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Policy Papers

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PP 2016-07

Suggested citation:

M. Dupoux *(2016).* The land use change time-accounting failure.
FAERE Policy Paper, 2016-07.

The land use change time-accounting failure[*]

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Abstract

Land use change (LUC) is the second largest human-induced source of greenhouse gases. While LUC impacts are mostly immediate, policy makers consider it to be evenly spread over time. In the context of public evaluation of projects, I theoretically show that, as long as the discounting process perfectly offsets the rise of carbon prices, cost-benefit analysis outcomes are not affected. When this condition does not hold, which is particular to the global warming issue, the *uniform* time-accounting of LUC distorts present values by emphasizing both the discounting process and the increase in the carbon price over time. This induced bias is quantified in a case study of bioethanol in France. Depending on the type of impact and discounting and carbon pricing assumptions, a downward/upward bias between ±15% and ±30% of the LUC value is found. Two simple decision tools are provided to improve accounting of LUC impacts.

Keywords: cost-benefit analysis, public evaluation of projects, land use change, discounting, relative carbon price, non-constant impacts, bioethanol

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

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[*] I am particularly grateful to Laurent Faucheux for his valuable help in coding the Python program in the application part of the paper. I specifically thank Frédérique Bouvart, Vincent Martinet, Pierre Collet and an anonymous referee for their very useful comments and help in the search for data. I also thank Joe Vecci from Monash University, Daphné Lorne, Cécile Querleu, Benoît Chèze from the Department of Economics of IFPEN, Alain Ayong Le Kama from the University of Paris 10, Serge Garcia, Alexandra Niedwiedth, Raja Chakir, Stéphane De Cara from INRA, for their feedbacks.

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1 Introduction

It is common knowledge that the relative prices of environmental resources are important to prevent climate change. These prices are now progressively incorporated in the estimation of the value of the discount rate (Guesnerie 2004; Weikard and Zhu 2005; Hoel and Sterner 2007; Sterner and Persson 2008). As put forward by Hotelling (1931), the price of a resource changes at the discount rate. This was first established in the context of exhaustible resources and more recently applied to carbon prices (Aaheim, 2010). However, determining the change of carbon prices over time using the same methods employed for exhaustible resources is problematic for at least two reasons. First, the capacity of the atmosphere to store greenhouse gas (GHG) emissions is not fixed but limited, which makes it a renewable resource rather than exhaustible (Tol, 2013). Indeed, there is a natural carbon absorption which tends to raise the carbon price growth rate above the discount rate (Bowen, 2011). Second, climate change is surrounded by a large degree of uncertainty (Pindyck, 2012) which tends to decrease the carbon price growth rate compared to the discount rate (Gollier and Baumstark, 2009). Considering these two deviations from the Hotelling rule, the carbon price growth rate and the discount rate should differ unless the two effects perfectly offset each other. As a consequence, carbon pricing and discounting have different effects at each point in time. This is fundamental when evaluating projects which impact global warming, particularly when using cost-benefit analysis.[1]

This leads to the central question of the paper: when GHG impacts are not constant over time but considered as such, what are the effects on cost-benefit analysis outcomes? This question is important as it directly affects the public evaluation of GHG-related projects.[2]

I examine this question in the context of land use change (LUC). LUC, which constitutes the second largest source of human-induced GHG emissions (IPCC, 2007), is particular in that its impacts mostly occur immediately (De Gorter and Tsur, 2010; Broch et al., 2013). Put differently, its impacts are not constant over time. Despite this, many energy policies[3] such

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

[2] In practice, before their implementation, GHG-related projects go through an evaluation by policy makers which grant licenses whenever the project is welfare-improving. Otherwise, the application is rejected.

[3] Usually underpinned by life cycle assessment models, the most common approach to assess environmental impacts.

as the European Renewable Energy Directive (RED) and the U.S. Renewable Fuel Standard 2 (RFS2), examine LUC impacts over time in a *uniform* way *i.e.* under the assumption they are spread evenly over time[4] (Martin et al., 2010; Broch et al., 2012; Broch et al., 2013; Kløverpris and Mueller, 2013).

By connecting the literature on the time distribution of LUC impacts and the literature on relative carbon prices, this paper raises and overcomes the bias that policy makers may overlook when evaluating projects with non-constant GHG impacts. The paper also suggests two tools to improve accounting of LUC impacts over time within the cost-benefit analysis process.

In this paper, I compare the *uniform* and the *differentiated* annualization approaches. Contrary to the uniform annualization, the differentiated[5] approach accounts for the non-constant temporal profile of carbon in both soils and plants after a change in land use. To compare these approaches, I develop a simple theoretical model to first assess the direction of the bias induced by the uniform approach within a cost-benefit analysis framework. The results only rely on the assumption of diminishing impacts of LUC over time, which is supported by the biology literature (see Poeplau et al. (2011) and Qin et al. (2015) for recent studies).

It follows that the direction of the bias depends on the interplay between the discount rate and the growth rate of the carbon price. I find that, when the carbon price grows faster than the discount rate, the uniform approach induces a downward (upward) bias of the project value when GHG are emitted to (sequestered from) the atmosphere. A carbon price growth rate smaller than the discount rate generates the reverse. More generally, the uniform annualization emphasizes both the discounting overwhelming effect and the carbon price hike compared to what should be accounted for *i.e.* carbon (hence CO_2) changes as incorporated in the differentiated approach. This combined effect of the discount rate and relative carbon prices ties up with the literature on dual-rate discounting (Guesnerie, 2004; Weikard and Zhu, 2005; Hoel and Sterner, 2007; Gollier, 2010).

