public evaluation of projects, discounting, relative carbon prices, biofuel

JEL Classification: D61, H43, Q15, Q16, Q48, Q54

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1 Introduction

Biofuels were originally considered an important tool in the response to global warming. However, this belief changed dramatically once land use change was incorporated into the analysis. As biofuel production was encouraged worldwide, the need for energy crops has risen, competing and displacing food crops. As the use of land is subject to continuous change in many areas, understanding how land use change (LUC) impacts the climate is very important. The study by Searchinger et al. (2008) was the first to highlight that LUC emissions induced by biofuel production partly or even totally cancel out the environmental benefits of using biofuels. LUC emissions stem from carbon stock changes both in vegetation and soil after a land (e.g. grassland, forestland) is converted into a new use (e.g. energy crops). These emissions are unique in their distribution over time as they do not follow a steady time profile in the same way industrial emissions do. Instead, LUC emissions mostly occur immediately (Broch et al., 2013; Gorter and Just, 2010). Such a time distribution is specific to carbon releases from both biomass and soil carbon sinks. The release of carbon is instantaneous for biomass, whereas for soil carbon sinks it is a more long-term process with decreasing emissions levels over time. Scientists have found that carbon releases from soils following conversion of forests and grasslands into cropland in temperate regions decrease exponentially over time (see the meta-analysis by Poeplau et al. (2011)). However, European policies assume that LUC emissions, irrespective of type of carbon sink, have a constant time profile (The European Commission, 2009; The European Parliament and the Council of the European Union, 2015). So, what are the consequences of not using the proper time distribution of LUC emissions in appraisals of biofuel projects? Shedding light on this question and suggesting tools to support decision-making in this context are the two main objectives of the present paper.

Project appraisals mainly rely on cost-benefit analysis.[1] Discount rate and time path of carbon prices are the two key elements of cost-benefit analysis. Both affect emissions at different times differently except when carbon prices grow exactly at the discount rate, i.e. when the Hotelling rule applies. This rule prevents the discounting effect from cancelling the carbon price effect and is widespread in climate change modelling (Dietz and Fankhauser, 2010). Nonetheless, in practice, carbon prices usually deviate from this rule (Hoel, 2009). By connecting the biophysics literature on the time distribution of LUC emissions and the economics literature on project evaluation, the present paper addresses the bias that policymakers may overlook when evaluating projects involving non-constant LUC emissions. A discussion on the options to overcome this issue is provided with the aim of supporting decision-makers when implementing biofuel projects. To this end, I develop a simple two-period model that computes net present values of LUC-related emissions under two different time distributions of LUC emissions: the *uniform* (constant emissions) time distribution typically, yet wrongly, used by

[1] According to Atkinson and Mourato (2008), "even if policies are not solely formulated on the basis of [cost-benefit analysis], decisions at least should be informed by this tool".

policymakers, and the *differentiated* (across time) distribution that reflects the proper dynamics of carbon and thus of emissions, as put forward by natural scientists. The model aims to shed light on the distortion of the net present value of LUC emissions when a constant time profile is adopted. Simulations are run based on the data provided by the European Commission on carbon stock changes in the context of bioethanol production in France in order to quantify the resulting bias across various land conversions and with different carbon price and discount rate scenarios. We find that LUC emission costs are on average under- or overestimated by 20% depending on the relative weight of the discount rate compared with the carbon price increase. This figure only takes into account direct land use change, which may lead to an underestimation compared with what would be found if incorporating indirect land use change. I provide two simple tools to help policymakers understand the underlying distortion induced by project appraisals under the assumption that LUC emissions are constant over time. Understanding and dealing with this distortion is important since the decision of whether or not to implement a project can radically change depending on the chosen time profile. The first tool is the compensated rate, which cancels out the value difference between the uniform and the differentiated time profiles. This rate is useful in that it can be compared with the discount rate chosen for the project evaluation, and this comparison can in turn indicate in which direction policymakers misestimate the LUC costs. The second tool is the carbon profitability payback period. Contrary to the classical payback period stemming from the carbon debt concept, the carbon profitability payback period is price-based and likely to better incentivise reductions of LUC emissions. I recommend the use of a carbon profitability payback period benchmark established on economic and political grounds for the purpose of comparing the uniform and differentiated approaches. These two tools are implemented in a Python program, described in the supplementary material and available online,[2] which computes LUC emissions under the uniform approach (mimicking the European energy policy method) and the differentiated approach (based on the meta-analysis of Poeplau et al. (2011)).

The paper is organised as follows. Section 2 describes and reviews the literature on the particular time distribution of LUC emissions and confronts it with the assumption of constant emissions over time employed by the European Commission. Section 3 presents the theoretical model and a numerical illustration of the distortion of LUC costs under the uniform time distribution approach. Section 4 proposes two simple tools created to aid in decision-making regarding LUC projects expected to affect global warming. Section 5 discusses the results in the actual policy context and provides some policy recommendations.

[2]The tool is available on GitHub, *https://github.com/lfaucheux/PyLUCCBA*.

2 Land use change time distribution: actual vs. accounted for in EU policy

In the context of greenhouse gas emissions reductions, biofuels constitute an alternative to fossil fuels in the transport sector and have therefore been strongly promoted and subsidised across the world (from the US, through Asia and South America, to Europe). In particular, the European Union is committed to a mandatory 10% minimum share of biofuels in transport petrol and diesel consumption by 2020. However, the incentive to incorporate biofuels in the energy mix was dampened by the publication of the study of Searchinger et al. (2008)), which pointed out that some biofuels began to perform even worse (in terms of emissions) once LUC started to be taken into consideration. There are two categories of LUC. *Direct* LUC refers to the replacement of a given land by cropland entirely dedicated to biofuel production. *Indirect* LUC occurs when the replacement of land dedicated to food crops[3] with farming of biofuel crops reduces the availability of land for food production. This reduction is compensated for in other places where land is converted into use for food crops, thereby generating carbon emissions. Indirect LUC is more difficult to quantify as it involves economic forces (see e.g. (Feng and Babcock, 2010)) following an increased biofuels production and therefore often requires modelling. Nevertheless, the mechanism at the origin of LUC emissions is the same for both categories of LUC. While feedstock cultivation and biofuel production processes generate emissions that roughly remain constant over time, land conversion occurs just once, i.e. as a shock (De Gorter and Tsur, 2010). Notably, the loss in vegetation carbon stocks (resulting in CO2 emissions) is in most cases instantaneous, while the process is slower in the soil. In the latter, emissions follow an (exponentially) decreasing profile over time (Poeplau et al., 2011). This particular time distribution of emissions related to LUC is the key focus of the present paper.

To calculate the impact of land use change on the climate, the European Renewable Energy Directive (RED) assumes a constant temporal distribution of LUC emissions over 20 years. Indeed, the Directive states that "[a]nnualised emissions from carbon stock changes caused by land-use change [. . .] shall be calculated by dividing total emissions equally over 20 years" (The European Commission, 2009). This straight line amortisation method has the advantage of being simple and consistent (Broch and Hoekman, 2012), unfortunately at the expense of not considering the genuine dynamics of LUC emissions. For the sake of clarity, we name the two temporal distributions tackled in this paper as follows:

- Uniform temporal distribution: constant time profile as assumed in European energy policies.
- Differentiated[4] temporal distribution: decreasing time profile as reported in the bio-

[3] E.g. corn initially produced for food supply purposes are turned into energy crops to be used for biofuel production.

[4] In the sense, differentiated across time.

physics literature.

These two temporal distributions are illustrated in Figure 1, where land conversion occurs at time $t = 0$. Note that the sum of emissions under both temporal distributions is the same. Therefore, the problem lies not so much in how emissions are quantified over time *per se* (i.e. in physical terms) as in the pricing over time of these emissions as explained next.

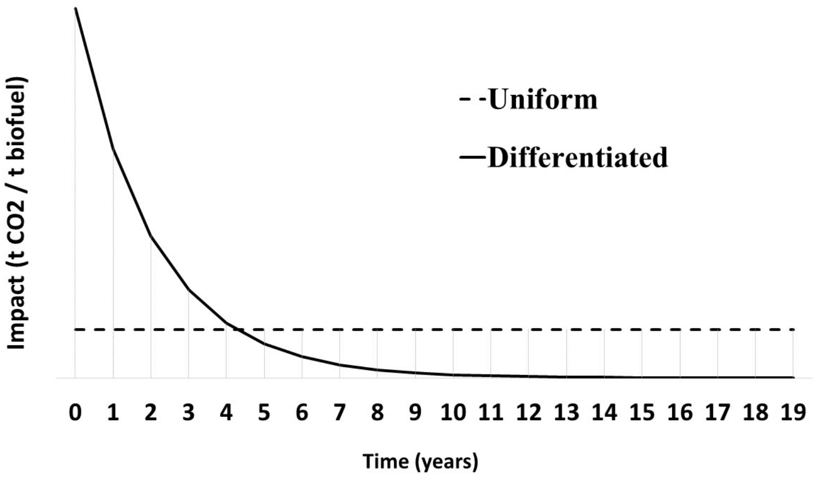

Figure 1: Temporal distributions of LUC emissions (uniform vs. differentiated).

Economic appraisal is a key tool in policymaking and usually relies on cost-benefit analysis. We follow De Gorter and Tsur (2010) in that biofuel policy triggers economic consequences and thus requires cost-benefit analysis. Cost-benefit analysis relies on *i)* pricing emissions at each point in time and *ii)* discounting the future to aggregate emissions costs over time. Both carbon prices and the discount rate affect points in time differently. Only when carbon prices grow at the discount rate are emissions at different times not affected by the time distribution. This is known as the Hotelling rule, originally established for exhaustible resources.[5] Providing an exhaustive literature review on the way carbon prices *should* evolve is beyond the scope of this paper. Rather, we emphasise that in the policy sphere, discount rates (employed in cost-benefit analyses of projects) often differ from the rate at which carbon prices rise.[6] For example, the 2008 Joint Research Center report on environmental benefits of biofuels by the The European Commission (2008) relies on a carbon price ranging from 30 to 60€/tonne between 2010 and 2020 (amounting to an average 7.2% growth) while a constant 2% discount rate is used to assess the project value. Additional examples can be found in OECD and IEA (World Energy Outlook) reports where the carbon price increases "much faster than any reasonable value of

[5] Applied to global warming, this rule assumes that the capacity of the atmosphere to manage a certain concentration of GHGs is an exhaustible resource. The emissions cap determines the amount of allowed emissions within a given period and this amount depletes over time as one emits GHGs. Consuming the entire amount implies an equivalence between emitting one tonne of CO2 today or in a year, which in turn implies that the carbon price should increase at the discount rate.

[6] Though, in economic theory, the discount rate is related to the carbon price growth rate (see e.g. Gollier (2012) and Weikard and Zhu (2005)).

the discount rate" (Hoel, 2009). In other studies, importance is given to when an upper limit on GHG concentration is reached and how uncertain future damages, technical progress and co-operation efforts to reduce emissions are (Gollier and Baumstark, 2009). The aforementioned elements usually make the carbon price grow slower than the discount rate, with counterpart a high initial carbon price. Despite being based on economic models beforehand, discount rates and carbon price paths in the policy sphere are the result of a series of compromises with all stakeholders. With *i)* the incorrect time distribution of LUC emissions used by the European energy policy and *ii)* the common use of cost-benefit analysis as a decision-making tool in the policy sphere in mind, I address the issue of project appraisal distortion in the context of emissions induced by LUC.

3 Distorted present values as a result of incorrect time distribution of LUC emissions

The model presented here aims to mimic cost-benefit analysis as employed in policymaking. It assumes that carbon prices are not correlated with the discount rate within cost-benefit analysis as in De Gorter and Tsur (2010). While such an assumption may be inconsistent with economic theory, it is consistent with common practice in the policy sphere. While both the discount rate and the carbon prices used in the evaluation of biofuel-related projects are estimated by economic models that follow economic theory, the resulting values are usually adjusted through compromises between stakeholders in the policy sphere. Therefore, the carbon price growth rate and the discount rate used in project appraisal tend not to be correlated.

3.1 A two-period net present value (NPV) model

Consider two periods $t=\{0,1\}$, and denote as $z_t \in \mathbb{R}^+$ the actual emission flow occurring at time t. The model aims to compare the LUC-related net present value (NPV)[7] under the uniform (u) and the differentiated (d) time distributions. The differentiated approach preserves the actual emission flows as such (i.e. z_t at time t). By contrast, the uniform approach averages emissions over a chosen time period of time (here 2 years), modifying the actual flows z_0 and z_1 into $\frac{z_0+z_1}{2}$ $\forall t=\{0,1\}$.

Consider a project which releases emissions as a result of land conversion[8] at $t=0$. The carbon price grows at the carbon price growth rate denoted by $g \in [0,1]$ such that the carbon price at $t=0$ and $t=1$ are respectively $p_0 \geq 0$ and $p_1 = p_0(1+g) \geq 0$. Denoting the discount

[7] In this model, we exclusively focus on the LUC part of the total net present value of a project. The economic part is beyond the scope of the paper. The other GHG emissions, such as those from biofuel production processes and cultivation of energy crops are incorporated in the analysis in subsection 4.2.

[8] From high carbon-concentrated land (e.g. forestland, grassland) to lower carbon-concentrated land (e.g. cropland).

rate used in the project $r \in [0,1]$, the NPVs associated with the uniform and differentiated approaches are such that, for all $z_0,\ z_1 \in \mathbb{R}^+$:

$$NPV_u = -\left(p_0 \frac{z_0+z_1}{2} + p_0 \frac{(1+g)}{(1+r)} \frac{z_0+z_1}{2} \right) \tag{1}$$

$$NPV_d = -\left(p_0 z_0 + p_0 \frac{(1+g)}{(1+r)} z_1 \right) \tag{2}$$

The negative sign indicates that emissions constitute a cost to society. The model can easily be extended to sequestrations of carbon (see Appendix A).[9] In line with the biophysics literature, we assume that $z_0 > z_1$ (Poeplau et al., 2011).

Considering the differentiated time distribution as the baseline (the one that should be accounted for in policymaking), next I assess the bias induced by the use of the uniform time distribution. This amounts to analysing the NPV difference $\Delta NPV = NPV_u - NPV_d$ whose sign provides information about the downward or upward bias induced by the uniform time distribution. Since the discount rate and carbon prices affect points in time differently, we first disentangle one effect from the other before analysing the combined effect.

3.1.1 Discounting effect ($\mathbf{0 < r \leq 1}$ and $\mathbf{g = 0}$)

To isolate the discounting effect, I assume that $p_1 = p_0 > 0$ and a strictly positive discount rate. The NPV difference is

$$\Delta NPV = \frac{p_0 r (z_0 - z_1)}{2(1+r)} > 0, \tag{3}$$

and deriving the NPV difference with respect to the discount rate gives

$$\frac{\partial \Delta NPV}{\partial r} = \frac{p_0 (z_0 - z_1)}{2(1+r)^2} > 0, \tag{4}$$

leading to Proposition 1.[10]

Proposition 1 (discounting effect) *Employing the uniform time distribution of LUC emissions increases the discounting effect. As a result, the value of projects entailing such emissions is overestimated, i.e. the costs of emissions are underestimated. The higher the discount rate, the larger the bias induced.*

The key difference between the uniform and differentiated time distributions lies in the fact that emissions mostly occur upfront in the latter. Therefore, in the uniform approach, a greater

[9] We focus on the emission case here since it constitutes an environmental issue in the context of biofuel production. Sequestrations are beneficial for the environment in contrast.