To underpin my theoretical framework, I quantitatively measure the magnitude of the bias through the case of bioethanol production in France. Only direct LUC is considered but the reasoning and conclusions can be extrapolated to indirect LUC, since the same physical mech-

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[4] *I.e.* regardless of the effective time profile of LUC impacts in both soils and vegetation.

[5] Differentiated because the accounting for carbon dynamics makes LUC impact flows different across years.

anisms underlie these impacts. A quantification of the bias is made in the case of a conversion of an annual cropland into a second-generation biofuel feedstock, *Miscanthus*, generating sequestrations of GHG. As an example, combining discounting (3%) and relative carbon prices (1% growth rate), a 16.14% upward bias of the LUC value due to the uniform time-accounting is found, the discounting effect dominating the carbon price effect. In the case where data are only available in the form of constant annual flows, I suggest the use of a simple tool, namely the compensatory discount rate, which informs decision makers about the direction of the misestimation.

Additionally, I introduce a second tool, the *carbon profitability* payback period. It is defined as the point at which a biofuel project starts to generate net carbon gains in monetary terms compared to conventional fuels. In this framework, LUC can be thought of as a *monetized carbon investment* since the initial impact constitutes a social cost in order to get future GHG savings[6] which are expected to counterbalance the initial impact (hence the payback period concept). Such a payback period can constitute an interesting decision tool or at least inform policy makers in the context of evaluation of LUC-related projects. I provide numerical evidence that this payback period is shorter (higher) in the differentiated than in the uniform approach when discounting applies stronger (weaker) to impact flows than the increase of the carbon price. The use of the uniform approach particularly in biofuel policies may be substantial and even reverse a decision about implementing or not a project depending on the decision criterion chosen by policies. This supports the importance of using the right data *i.e.* considering real CO_2 dynamics, before proceeding to the economic evaluation of any project with LUC impacts.

The remainder of the paper is organized as follows: Section 2 describes the peculiar time distribution of LUC and explains why a deviation from the Hotelling rule is required when it comes to impacts on global warming. Section 3 presents the model and the results. Section 4 offers numerical evidence with the case of bioethanol in France. Section 5 concludes.

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[6] Compared with conventional fuels.

2 Background

This section reports the two crucial elements whose interaction is at the origin of skewed economic evaluation of LUC-related projects, namely the time distribution of LUC impacts and the carbon price path considered within cost-benefit analysis.

2.1 *Land use change time distribution: effective vs. accounted for in policies*

LUC results in carbon stock changes after a land is converted to a new use, both in the vegetation and in the soil[7] which both constitute important carbon sinks. Many factors influence the magnitude of the disturbance: climate region, type of land converted, nature of the new land, agricultural practices. Depending on the carbon fraction of both the land which undergoes the change and the new land, the impact can occur in both directions: either a release of carbon generating GHG emissions[8], or a sequestration of carbon inducing GHG uptakes from the atmosphere.[9] Therefore it is crucial to understand the impact of LUC on carbon balances in order to reduce GHG emissions since it can either be beneficial or harmful to the climate.

Biofuels can constitute both an alternative to fossil fuels and a source of LUC. Changes in land use are the most important environmental impact of biofuels production (Feng and Babcock, 2010). They can either result from the replacement of other types of lands *i.e.* direct LUC[10] or from the displacement of existing crops *i.e.* indirect LUC[11] (Broch et al., 2012). Many energy policies in different parts of the world[12] foster a switch from fossil fuels to biofuels, resulting in an expansion of lands for energy crops hence an increase of LUC. As a consequence, considerable attention has been drawn towards the potential significant emissions due to LUC up to the possibility of switching a positive[13] environmental balance into a negative

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[7] Carbon in the soil is commonly named SOC, for Soil Organic Carbon.

[8] *E.g.* a forestland is converted into a cropland.

[9] *E.g.* afforestation.

[10] Direct LUC refers to the substitution of a given land for a cropland entirely dedicated to other uses such as energy crops.

[11] A cropland initially used for food supply purposes can be deviated from its original purpose for, say, energy purposes in a context of biofuel production. Since the initial food demand remains, the associated production may be partly displaced to previously non-cropland.

[12] *E.g.* the Energy Independence and Security Act of 2007 in the United States and the EU Renewable Energy Directive of 2009.

[13] In the sense that the environmental balance of biofuels is better than the oil's.

one (Searchinger et al., 2008; Tyner et al., 2010).

LUC from biofuel production can also help mitigate climate change. Lignocellulosic biofuels such as *Miscanthus*[14] have indeed the potential to increase carbon storage in soils specifically when replacing a cropland (Qin et al., 2015). Based on these findings, the main biofuel policies namely the Renewable Energy Directive (RED) in the European Union and the Renewable Fuel Standard (RFS2) in the United States, progressively include these impacts in the environmental requirements for the development of biofuel production.

Although this gradual consideration, LUC is characterized by a particular time profile which is not usually dealt with in the models on which policies are based.[15] Land conversion occurs just once as a shock, involving a decreasing temporal distribution of the impact by contrast to the steady time profile of emissions from *e.g.* feedstock cultivation or biofuel conversion. While the change in vegetation carbon stocks is in most cases instantaneous, the stock changes in the soil spread out over several years till the carbon stock reaches a new equilibrium (Marshall, 2009; Delucchi, 2011; Poeplau et al., 2011).[16]

The quantification of LUC impacts and their associated temporal dynamics is a difficult task. In life cycle assessments (LCAs) of biofuels, global warming impacts are totalled over a chosen period and divided equally across years (Martin et al., 2010; Broch et al., 2012; Kløverpris and Mueller, 2013). This straight line amortization method (henceforth *uniform* annualization) constitutes the basis of most biofuel policies, specifically the European RED.[17] Those take advantage of the simplicity and consistency of this approach but fail to account for the real dynamics of each carbon sink, henceforth *differentiated* annualization. The two different time distributions are illustrated in Figure 1 where the areas under the two curves are equal. This confusion is not an issue when only accounting for impact: as far as LCAs are

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[14] A perennial grass.