[10] The proof of Proposition 1 is straightforward: $\Delta NPV > 0$ means that $NPV_u > NPV_d$. The positive derivative of ΔNPV with respect to the discount rate indicates that the difference (overestimation) increases with the discount rate.

amount of emissions (at $t = 1$) are suffering from the discounting effect, which softens the monetary cost of emissions and thus underestimates the costs (compared with the differentiated approach, which fully accounts for the decrease of carbon releases).

3.1.2 Carbon price effect ($\mathbf{0 < g \leq 1}$ and $\mathbf{r = 0}$)

To isolate the carbon price effect, I assume that $g > 0$ (i.e. $p_1 > p_0$) and a zero discount rate. The NPV difference is

$$\Delta NPV = \frac{1}{2} p_0 g \left(z_1 - z_0\right) < 0, \tag{5}$$

and deriving the NPV difference with respect to the carbon price growth rate gives

$$\frac{\partial \Delta NPV}{\partial g} = \frac{1}{2} p_0 \left(z_1 - z_0\right) < 0, \tag{6}$$

leading to Proposition 2.[11]

Proposition 2 (carbon price effect) *Employing the uniform time distribution of LUC emissions increases the carbon price effect. As a result, the value of projects entailing such emissions is underestimated, i.e. the costs of emissions are overestimated. The higher the carbon price growth rate, the larger the bias induced.*

Because the carbon price is increasing over time, the earlier the emissions the lower their social cost. In the differentiated approach, emissions mostly occur upfront when the carbon price is lower. By contrast, the uniform approach entails emissions equally spread out over time. Therefore, a greater amount of emissions is priced higher at time $t = 1$. Higher priced emissions, which constitute a higher social cost, lead to an underestimated NPV under the uniform approach.

3.1.3 Combined effect ($\mathbf{0 < r \leq 1}$ and $\mathbf{0 < g \leq 1}$)

The use of the uniform time distribution in economic appraisals boosts both the discounting effect (reduction of the value of future emissions) and the carbon price effect (increase of the value of future emissions). Proposition 3 follows from the combination of both effects (proof in B).

Proposition 3 (combined effect) *Under the Hotelling rule, no bias is induced by the uniform approach. When the Hotelling rule does not apply, employing the uniform time distribution in cost-benefit analysis causes an upward (downward) bias of the project value if and only if the carbon price grows slower (faster) than the discount rate.*

[11] The proof of Proposition 2 is straightforward: $\Delta NPV < 0$ means that $NPV_u < NPV_d$. The negative derivative of ΔNPV with respect to the carbon price growth rate indicates that the difference is increasingly negative (i.e. the underestimation is increasing), generating an increasing bias induced by the uniform approach.

When the discounting and carbon price effects perfectly cancel each other out, the uniform and differentiated time distributions are strictly equivalent within cost-benefit analysis (i.e. the same NPV). This means that the construction of the carbon price trajectory either strictly follows the Hotelling rule or involves perfect compensation between elements that make the carbon price grow slower than the discount rate (e.g. uncertainty) and elements that make it grow faster (e.g. lower initial carbon price, larger natural absorption of carbon). However, Section 2 puts forward that the carbon price often deviates from the Hotelling rule in practice.

When the discounting effect outweighs the carbon price effect (see Proposition 1), using the uniform approach results in an upward bias of the project value. In monetary terms, it means that the cost of emissions is given relatively less value under the uniform approach, leading to an overestimation of the value of the project. A lower carbon price growth rate than the discount rate may be due to the consideration by policymakers of the uncertainty about the magnitude of environmental damages and advocates for a strong carbon price signal today to incentivise the reduction of emissions immediately (in line with Stern (2006).

When the carbon price effect dominates the discounting effect, the uniform approach leads to underestimation of the value of the project (see Proposition 2). Under the uniform approach, carbon emissions 'gain' (monetary) value over time even after discounting, whereas under the differentiated approach, emissions 'benefit' virtually nothing from the price hike since emissions occur mainly upfront. Such a situation where the growth rate of the carbon price is greater than the discount rate is likely to occur when the carbon price path starts at a low level, requiring a strong rise to meet future emissions reductions objectives (rather in line with Nordhaus' idea of "climate policy ramp").

3.2 Numerical illustration

In this subsection, I provide a numerical illustration of the theoretical results with the example of direct land use change engendered by bioethanol production in France. France is the biggest bioethanol producer in Europe and the second biggest consumer after Germany.

Assumptions France is located in a temperate region where the increasing demand for bioenergy is leading to increasing rates of LUC (Poeplau et al., 2011). The lands likely to be converted in France are croplands (here only wheat will be considered) and grasslands, while conversion of forestlands is less likely (Chakir and Vermont, 2013).[12] Since this paper is mostly addressed to European policymakers, I use a 20-year time horizon for LUC emissions as in the European RED. For the differentiated time distribution, I assume that *i)* carbon dynamics in the soil follow an exponential decrease across time in line with Poeplau et al. (2011) and

[12] Despite the regulations prohibiting the conversion of high-carbon land types, grasslands and some forestlands continue to be ploughed and cleared due to the considerable incentive to develop energy crops.

that *ii)* biomass-related emissions are instantaneous.[13] For the sake of simplicity, the discount rates I employ are constant and range from 0 to 5% in the analysis, which is in line with the estimated values of the discount rate found in cost-benefit analyses of European public projects and policies (Florio, 2014, p.187). Finally, I construct time trajectories of the carbon price from 2020. Each trajectory is characterised by the initial carbon price in 2020 denoted by p_{2020} and the carbon price growth rate, g, resulting in a values pair $\{p_{2020},\ g\}$ as follows:

- O Constant price of carbon $\{40, 0\%\}$
- A Low initial price and high growth rate $\{40, 5\%\}$
- B Low initial price and medium growth rate $\{40, 3\%\}$
- C High initial price and low growth rate $\{80, 1\%\}$

By constructing my own pathways, I avoid the complex assumptions that underpin carbon price scenarios in the literature. For example, the assumptions made about the discount rate value (which I vary in my analysis) are not clear in the World Energy Outlook scenarios. Scenario *O*, *i.e.* no carbon price increase, is the baseline scenario. In Scenario A, the carbon price increases fast. In Scenario B, it grows slower from the same initial price. Scenario C, characterised by a high initial price, represents a strong value signal to reduce emissions and hence to avoid abrupt climate change. Roughly, Scenario A is more in line with Nordhaus' idea of *climate policy ramp* (Nordhaus, 2007), which promotes progressive cuts in emissions, hence larger cuts in the future, whereas Scenario C calls for more aggressive emissions reductions today as Stern puts forward in his review (Stern, 2006).

Data The computation of LUC emissions relies on the formal definitions of the uniform and the differentiated approaches as described in Appendix C. To determine carbon stock changes in soil and vegetation, I rely on the guidelines provided by the The European Commission (2010), which are based on IPCC (2006). Such a calculation requires knowledge about climatic region, soil type, agricultural management, agricultural practices (input level) and crop yields, adapted to our case study (see Appendix D). Regarding the shares of carbon that are converted into CO2 emissions, I assume that 30% of the carbon stock in soil is converted into CO2. This figure falls in the range given by the Winrock database (see Table 1 in Broch et al. (2013)) and is very close to the assumption of 25% made by Tyner et al. (2010). I assume that the reverse conversion is symmetric. Regarding the carbon stored in vegetation, I hypothesise that 90% is converted into emissions – a figure in line with the CARB policy in the United States.[14] An overview of the data used in the study, including sources, is provided in Appendix D.

[13] Nonetheless, the rate of decay of the initial biomass depends on how it is managed afterwards, e.g. whether it is left to decompose or is burned, buried or converted into long-lived products such as furniture (Delucchi, 2011). This is taken into account through the variables ω_s and ω_v described in Appendix C.

[14] Tyner et al. (2010) and Searchinger et al. (2008) assume that 75% and 100% is converted into emissions, respectively.

Computation tool I develop a Python program[15] to generate the uniform and differentiated time distributions and calculate the NPV of the GHG emissions of bioethanol projects. Once LUC emissions due to soil and biomass carbon stock changes as well as their dynamic over time are determined,[16] emissions are converted into CO2 emissions according to Appendix C, and finally priced using one of the scenarios listed above. Regarding price scenarios, an algorithm that exponentially extrapolates prices allows me to generate a complete trajectory of carbon prices over the time horizon considered, since only one-time carbon prices are provided in most scenarios such as the World Energy Outlook's (IEA, 2015). The program essentially returns all the NPV types necessary to the analysis, i.e. LUC emissions (under each type of time distribution), non-LUC emissions and total emissions from biofuel production (i.e. LUC + non-LUC).

Results All results assume a conversion of grassland or forestland into cropland (wheat crop). Note that NPVs are always negative throughout the results since we focus on emissions that generate costs to society. Because there are no scale effects on emissions due to LUC from the production of one unit of bioethanol, for the sake of simplicity I consider that one tonne of bioethanol is produced each year for 20 years.[17]

➤ ***Discounting effect***

Figure 2 illustrates the discounting effect in the case of a forestland converted into cropland. Carbon prices are constant over time and equal to 40€/tonne of CO2.

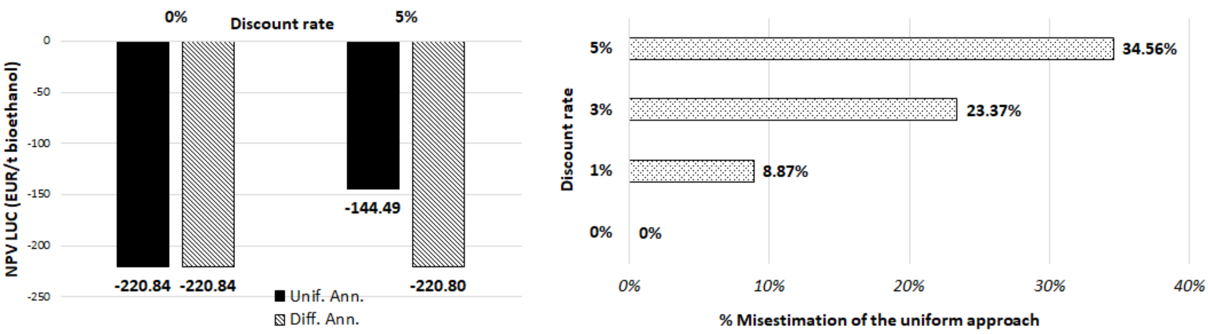

Figure 2: Net Present Value of LUC emissions (left) and relative upward bias induced by the uniform approach (right) for different discount rate values. For forestland conversion.

When no discounting is applied (0%), the NPVs under the uniform and differentiated approaches are equal since points in time are affected in the same manner. When a 5% discount rate is applied, the uniform approach raises the NPV (or equivalently, drops

[15] Namely PyLUCCBA. The program (complete tool coded in Python language) is described in the supplementary material linked to this paper and provided on GitHub, $https://github.com/lfaucheux/PyLUCCBA$.

[16] Referring to Appendix C regarding the differentiated approach (Definition 2), the program determines the coefficient a of the carbon response function provided by Poeplau et al. (2011), while taking into account the associated time horizon (for soil or vegetation).

[17] Of course, this trajectory can be changed in the Python tool in order to obtain NPVs in line with a specific project.

the cost) of emissions due to LUC from -220.80€ to -144.49€ per tonne of bioethanol. The higher the discount rate, the larger the bias induced by the uniform time distribution (ranging from 8.87% for a 1% discount rate to 34.56% for a 5% discount rate).

Figure 3 illustrates the discounting effect for grassland converted into cropland.

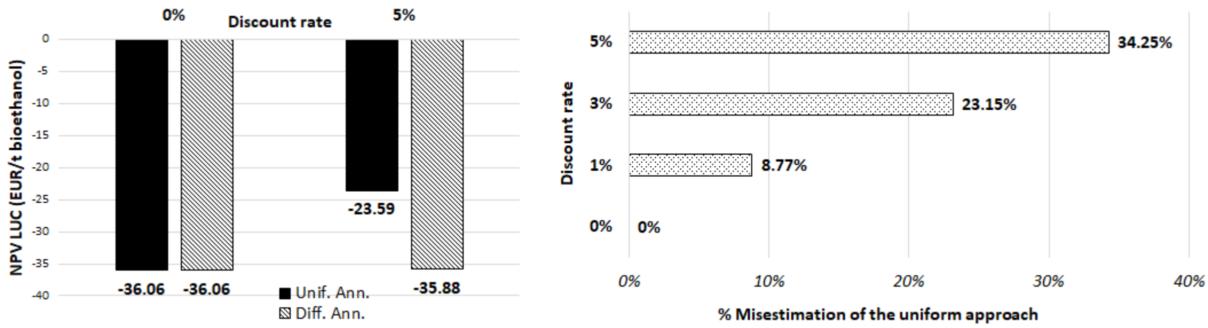

Figure 3: Net Present Value of LUC emissions (left) and relative upward bias induced by the uniform approach (right) for different discount rate values. For grassland conversion.

Since grassland contains less vegetation than forests, carbon losses are lower, leading to a smaller absolute difference in NPV between the uniform and differentiated approaches (from 35.88€ to 23.59€/tonne of bioethanol with a 5% discount rate). However, the range of NPV distortion in relative terms is very similar to the case of forestland conversion (ranging from 8.77% overestimation with a 1% discount rate to 34.25% with a 5% discount rate).

➤ ***Carbon price effect***

Figure 4 illustrates the carbon price effect in the case of a forestland converted into cropland. Carbon prices are now increasing according to the different scenarios defined above (O, A, B, C) and the discount rate is zero.

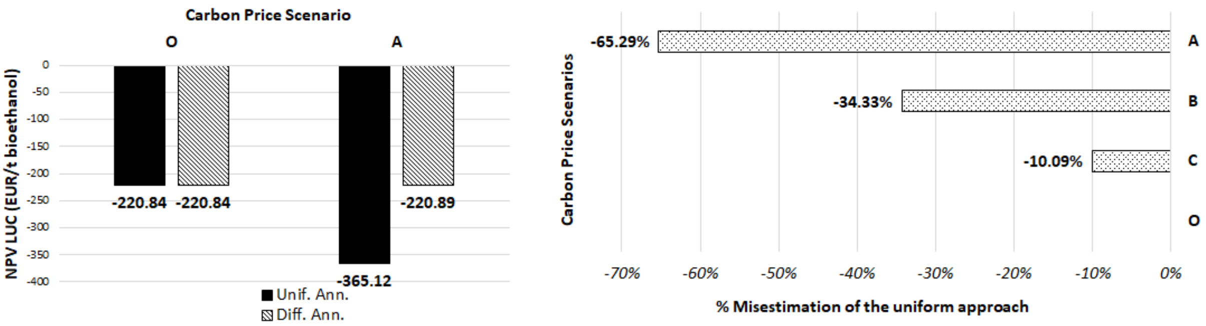

Figure 4: Net Present Value of LUC emissions (left) and relative downward bias induced by the uniform approach (right) for different carbon price scenarios. For forestland conversion.