[15] A formal categorization of the American and the European energy policies regarding the time-accounting of LUC they employ is provided in Appendix D in Definition 3.

[16] In the case of emissions, LUC impacts divide into *(i)* a large upfront release of carbon to the atmosphere especially due to the above-ground biomass and *(ii)* smaller ongoing releases of carbon from the soil during a specific period of time (De Gorter and Tsur, 2010; Broch et al., 2013). In the case of sequestrations, which mainly refers to a land conversion from an annual cropland to a lignocellulosic feedstock such as *Miscanthus*, research still goes on regarding the dynamic of SOC. The general trend is though a decreasing profile of sequestrations in the soil over time (Qin et al., 2015).

[17] The U.S. policy (RFS2) goes forward by distinguishing vegetation and soil time horizons: emissions from vegetation are fully accounted for at time zero whereas soil emissions are equally scattered over 30 years. Nonetheless, there is no carbon dynamic.

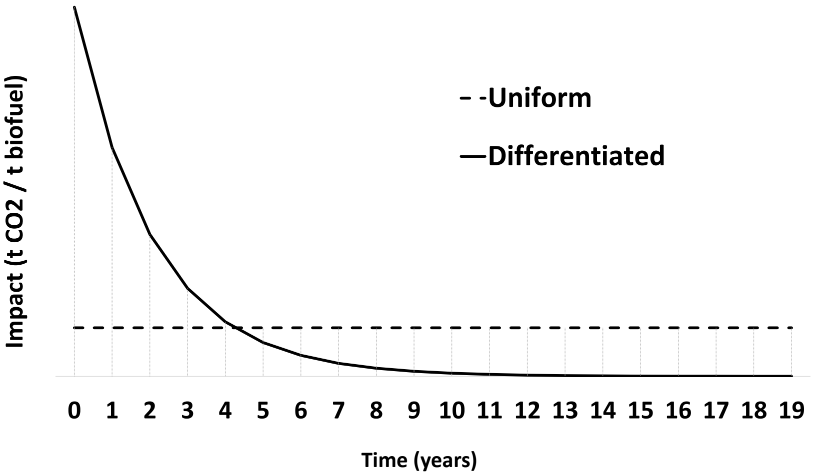

Figure 1: Time distributions of LUC impact flows: uniform annualization *vs.* differentiated annualization

founded on the summation of physical GHG flows and as long as no temporal parameter affect differently points in time, the two time allocations are strictly equivalent (De Gorter and Tsur, 2010). Beyond LCA though, the process of decision-making about whether or not to develop a biofuel production requires economic tools implemented to evaluate the social net benefit of the project in monetary terms. De Gorter and Tsur (2010) emphasize that the economic outcomes of under-policy GHG impacts must be assessed through cost-benefit analysis, beyond LCA methods.

2.2 *Carbon prices and the Hotelling rule*

Evaluating a project that impacts global warming requires *(i)* giving a monetary value to GHG emissions (usually to $CO_2 eq$) at each point in time and *(ii)* aggregating costs and benefits of the project over time by discounting them to a chosen time period. These two steps are fully part of the time dimension which characterizes a cost-benefit analysis, the common tool employed in economic assessments of projects.

A fundamental question in a context of public evaluation of GHG impacts is how does the carbon price grows over time? Most climate-economy models (hence policies) are run as if climate change were an exhaustible resource to which the Hotelling rule applies (Aaheim, 2010). It means that relative carbon prices follow from a standard Hotelling rule which results in a carbon price growing at the discount rate.[18]

However, it is crucial to depart from the well-known context of the theory to fully account for the global warming framework. Indeed, the Hotelling rule may not apply unless the two following reasons thoroughly offset each other. First, emissions of GHG can be absorbed naturally, which partially corrects the context by switching it into a renewable resource problem (Tol, 2013). Following this, the carbon price grows at a rate equal to the sum of the discount rate and the natural carbon absorption rate.[19] Indeed, a positive natural absorption generates additional decay thus encourages emissions today rather than in the future (Ulph and Ulph, 1994). This makes the carbon price rise over time at a faster pace than the discount rate (Greaker et al., 2009; Quinet, 2009; Becker et al., 2010). Second, the consequences of global warming are largely uncertain (Pindyck, 2012). Uncertainty particularly applies to damages in the future, technological progress and the efforts and cooperation necessary to the emissions reduction (Gollier and Baumstark, 2009). By accounting for uncertainty, economic agents[20] prefer to diminish the risk of climate change *e.g.* by making more efforts upfront (Stern, 2008). As a consequence, the carbon price is emphasized today, which counterbalances its slow growth (slower than the discount rate) further after (Philibert, 1999; Gollier and Baumstark, 2009; Anthoff et al., 2011).

Therefore these two features of global warming induce a potential deviation from the Hotelling rule that is, a growth rate of the carbon price which is not the same as the discount rate.

3 Theoretical framework

This section develops a simple two-period model to assess the direction of the bias induced by the uniform approach on cost-benefit analysis outcomes, depending on the involved temporal effect (discounting *vs.* relative carbon prices).

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[18] The capacity of the atmosphere to manage a certain concentration of GHG is treated as an exhaustible resource. The emissions cap (quotas) determines the amount of allowed emissions within a given period and this margin depletes over time as one emits GHG. Consuming the entire quota implies an equivalence between emitting one tonne of CO_2 today or in a year, which underlies that the carbon price increases at the discount rate.

[19] In the DICE model (Nordhaus, 2007), this rate is referred to as the "net carbon interest rate".

[20] Supposed risk-averse.

3.1 *The model*

Consider two periods $t = \{0,1\}$ and denote by z_t the effective impact flow occuring at time t. The model aims to compare the LUC-related net present value[21] (NPV) under the uniform (index u) and the differentiated (index d) annualization approaches. It also allows me to disentangle the effects of the two main parameters of the cost-benefit analysis namely the discount rate and the carbon price over time. The differentiated annualization preserves the effective flows at their respective time. By contrast, the uniform annualization which averages emissions over a chosen period of time (here 2 years) , modifies the effective flows z_0 and z_1 into $\frac{z_0+z_1}{2}$ $\forall t = \{0,1\}$.

Consider a project which generates LUC impacts from time $t = 0$ to time $t = 1$. The price of carbon grows at the carbon price growth rate denoted by $r_p \in \ [0;1]$ such that $p_0 \geq 0$ and $p_1 = p_0(1+r_p) \geq 0$. Denoting by $0 \leq r \leq 1$ the discount rate, the NPVs respectively associated to the differentiated and uniform approaches are as follows:

$$\forall z_0, z_1 \in \mathbb{R} \begin{cases} NPV_d = p_0 z_0 + p_0(1+r_p)\frac{z_1}{1+r} \\ \\ NPV_u = p_0 \frac{z_0+z_1}{2} + p_0(1+r_p)\frac{z_0+z_1}{2(1+r)} \end{cases} \qquad (1)$$

So far, I did not specify the nature of the impact z_t. Henceforth, based on the literature about the dynamic profiles of emissions and sequestrations put forward in Section 2, I rely on the following assumption.[22]

Assumption 1 (Emissions and sequestrations time monotonicity) *Emissions are considered as a social cost ($z_t < 0 \ \forall t$) whereas sequestrations are considered as a social benefit ($z_t > 0 \ \forall t$). Both impacts in the conversion year are greater than impacts at the next time i.e. formally $|z_0| > |z_1|$.*

In the following subsections, Equation 1 is divided into specific cases which correspond to

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[21] Which is a component of the more global NPV which accounts for both economic and environmental impacts.

[22] To keep the model general, I do not specify the functional form of the carbon dynamics but only the time monotonicity. Indeed, as highlighed in Poeplau et al. (2011), the functional form for one conversion (*e.g.* linear, exponential or polynomial) does not necessarily hold for other conversion types.

particular values of the discount rate and the carbon price growth rate. Considering the differentiated annualization as the baseline, I assess the bias induced by the uniform approach.

3.2 *Discounting effect ($r_p = 0$ and $0 < r \leq 1$)*

To isolate the discounting effect, I assume in this subsection that the carbon price is constant such that $p_0 = p_1 = p$. Denoting by $\Delta NPV = NPV_u - NPV_d$ the NPV difference between the two kinds of annualization, the resulting sign of ΔNPV gives information about the downward or upward bias generated by the use of the uniform annualization. Deriving the NPV difference relatively to the discount rate allows me to determine how the bias varies when the discount rate value changes. In other words, it indicates whether the bias is emphasized or reduced when the discount rate increases. I get:

$$\Delta NPV = \frac{p\, r(z_1 - z_0)}{2(1+r)} \qquad \& \qquad \frac{\partial \Delta NPV}{\partial r} = \frac{p(z_1 - z_0)}{2(1+r)^2} \tag{2}$$

The results are summarized in Proposition 1 whose proof is in Appendix A.

Proposition 1 (Discounting effect) *The uniform annualization emphasizes the process of discounting, which results in:*

- *an overestimation of the project value in the net emissions case;*
- *an underestimation of the project in the net sequestrations case.*

The higher the discount rate, the larger the bias for both cases.

Indeed, from Eq. 2, ΔNPV is positive (negative) in the case of net emissions (sequestrations) and the misestimation increases as the discount rate grows for both impacts.[23]

Emissions interpretation: Since emissions are equally scattered over time in the uniform approach, the emissions at $t = 1$ are overwhelmed by the discounting effect which softens the monetary cost of the impact and thus underestimates the costs of the project or equivalently

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[23] Regarding emissions, since $\Delta NPV > 0$, $\frac{\partial \Delta NPV}{\partial r} > 0$ implies an increasing bias. Regarding sequestrations, since $\Delta NPV < 0$, $\frac{\partial \Delta NPV}{\partial r} < 0$ means a more and more negative ΔNPV as r increases, hence an increasing bias as well.

overestimates the project value. On the contrary, in the differentiated approach, the emissions are mostly gathered at $t = 0$ hence not subject to discounting; therefore, the costs associated with these upfront emissions are fully accounted for.

Sequestrations interpretation: The dynamic of sequestration being taken into account in the differentiated approach, the sequestered quantities are higher at $t = 0$ than $t = 1$ (Assumption 1) thus less subject to the discounting pressure than in the uniform approach. In the latter though, sequestrations are relatively more accounted for at the end of the project when discounting applies, leading to the downward bias on the project value.