The NPV of emissions due to LUC is underestimated under the uniform approach (drops from -220.89€ to -365.12). The higher the carbon price growth rate (from Scenario O to Scenario A), the larger the bias induced by the uniform approach (downward bias ranging from 10.09% under Scenario C to 65.29% under Scenario A). Figure 5 illustrates the case of a conversion of grassland into cropland.

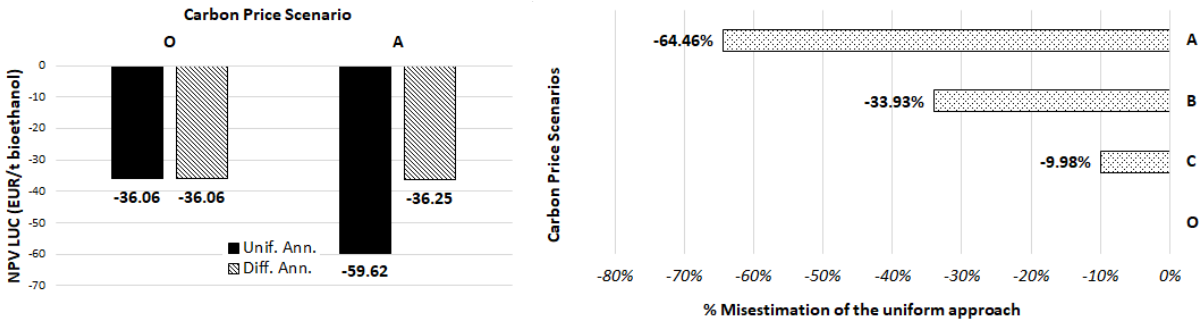

Figure 5: Net Present Value of LUC emissions (left) and relative downward bias induced by the uniform approach (right) for different carbon price scenarios. For grassland conversion.

As can be seen, the conversion results in a smaller underestimation in absolute terms (a drop from -36.25 to -59.62 €/tonne bioethanol) and similar relative differences.

➤ ***Combined effect***

When combining a positive discount rate (fixed to 3% here) with a carbon price growth rate ranging from 0% (Scenario O) to 5% (Scenario A), the direction of the bias depends on whether the carbon price growth rate grows faster or slower than the discount rate (see Figure 6 for forestland conversion and Figure 7 for grassland conversion).

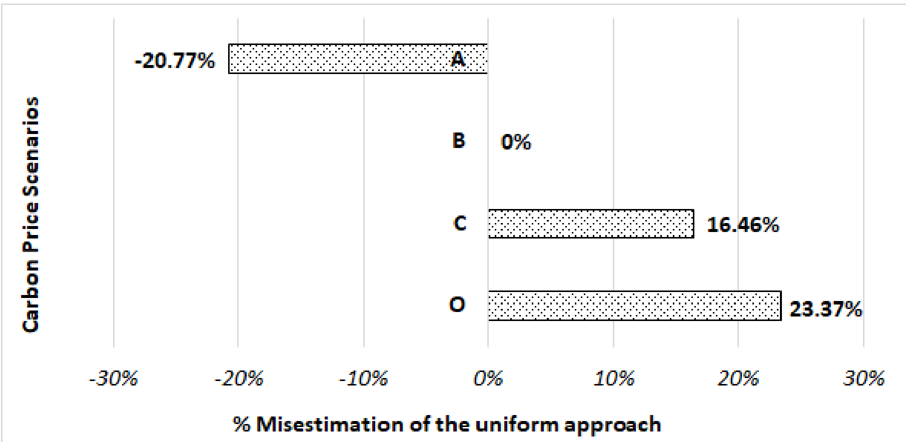

Figure 6: Relative bias induced by the uniform approach (3% discount rate and different carbon price scenarios). For forestland conversion.

In Scenario B, the Hotelling rule applies, which cancels the bias induced by the uniform approach. In Scenarios O and C, the discount rate is greater than the carbon price growth rate, and hence the overestimation engendered by the uniform time distribution. In Scenario A, the carbon price grows faster than the discount rate, which makes the uniform approach distort the cost of emissions upward (i.e. changing the NPV downward).

It is worth highlighting that these results only apply for direct LUC. But the (physical) mechanism of land use conversion is the same whether the LUC is direct or indirect,

Figure 7: Relative bias induced by the uniform approach (3% discount rate and different carbon price scenarios). For grassland conversion.

which means that the resulting (already substantial) bias is underestimated here compared with an analysis also incorporating indirect LUC.

4 Proposal of two simple tools for policymakers

4.1 Compensatory rate

In this subsection, I introduce the concept of compensatory rate, which I define as the discount rate value that cancels the bias induced by the uniform approach given a carbon price path. Put differently, it is the rate that equalises NPVs under the uniform and differentiated approaches. The compensatory rate is of particular interest when using existing carbon price paths such as those provided by the World Energy Outlook (WEO) or national reports (e.g. the Quinet (2009) report in France). Such a concept may seem trivial if we consider that carbon prices grow at a constant rate, as assumed in my theoretical model.[18] In practice, however, the carbon price growth rate is not constant (e.g. the Current Policy Scenario [CPS], New Policy Scenario [NPS] and 450 ppm Scenario [450S] in the World Energy Outlook report IEA (2015)).

Therefore, the compensatory rate depends on the carbon price path, the time distribution of emissions (to which carbon prices apply) and the time horizon considered in the analysis. The compensatory rate serves as a benchmark for the discount rate chosen in a project evaluation. If the discount rate chosen is greater (smaller) than the compensatory rate,[19] policymakers are informed that their project will be overestimated (underestimated). Therefore, this tool provides information about the direction of the estimation bias due to the use of the uniform time distribution given a specific carbon price trajectory. Figure 8 provides a numerical illustration of the compensatory rate applied to the carbon price trajectories established in the World Energy

[18] If carbon prices grow at a constant rate, the compensatory rate would be equal to the carbon price growth rate.

[19] Calculated by the Python program described in the supplementary material and available on GitHub.

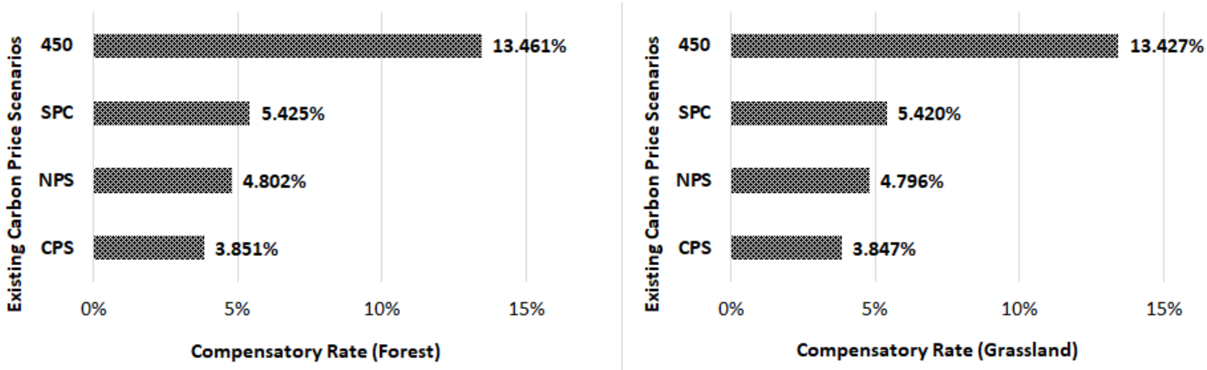

Figure 8: Compensatory rate across different carbon price scenarios for forestland (left) and grassland (right) conversions.