Generally, the discount rate exercises an increasing weight on GHG impacts in the future. Since *(i)* sequestrations are benefits to the society and mostly occur in the years following land conversion and *(ii)* emissions are costs to the society and mainly upfront, the scattering of impacts equally over time, stipulated by the uniform approach, induces an upward (downward) knock-on effect on the NPV when GHG are emitted (sequestered) to (from) the atmosphere.

3.3 *Carbon price effect ($r = 0$ and $0 < r_p \leq 1$)*

To isolate the carbon price effect, I apply in this subsection a discount rate equal to zero. Denoting by $\Delta p = p_1 - p_0 = p_0 r_p > 0$ the carbon price difference between the two periods, the NPV difference between the two approaches and its derivative with respect to Δp are:

$$\Delta NPV = \frac{1}{2}\Delta p(z_0 - z_1) \qquad \& \qquad \frac{\partial \Delta NPV}{\partial \Delta p} = \frac{1}{2}(z_0 - z_1) \tag{3}$$

which leads to Proposition 2 proved in Appendix B.

Proposition 2 (Carbon price effects) *The uniform annualization enhances the increase of the carbon price over time, which results in:*

- *an underestimation of the project value in the net emissions case;*
- *an overestimation of the project in the net sequestrations case.*

The higher the carbon price growth, the larger the bias for both cases.

Indeed, ΔNPV is negative (positive) in the case of net emissions (sequestrations) and the bias increases for both emissions as the carbon price grows faster.[24]

Emissions interpretation: Because the carbon price is increasing over time, the earlier the emission the lower its 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 thus more emissions are priced higher at time $t = 1$. Higher priced emissions constituting an emphasized cost leads to an understated NPV under the uniform approach.

Sequestrations interpretation: Sequestrations are mostly accounted for at $t = 0$ in the differentiated approach hence given a smaller value than in the uniform approach. This overestimates the project value under the uniform approach and all the more the carbon price scenario is constraining.

The scattering of GHG impacts over time in the uniform approach emphasizes the carbon price effect compared with the differentiated approach *i.e.* flows are given more value regardless the sign. However, as sequestrations are environmental benefits and emissions are environmental costs, the former has an upward knock-on effect on the NPV whereas the latter induces a downward knock-on effect.

3.4 *Combined discounting and carbon price effects*

As showed in the two previous subsections, the uniform annualization enhances both the discounting overwhelming effect and the carbon price increase. Those have opposite impacts on the NPV. Here, the two effect are combined as to determine the dominant one. Evaluating the NPV difference between the two approaches results in opposite conditions for the net emissions case and the net sequestrations case. Propositions 3 and 4 are based upon the results in Table I

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[24] Since $\Delta NPV < 0$ in the case of emissions, $\frac{\partial \Delta NPV}{\partial r} < 0$ means that ΔNPV is more and more negative involving an increasing bias. Regarding sequestrations, since $\Delta NPV > 0$, $\frac{\partial \Delta NPV}{\partial r} > 0$ also implies an increasing bias as well.

and proved in Appendix C.

Table I: Results of the combined discounting and carbon price effects

Emissions	Sequestrations
$\Delta NPV = 0 \Leftrightarrow r_p = r \quad (a)$	
$\Delta NPV > 0 \Leftrightarrow r_p < r \quad (b_{emi})$	$\Delta NPV > 0 \Leftrightarrow r_p > r \quad (b_{seq})$
$\Delta NPV < 0 \Leftrightarrow r_p > r \quad (c_{emi})$	$\Delta NPV < 0 \Leftrightarrow r_p < r \quad (c_{seq})$

Proposition 3 (Combined effect under the Hotelling rule) *Under the Hotelling rule, no bias is induced by the uniform approach: the uniform and differentiated annualizations result in the same value of the project whether greenhouse gases are emitted to or sequestered from the atmosphere.*

There is no bias induced by the uniform annualization (case (a)) when discounting and carbon price effects perfectly offset one another. Distributing the impacts uniformly or differentiately gives the same NPV of the project since the temporal parameters at stake thoroughly balance out each other. This situation underlies that the construction of the carbon price trajectory either stricly follows the Hotelling rule or involves a perfect compensation between *(i)* the uncertainty surrounding climate change which tends to diminish the growth rate of the carbon price and *(ii)* the natural absorption of CO_2 emissions which on the contrary tends to elevate it. The latter is one of the conclusions drawn out of the shadow value of carbon report in France (Quinet, 2009).

Proposition 4 (Combined effect out of the Hotelling rule) *When the carbon price time evolution deviates from the Hotelling rule, the uniform annualization approach induces :*

- *an upward bias of the project value if and only if the carbon price grows slower (faster) than the discount rate, in the case of net emissions (sequestrations);*
- *a downward bias of the project value if and only if the carbon price grows faster (slower) than the discount rate, in the case of net emissions (sequestrations).*

Emissions interpretation: The upward bias (case (b_{emi})) comes from the discounting effect which outweighs the carbon price effect. In other words, the discounting effect overwhelms the global warming impacts of the project faster than the carbon price raises. This effect is partly avoided in the differentiated approach since most emissions are immediate when no discounting applies. The uniform distribution of the total impact over time though suffers more from this outcome. In monetary terms, it means that the cost of upfront emissions is given relatively more value in the differentiated approach, leading to an overestimation of the project. A lower growth rate of the carbon price than the discount rate puts forward the uncertainty about the magnitude of the damages of climate change. This view calls for a strong price signal today to incentivize the reduction of emissions immediately.

By contrast, the uniform approach understates the project value when the carbon price effect dominates the discounting effect (case (c_{emi})), which allows GHG impacts to gain (monetary) value over time even after discounting: the undiscounted initial emission in the differentiated approach is then counterbalanced by the increasing price of carbon which applies to the ongoing impacts over time in the uniform approach. The differentiated approach benefits virtually nothing from increasing the price, since emissions are mainly upfront. Such a situation where the annual growth rate of the carbon price is greater than the discount rate is likely to occur when the natural absorption of CO_2 is not negligible.

Sequestrations interpretation: The upward bias (case (b_{seq})) comes here from the carbon price effect which outweighs the discounting effect. The same logic as emissions applies since most sequestrations occur right after land conversion. Nevertheless, in monetary terms, sequestrations are benefits. Those are raised by the carbon price increase in the uniform approach leading to such an overestimation of the project value. On the contrary, the downward bias (case (c_{seq})) comes from the dominant discounting pressure which overwhelms the monetary flows of sequestration in the uniform approach, resulting in an undervaluation of the project.

4 Numerical illustration

Bioethanol constitutes an alternative to gasoline. It can be produced from a variety of feedstocks such as wheat, corn, sugarbeet (first generation biofuels), switchgrass, *Miscanthus* (second generation biofuels). The production of first generation bioethanol is well-established at the commercial scale in contrast with the second generation which is more recent. However, the Futurol project[25] initiated by French stakeholders will be launched in 2016 to produce second generation bioethanol. France is the first bioethanol producer in Europe and the second consumer after Germany. It is located in a temperate region where the increasing demand in bioenergy currently leads to more and more LUC (Poeplau et al., 2011). The lands which are likely to be converted for both first and second generations are: croplands, grasslands and less likely forestlands (Chakir and Vermont, 2013).[26] The two types of biomass I consider in the analysis are wheat for the first generation and *Miscanthus* for the second generation of biofuel, which is representative of the feedstocks used in France.[27]

4.1 *Scope and assumptions*

As a locally assessed change, direct LUC is easier to estimate than the global-scale issue of indirect LUC which involves market responses (Feng and Babcock, 2010). Estimating indirect LUC is more complex since it can occur in a different location from the one where biofuels are produced. It particularly involves various market mechanisms (Broch et al., 2013; Zilberman et al., 2013) (see for example Keeney and Hertel (2009)). Thus, to avoid controversy about how to measure indirect LUC, I only focus on direct LUC. Still, as shown below, the impact of direct LUC is remarkable. Nonetheless, all the results in this section extend to the issue of indirect LUC.

I argue it is reasonable to use a 20 year time horizon[28] for a number of reasons. First this is the time horizon considered in the Renewable Energy Directive in Europe (The European Commission, 2009). Second, the lifetime of an industry producing ethanol is often about 20

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[25] Futurol is one of the top five international second generation bioethanol projects in the world.

[26] Indeed, despite the regulations which prohibit the conversion of high carbon land types, grasslands and some forestlands are still respectively ploughed and cleared because the incentive to develop energy crops is considerable.

[27] To get an idea of the scale of LUC impacts due to French bioethanol compared to the other emission types, wheat-based ethanol generates LUC emissions which account for 23% of the environmental balance: 46.2 gCO_{2eq}/MJ for the overall process and 14 gCO_{2eq}/MJ for LUC. These data come from Chakir and Vermont (2013) and the IFPRI report Laborde (2011).

[28] Time $t = 0$ refers to the land conversion. The production starts at $t = 1$ once the biomass is mature, ready to be used and time $t = 20$ refers to the end of the biofuel production. Note that I consider the project always starts in 2020. Additionally, I hypothesize that, as an annual crop such as wheat, *Miscanthus* is mature within a year instead of two or three in reality for the sake of simplicity.

years (Humbird et al., 2011). Third, the second generation crop considered in this paper *i.e. Miscanthus* has a producing life of around 20 years (Khanna, 2008). Fourth, the temporal dynamics of SOC changes are assumed to occur over 20 years (IPCC, 2006). Fifth, uncertainty increases the longer the time horizon (see Stern (2008)). Finally, I assume that biofuels are more often considered a transition technology rather than a long run technology as in Searchinger et al. (2008, supplementary material).

Regarding emissions (*i.e.* conversions of both grasslands and forests into a cropland in this section), I suppose that *(i)* SOC dynamics follow an exponential decrease based on Poeplau et al. (2011) and *(ii)* biomass-related impacts are instantaneous[29] (*i.e.* only accounted for at t_0) as put forward by De Gorter and Tsur (2010). Regarding sequestrations (*i.e.* when replacing an annual cropland by *Miscanthus* in this section), *(i)* I also consider an exponential decrease of sequestrations in the soil which can fit the description of Qin et al. (2015) while awaiting further research and *(ii)* I do not consider any carbon dynamic for the biomass since *Miscanthus* biomass is harvested every year for bioethanol production.

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 social discount rate found in Europe for cost-benefit analyses of projects and policies (Florio, 2014, p.187).

Finally, I construct trajectories of the price of carbon from 2020 as follows, characterized by the values pair $\{p_{2020},\ r_p\}$ with p_{2020} the initial price and r_p the carbon price growth rate:

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 which underpin carbon price scenarios in the literature. For example, it is not clear in the World Energy Outlook scenarios which assumptions are made about the discount rate value (which I make vary in my analysis). Scenario O is the baseline *i.e.* no carbon price growth. Scenarios A, B and

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

C illustrate different situations: in Scenario A, the price of carbon grows fast; in Scenario B, it grows slower from the same initial price; Scenario C, characterized by a high initial price, represents a strong value signal to reduce emissions hence to avoid abrupt climate change. Roughly, Scenario A is more in line with Nordhaus' idea of *climate policy ramp* (Nordhaus, 2007) which promotes a progressive cut 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; Stern, 2008).