Outlook (IEA, 2015) and the Quinet (2009) report (Scenario SPC for shadow price of carbon) in the context of bioethanol production in France (forestland conversion to the left and grassland conversion to the right). The more constraining the scenario, the higher the compensatory rate. The resulting rates in the forestland and grassland cases are very similar since their values primarily depend on the carbon price trajectory. Let's look at an example of project evaluation. If the uniform approach is used (the most common case) and a 4% discount rate is chosen to discount future emissions, then using the 450S, NPS and SPC scenarios leads to overestimation of emissions costs, while using the CPS scenario result in an underestimation.

4.2 Carbon profitability (CP) payback period

To introduce the second tool, namely the carbon profitability (CP) payback period, let's consider a broader scope of emissions in the following numerical illustrations. In contrast to the previous effects, I now consider all emissions linked to biofuel production, i.e. both LUC and non-LUC emissions are accounted for in the NPV. Non-LUC emissions include emissions from the production of biofuels and the cultivation of energy crops. The land conversion considered here is from a grassland to a wheat field. Bioethanol projects are compared with fossil fuel production projects based on equivalent amounts of energy produced. In this context, GHG savings are allowed because aside from LUC emissions, the amount of GHGs emitted from the production and consumption of fossil fuels is greater than the energy-equivalent GHG amount from bioethanol production and consumption. Let me introduce the concept of monetised carbon investment, which is illustrated in Figure 9 (right chart) for the 450S scenario.[20] Land conversion simulates a (shadow) carbon investment since upfront emissions constitute a social cost incurred at $t = 0$ that is refunded through future GHG savings (hence relative carbon benefits). These future GHG savings are expected to counterbalance the initial cost at the so-called CP payback period. The monetised carbon investment could also be considered as a borrowed

[20] Note that in the differentiated approach, the initial kink on every curve is due to the one-year delay of biofuel production. LUC occurs at $t = 0$ and the process of production that allows for "GHG refunding" starts at $t = 1$. Under the uniform approach, there is no monetised carbon investment as emissions are spread over time.

(monetised) amount of carbon from the atmosphere which is returned later in the future. It is worth mentioning that it differs from the widespread "carbon debt" concept in its being monetary and not physical (i.e. emissions quantities are priced here). In Figure 9, different existing carbon price scenarios are tested for both the uniform and differentiated approaches. Under the uniform approach, emissions are spread out over 20 years, which does not make clear the initial carbon investment that, in contrast, the differentiated approach involves.

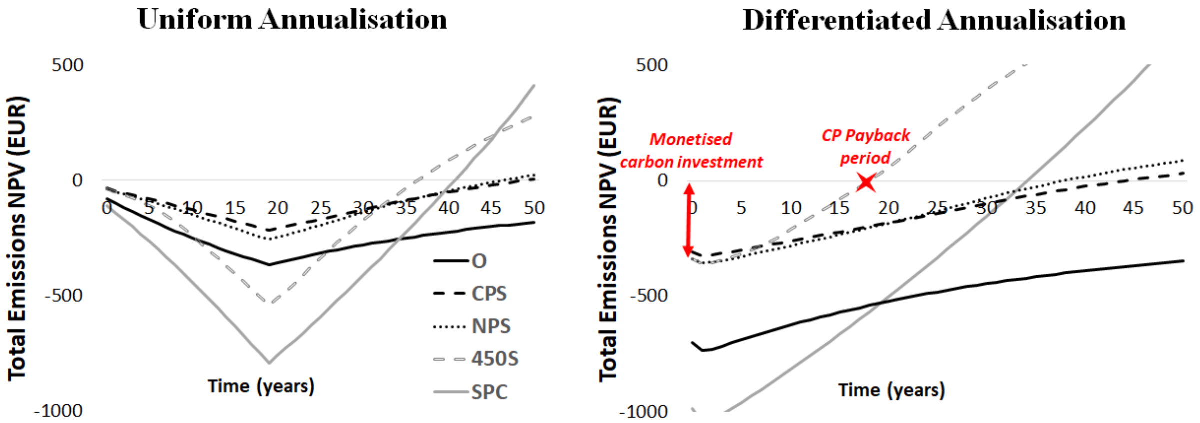

Figure 9: Carbon profitability payback periods across different carbon price scenarios under the uniform (left) and the differentiated (right) time distribution approaches.

The CP payback period changes across scenarios and across time distributions as reported in Table I (see Appendix E for payback periods related to Scenarios A, B, C).[21] With these examples, all payback periods computed under the uniform approach are greater than those under the differentiated approach.[22]

Table I: Carbon profitability payback period across carbon price scenarios and time distributions.

	Uniform	Differentiated	% Bias
O	>150	>150	/
CPS	49	45	8.89%
NPS	47	38	23.68%
450S	37	18	105.56%
SPC	41	35	17.14%

The problem lies in an LUC-related project passing the cost-benefit analysis test under the differentiated approach but not under the uniform approach or vice-versa. This involves the use of a benchmark CP payback period that I recommend to establish on political and economic grounds. Such a benchmark could be compared to the CP payback period of projects. E.g.

[21] CP payback periods are also calculated by the Python program described in the supplementary material and available on GitHub.

[22] Note however in Appendix E that e.g. in Scenario C (1% carbon price growth rate), the payback period would be lower under the uniform approach (more than 150 years) than under the differentiated approach (81 years).

in the 450ppm scenario, if the benchmark were fixed to 20 years, the project would not pass under the uniform approach while in reality (i.e. under the differentiated approach), emissions do comply with such a requirement, thereby penalising projects which are actually beneficial to the environment. On the contrary, with Scenario C (see Appendix E), where the carbon price grows slower than the discount rate, the uniform approach may end up lending support to projects that are actually harmful to the environment. This could happen if uncertainty prevails as a decision aspect. Therefore, the CP payback period addresses the issue of decision error when based on cost-benefit analysis. The uniform approach may either be at odds with the primary objective of cutting emissions by not rejecting environmentally harmful projects[23] or disapproving of projects that actually comply with the requirements (e.g. the benchmark payback period).

A limitation of this tool may be the absence of consideration of potential scale effects in biofuel production. Indeed, the carbon profitability payback period also involves non-LUC emissions from the production process, and thus, it is subject to economies of scale (which is not the case for LUC emissions). Intuitively, taking these economies of scale into account will shorten the estimated payback periods for both time distributions since economies of scale lead to higher energy efficiency in biofuel production and thus faster net GHG savings across the whole project time horizon. Nevertheless, nothing would change regarding the comparison between the uniform and the differentiated approaches (CP payback period differences).

5 Discussion and policy recommendations

Summary By relying on the intertwining of literatures in biophysics and economics, this paper gives a warning about the failure of European energy policy to correctly internalise LUC emissions costs in economic appraisals. Current LUC analysis in the context of biofuel production assumes an even distribution of emissions over time. This is at odds with biophysics research evidence and therefore distorts subsequent policy recommendations. The consequences are at two levels. First, assuming a uniform time distribution in appraisals, as done in the European RED (The European Commission, 2009) provides NPVs that do not reflect actual carbon releases (emissions) due to land use change, thereby jeopardising correct comparisons of projects. Second, as a support for decision-making, cost-benefit analysis may result in decision errors if policymakers rely on benchmarks (like payback periods). More accurately, assuming a uniform time distribution in economic appraisals may lead to implementation of projects that do not meet the environmental criteria specified by policymakers (when the carbon price increases slower than the discount rate), or non-implementation of projects that actually do meet such criteria (when the carbon price increases faster than the discount rate).

[23] In this case, the benchmark payback period would be violated under the differentiated but not the uniform approach.