4.2 *Data and computation*

The computation of LUC impacts relies on the formal definitions of the uniform and the differentiated annualizations as described in Appendix D. An overview of the necessary data to the study is provided in Appendix E.

Agronomic data: To determine carbon stocks in soil and vegetation, I rely on the guidelines provided by The European Commission (2010) which are based on the IPCC (2006). Such a calculation requires the following information: climatic region, soil type, agricultural management, agricultural practices (inputs level) and crop yields.

Environmental data: Regarding the shares of carbon which are translated into CO_2 impacts, I assume that 30% of the carbon stock in soil is translated into CO_2, which is in the range given by the Winrock database (see Table 1 in Broch et al. 2013) and very close to Tyner et al. 2010's assumption of 25%. I assume that the reverse is symmetric (same coefficients from carbon to CO_2 (emissions), and from CO_2 to stored carbon (sequestrations). Regarding the carbon stored in vegetation, I hypothesize that 90% is translated into global warming impacts as the CARB policy in the United States assumes.[30] I suppose that the sequestration implies 100% of sequestrations of CO_2 transformed into carbon in biomass.

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[30] Tyner et al. 2010 assume that 75% is lost and Searchinger et al. 2008 suppose that 100% goes to the atmosphere.

Computation tool: I develop a Python program[31] to calculate the NPV of the GHG impacts of bioethanol projects. Once land use change impacts on SOC and biomass as well as their dynamic over time are determined, they are converted into CO_2 emissions or sequestrations according to Appendix D, and finally priced with one of the scenarios listed above.[32] Regarding price scenarios, an algorithm which exponentially extrapolates prices allows me to generate a complete trajectory of carbon prices over the time horizon considered, from one-time carbon prices as provided in most scenarios such as those from the Quinet report or the World Energy Outlook. The program essentially returns all the NPV types necessary to the analysis *i.e.* LUC impacts, non-LUC impacts and total global warming impact (*i.e.* LUC + non-LUC).

4.3 *Results*

The results on the discounting, carbon price and combined effects exclusively refer to the net CO_2 sequestration case (conversion from an annual cropland to *Miscanthus*). Other land cover results (forestland/grassland into cropland) are provided in Appendix F and complement the illustration of Propositions 3 and 4. Only the last part regarding the borrowing effect, in which an emission is necessary for the analysis, deals with a conversion from a grassland to an annual cropland. Since there are no scale effects regarding emissions or sequestrations in terms of LUC from the production of one unit of bioethanol, I consider a trajectory of one tonne of bioethanol per year for 20 years for simplicity.

Discounting effects: To study the discounting effect, the price of carbon is set constant and equal to 40€ in 2020 ($t = 0$) *i.e.* Scenario O. As a consequence, all the differences in the NPVs across the two time distributions are exclusively attributed to the discounting effect. An underestimation induced by the uniform approach compared to the differentiated one is clearly put forward in Figure 2.[33] The underestimation raises from the lower sequestrations accounted for in the beginning of the project which are not subject to the discounting process. With only a 1%

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[31] Namely "CBA calculator". The program (complete tool) and associated input data are provided in the Data In Brief linked to this paper.

[32] Referring to Appendix D regarding the differentiated annualization (Definition 2), the program determines the coefficient *a* of the carbon response function as mentioned before, while taking into account the associated time horizon (for soil or vegetation).

[33] Since a net sequestration of CO_2 from the atmosphere is considered here, the NPVs are positive.

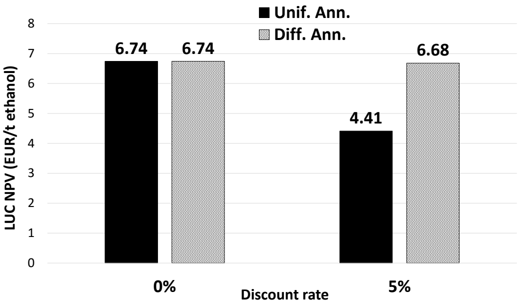

Figure 2: Discounting effects

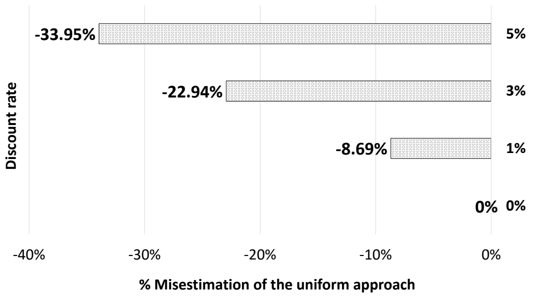

Figure 3: Relative downward bias induced by the uniform approch across different discount rate values

discount rate, there is almost a 9% downward bias of the LUC value because of the uniform approach, as pointed out in Figure 3. It increases till around 34% with a 5% discount rate, which is not negligible.

Carbon price effects: The discount rate is set to 0% in order to isolate the carbon price effect. An overestimation induced by the uniform approach compared to the differentiated one is clearly noted in Figure 4. Figure 5 quantifies in relative terms the errors induced by the uniform annualization on the LUC value. The overestimation comes from the higher sequestrations occuring at the end of the project in the uniform approach when higher prices of carbon are applied. As also shown in Figure 5, the higher (*i.e.* more constraining) the carbon price scenario, the larger the overestimation. There is a consequent bias especially with Scenario A (overvaluation of around 64%).