Assumptions and limitations First, our analysis assumes that there is no correlation between carbon prices and the discount rate. While some economists may argue that the Hotelling rule should be applied to the evaluation of projects or that carbon prices cannot be disentangled from the discount rate, practice in the policy sphere is not fully consistent with such a statement. Rather, carbon prices and discount rate values derive from compromises resulting in carbon prices growing slower or faster than the discount rate (Hoel, 2009). It is worth reminding here that the paper draws on the assumptions made in the European Renewable Energy Directive, which affect cost-benefit analysis in practice. Therefore, the way carbon prices should evolve according to economic modeling is beyond the scope of the paper. Second, the CP payback period is studied without considering economies of scale in biofuel production, which may lead to overestimation of the payback period irrespective of the time distribution. With information on their magnitude, economies of scale can easily be integrated in the Python program by changing emission flows over time in raw data (see the supplementary material). Third, the analysis assumes constant discount rates. This seems reasonable when dealing with LUC emissions with a time horizon of only 20 years. For longer time horizons, however, it would be interesting to extend our framework to decreasing discount rates.

Extension to indirect land use change So far, in the numerical illustrations, we only dealt with direct LUC for the sake of simplicity, but the philosophy behind the model can apply to any phenomenon that entails the same carbon dynamics, thus including indirect LUC. It is worth emphasising that the magnitude of the bias can be expected to increase with the accounting of indirect LUC, which is currently a central issue in the European energy policy (see e.g. The European Commision (2014) and Bourguignon (2015)). The bias may even be greater if one considers time lags of indirect LUC materialisation, as put forward by Zilberman et al. (2013) and empirically tested by Andrade De Sá et al. (2013).

Suggestions of decision-making support tools Adoption of the (uniform) approach is common in policymaking and it is uncertain whether this will change in the near future. Indeed, quantifying LUC emissions in physical terms (excluding temporal considerations) is a challenge that still needs to be met (see the proposals by Bourguignon (2015)). Nonetheless, the lack of consideration of temporal distributions of LUC remains a concern. Thus, I recommend two tools to policymakers. When relying on the uniform approach, the compensatory rate indicates the direction of the bias (i.e. over- or under-estimation of the value of a project) induced by this (simplistic) uniform time distribution. It is then the responsibility of policymakers to reckon whether such a (direction of) bias is acceptable in the context of their analysis. As a second tool, I suggest the use of a benchmark CP payback period. In contrast to the carbon debt, the CP payback period is price-based. It provides the time period in which land use change costs to society are refunded and may thereby constitute a better signal for stakeholders than emissions restrictions, which are quantity-based. To go further, in the future when carbon pricing will be a natural part of private decision-making, providing such benchmarks may create an interesting instrument to incentivise firms to reduce emissions or increase carbon sequestrations.

Final policy recommendations **(1)** Given the state of the literature in biophysics, I would recommend policymakers to use the carbon response functions provided in Poeplau et al. (2011), which account for the decreasing time profile of LUC emissions.[24] The Python program provided in the supplementary material can support such a choice. **(2)** Acknowledging the lack of broad evidence on LUC time profiles (for e.g. various regions, soil types, agricultural practices), a reasonable and close-to-reality alternative would be to consider that the total emissions from land conversion is felt immediately instead of spread evenly over time. Compared with the uniform time distribution, this is indeed closer to the exponential decrease described in Poeplau et al. (2011). It is worth mentioning that the US biofuel policy (RFS2) has gone a step forward (compared with the European Union) by disentangling the two carbon sinks (soil and biomass). Biomass-related LUC emissions are fully accounted for at the time of land conversion while soil-related LUC emissions are uniformly distributed over time. A broader classification of the time distribution approaches used by policymakers is provided in Appendix C. **(3)** Considering the current state of European energy policy, I recommend the two tools described above to support in decision-making.

Appendices

A The sequestration case

This paper only dealt with the case of emissions, which is the main problem that biofuels pose. Nevertheless, as second-generation biofuels are progressively incorporated in the fuel mix, it is worth mentioning that our framework applies to the case of carbon sequestrations as well. The main difference is that, unlike emissions, sequestration is considered a social benefit since carbon is stored in the soil and biomass. The NPVs of sequestrations (index s) under the uniform approach are therefore positive. Also, the temporal distribution of sequestrations is less accurate in the biophysics literature compared with emissions. Still, the decreasing temporal profile of sequestrations seems to hold (see Qin et al. (2015) for a recent study). Formally, z_0 and z_1 now stand for sequestration flows instead of emissions and we assume $z_0 > z_1$. Formally, we have:

[24] Regarding sequestrations, Poeplau and Don (2014) and Qin et al. (2015) are interesting references even though research is less advanced for carbon gains than carbon losses.

$$NPV_u^s = p_0 \frac{z_0+z_1}{2} + p_0 \frac{(1+g)}{(1+r)} \frac{z_0+z_1}{2} \tag{7}$$

$$NPV_d^s = p_0 z_0 + p_0 \frac{(1+g)}{(1+r)} z_1. \tag{8}$$

This leads to Propositions 4, 5 and 6, which are related to the discounting effect, the carbon price effect and the combined effect, respectively.

Proposition 4 (discounting effect (sequestrations)) *Employing the uniform time distribution of LUC-related sequestrations increases the discounting effect. As a result, the value of projects involving such sequestrations becomes underestimated, i.e. the benefits of emissions become underestimated. The higher the discount rate, the larger the bias induced.*

Proposition 5 (carbon price effect (sequestrations)) *Employing the uniform time distribution of LUC-related sequestrations increases the carbon price effect. As a result, the value of projects involving such sequestrations becomes overestimated, i.e. the benefits of sequestrations become overestimated. The higher the carbon price growth rate, the larger the bias induced.*

Proposition 6 (combined effect (sequestrations)) *Under the Hotelling rule, no bias is induced by the uniform approach. When the Hotelling rule does not apply, employing the uniform time distribution in cost-benefit analysis causes a downward (upward) bias of the project value if and only if the carbon price grows slower (faster) than the discount rate.*

The proofs of Propositions 4, 5 and 6 are straightforward since these stem from the computation of the difference $\Delta NPV^s = NPV_u^s - NPV_d^s$ and its derivatives with respect to r (see eq. (9)) and g (see eq. (10)).

$$\text{With } r > 0, g = 0, \quad \Delta NPV^s = \frac{p_0\, r(z_1 - z_0)}{2(1+r)} \qquad \& \qquad \frac{\partial \Delta NPV^s}{\partial r} = \frac{p_0(z_1 - z_0)}{2(1+r)^2} \tag{9}$$

$$\text{With } r = 0, g > 0, \quad \Delta NPV^s = \frac{1}{2} p_0(z_0 - z_1) \qquad \& \qquad \frac{\partial \Delta NPV^s}{\partial g} = \frac{1}{2}(z_0 - z_1) \tag{10}$$

Regarding the tools suggested in this paper, only the compensatory rate is useful since projects that entail net sequestrations are always more pro-environmental than oil-related projects. This implies that there is no monetised carbon investment made at the beginning of the project and therefore no GHG savings and no payback period since the NPVs is positive over the whole time horizon.

B Proof of Proposition 3

$$\begin{aligned}
\Delta NPV &= NPV_u - NPV_d && (11)\\
&= -(p_0 \frac{z_0+z_1}{2} + p_1 \frac{z_0+z_1}{2(1+r)}) - (-p_0 z_0 - p_1 \frac{z_1}{1+r}) && (12)\\
&= -\frac{p_0(z_0+z_1)(1+r) - p_0(1+g)(z_0+z_1) + 2p_0z_0(1+r) + 2p_0(1+g)z_1}{2(1+r)} && (13)\\
&= -\frac{p_0}{2(1+r)}(z_0(g-r) + z_1(r-g)) && (14)\\
\Delta NPV &= \frac{p_0}{2(1+r)}(z_0 - z_1)(r-g) && (15)
\end{aligned}$$

Since by assumption $z_0 > z_1$, the sign of ΔNPV only depends on the sign of $r-g$.

C LUC emissions time distribution: formal description

The following formal definitions of the uniform and the differentiated approaches are implemented in the Python program to generate the numerical results provided in subsection 3.2 and Section 4.

Let's denote by SOC and VGC the carbon stocks in soil and vegetation (biomass), respectively, expressed in tonnes of carbon per hectare. Then, $\Delta SOC = SOC_F - SOC_I$ and $\Delta VGC = VGC_F - VGC_I$ are the carbon stock differences between land conversion and equilibrium achievement where I and F refer to initial (before conversion) and final (after conversion) lands, respectively. z_t is expressed in tonnes of CO2 per unit, *e.g.* hectare or tonne of ethanol, per year. z_t is decomposed into z_t^s and z_t^v the *annual* LUC emission from soil and vegetation, respectively. z_t^s and z_t^v are respectively spread out over the time horizons T^s and T^v. ω_s and ω_v are introduced as the respective shares of soil and vegetation carbon that are converted into CO2 emissions.[25] A is a constant that includes at least the coefficient of conversion of carbon into CO2.[26]

Definition 1 (uniform annualisation) *LUC emission flows are uniformly annualised $T^v \leq T^s$ and emissions due to soil and vegetation carbon releases are constant over time i.e. $z_t^s = z_{t+1}^s \ \forall t \leq T^s$ and $z_t^v = z_{t+1}^v \ \forall t \leq T^v$. Then, the total annualised LUC emission is*

$$\forall t = \{0,1,\ldots,T^s\}, \quad z_t = z_t^s + z_t^v = A\left[\omega_s \frac{\Delta SOC}{T^s} + \omega_v \frac{\Delta VGC}{T^v}\right]$$

$$\textit{with } z_t^v = 0 \ \forall t \geq T^v.$$

[25]Carbon losses may be deferred when carbon vegetation is stored in wood products such as furniture or buildings (Marshall, 2009; Tyner et al., 2010).

[26]Typically, $A = \frac{44}{12}$ (IPCC, 2006). For biofuel production, $A = \frac{44}{12k}$ where the constant k refers to the biofuel yield in tonnes of biofuel per hectare.

Definition 2 (differentiated annualisation) *LUC emissions flows are "differentially" annualised when $T^v \leq T^s$, $z_t^s \neq z_{t+1}^s \ \forall t \leq T^s$ and $z_t^v \neq z_{t+1}^v \ \forall t \leq T^v$. Then, the total annualised LUC emission is*

$$\forall\, t = \{0, 1, ..., T^s\}, \quad z_t = z_t^s + z_t^v = A\left(\omega_s\, \Delta SOC.f_s(t)\ + \omega_v\, \Delta VGC.f_v(t)\right)$$

$$\textit{with } z_t^v = 0\ \forall t \geq T^v.$$

f^s and f^v are continuous and monotonic functions of time that underlie the carbon response of soil and vegetation, respectively, to land conversion.

For a grassland or a forestland converted into a cropland, the SOC dynamic decreases exponentially according to the meta-analysis of Poeplau et al. (2011).[27]

Definition 3 (weak and strong definitions of LUC time distributions) *The uniform and differentiated annualisations are characterised by the exclusion and inclusion of a carbon stock dynamic. The distinction between weak and strong definitions of LUC time distributions relies on whether $T^v < T^s$ or $T^v = T^s$ as described in Table II.*

Table II: Weak and Strong Definitions of LUC time distributions

		Time Horizons	
		$\mathbf{T^v < T^s}$	$\mathbf{T^v = T^s}$
Carbon Dynamic	**No**	Weak Uniform	Strong Uniform
	Yes	Strong Differentiated	Weak Differentiated

Definition 3 allows us to categorise energy policies according to the time distribution they consider for LUC emissions. The uniform annualisation definition is strong in the sense that it is the extreme case of uniformisation: emissions flows (from both soil and vegetation) are equal over the same time period. This is a far cry from the real dynamic of LUC. By contrast, the differentiated annualisation definition is strong in the sense that soil and vegetation LUC emissions are distinguished in both their time horizon and their dynamic. The strong differentiated annualisation is the closest definition to what is described in the scientific literature. The European RED is based on the strong uniform annualisation definition with the assumption that $T^v = T^s = 20$, and the U.S. RFS2 policy is based on the weak uniform approach with $T^v = 1$ and $T^s = 30$. However, neither of them account for carbon (hence CO2) dynamics in either soil or biomass.

[27] Such that $f^s(t) = e^{-\frac{t-1}{a}} - e^{-\frac{t}{a}}$ where a is a constant. Poeplau et al. (2011) estimate a stock dynamic such that $\forall t$, $SOC_t = \Delta SOC(1 - \exp(-\frac{t}{a}))$. My focus lies on flows, hence the flow from the soil at time t is $z_t^s = SOC_t - SOC_{t-1}$. Note that regarding vegetation carbon stocks, if $T^v = 1$ *e.g.* clearing a forest, no dynamic of carbon is considered since only one flow occurs at $t = 0$.

D Data

Table III: Data Used for the Bioethanol Case Study in France

About	Choice/Value	Reference
Region	France	-
Biofuel	Bioethanol	-
Biomass 1^{st} generation	Wheat	Chakir and Vermont (2013)
Biomass 2^{nd} generation	*Miscanthus*	Chakir and Vermont (2013)
Project Starting Year	2020	-
Conversion rates	Historical rates till 2014	Oanda Conversion Data
Discount rates	From 0% to 5%	Florio (2014)
Project Time Horizon	20, $t = 0$ land conversion Period of production: 20 yrs from $t = 1$ to $t = 20$	See The European Commission (2009) and The European Parliament and the Council of the European Union (2015)
Carbon Price Projections	"Home-made" Shadow price of carbon in France	See subsection 3.2 of the paper Quinet (2009)
Crop Yields	Wheat: 7.5 t DM/ha *Miscanthus*:16.5 t DM/ha	Agreste IFP energies nouvelles
Process Yields	Wheat: 0.28 t eth/t DM *Miscanthus*: 0.32 t eth/t DM	IFP energies nouvelles
Climatic Region	$\frac{1}{3}$ warm temperate dry $\frac{2}{3}$ warm temperate moist	See Map in The European Commission (2010)
Soil Type	High Activity Clay Soil	The European Commission (2010)
Land Cover	Cropland, *Miscanthus*, Improved Grassland, Degraded Grassland, Forest	-
Agricultural Management	Wheat: 60% Full tillage & 40% No till *Miscanthus*: No till	Agreste
Agricultural Practices	Wheat: 70% High input without manure 30% with manure *Miscanthus*: Medium Input	Agreste
Coefficient shares carbon to CO2	Emi: $\omega_s = 30\%$ and $\omega_v = 90\%$ Seq: $\omega_s = 30\%$ and $\omega_v = 100\%$	See subsection 3.2 of the paper

Non-LUC emissions	Wheat *Miscanthus*	Biograce Hoefnagels et al. (2010)
Gasoline emissions	87.1 g CO2/MJ	Joint Research Centre (JRC WTT report Appendix 2 version 4a, April 2014)

E CP payback periods across carbon price scenarios and time distributions (Scenarios O, A, B, C)

Table IV: Payback Periods across Carbon Price Scenarios and Time Distributions

	Scenario	Unif. Annu.	Diff. Annu.	% Misestimation
A	$\{40, 5\%\}$	39	34	14.71%
B	$\{40, 3\%\}$	48	48	0%
C	$\{80, 1\%\}$	81	>150	-
O	$\{40, 0\%\}$	>150	>150	-

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