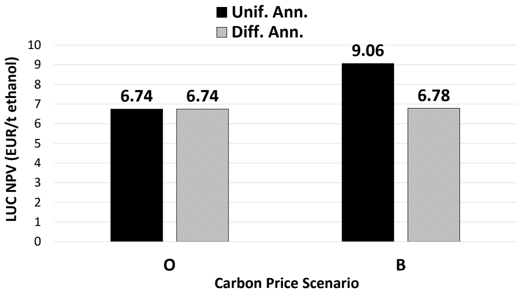

Figure 4: Carbon price effects

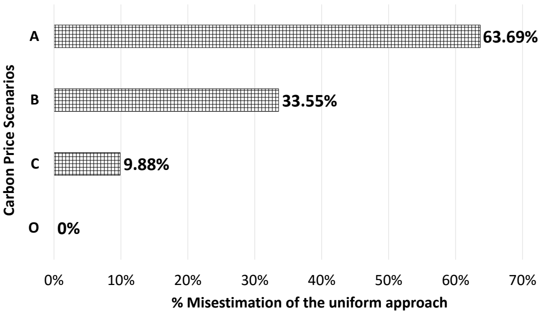

Figure 5: Relative upward bias induced by the uniform approach across different carbon price scenarios

Combined effects: Here, I consider a 3% discount rate and an increasing price of carbon. As a result, the uniform annualization induces either an underestimation of the LUC value if the discounting effect dominates the carbon price effect or an overestimation if the reverse holds.

Scenario	Initial Price	Growth Rate
A	40	5%
B	40	3%
C	80	1%
O	40	0%

Figure 6: Combined dicounting and carbon price effects: bias induced by the uniform approach

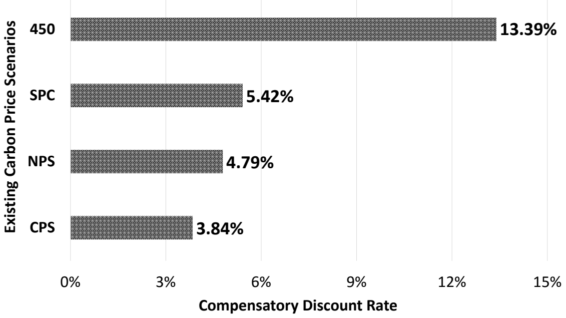

Figure 7: Compensatory discount rate for carbon price reference scenarios

Fixing the discount rate at 3% and varying the scenarios of the carbon price give Figure 6. It echoes Proposition 4 since in Scenario A, the carbon price (5%) grows faster than the discount rate, which results in an overestimation. In Scenarios O and C, the discount rate is greater than the carbon price growth rate hence the illustrated underestimation. Scenario B underlies a carbon price which grows at 3% thus perfectly offsets the discounting effect and implies an equivalence between the uniform and the differentiated approaches as stated in Proposition 3. On average, a fifth of the LUC value is either over- or underestimated because of the uniform way of accounting for LUC, which is considerable and calls for a correction of this bias.

Calculating the compensatory discount rate necessary to cancel the bias induced by the uniform annualization brings some interesting information when studying existing reference scenarios such as the French shadow price of carbon[34] (SPC) from Quinet (2009) and the World Energy Outlook scenarios (IEA, 2015) as put forward in Figure 7. This is the implicit discount rate that should be used in cost-benefit analysis to reach equal outcomes from both the uniform and the differentiated approaches. It particularly depends on the emissions or sequestrations flows generated by the LUC and the chosen time horizon. The calculation of such a discount rate can constitute a decision tool for policymakers. Indeed, for a given impact (net emission or sequestration) and a given carbon price scenario, if *(i)* policy makers are provided evenly spread over time LUC impacts data, as usually done by LCA models, and *(ii)* they choose a different

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[34] In the Quinet report, the shadow value of carbon is supposed to be 32 EUR in 2010 and 100 EUR in 2030. From 2030, the price increases at the public discount rate fixed at 4%.

discount rate than the compensatory discount rate while evaluating submitted projects, then according to Proposition 4, they have the information about the direction of their estimation bias.

Referring to Figure 7, Scenarios CPS, NPS and SPC result in average discount rates of the magnitude 4-5%, which is close to market rates (Greaker et al., 2009) as would probably support Nordhaus in contrast to Stern.[35] In particular, the 450ppm scenario underlies a very high discount rate of 13.39% compared to the usual discount rates employed in public project evaluation (Florio, 2014). The latter could either be interpreted as an unfeasible path or call for a necessary deviation from the Hotelling rule hence a real carbon dynamic accounting in cost-benefit analysis. Overall, as long as decision makers depart from these discount rates while using the respective scenarios, the uniform approach distorts a project value. And even if one *imagines* that these discount rates were used for any project assessment by policies, the best alternative, in order to avoid such calculations, remains the accounting for effective impact flows as described in the biology literature and summarized in the differentiated annualization.

Borrowing effects: In contrast to the previous effects, the borrowing effect is studied in the context of the entire global warming impacts value *i.e.* both LUC and non-LUC emissions are accounted for in the NPV. The land conversion considered is from a grassland to wheat (emission). Ethanol projects are compared to oil production projects based on equivalent produced energy. In this study, GHG savings are allowed because aside from LUC emissions, the amount of GHG emitted from the production and consumption of oil is greater than the energy-equivalent GHG amount from ethanol production and consumption. I introduce the concept of *monetized carbon investment* which is illustrated in Figure 8.[36] LUC looks like a (shadow) carbon investment since the initial emission constitutes a social cost in order to get future GHG savings (hence relative carbon benefits) which are expected to counterbalance the initial impact hence generate carbon-related profits. The monetized carbon investment could also be considered as a borrowed (monetized) amount of carbon from the atmosphere which

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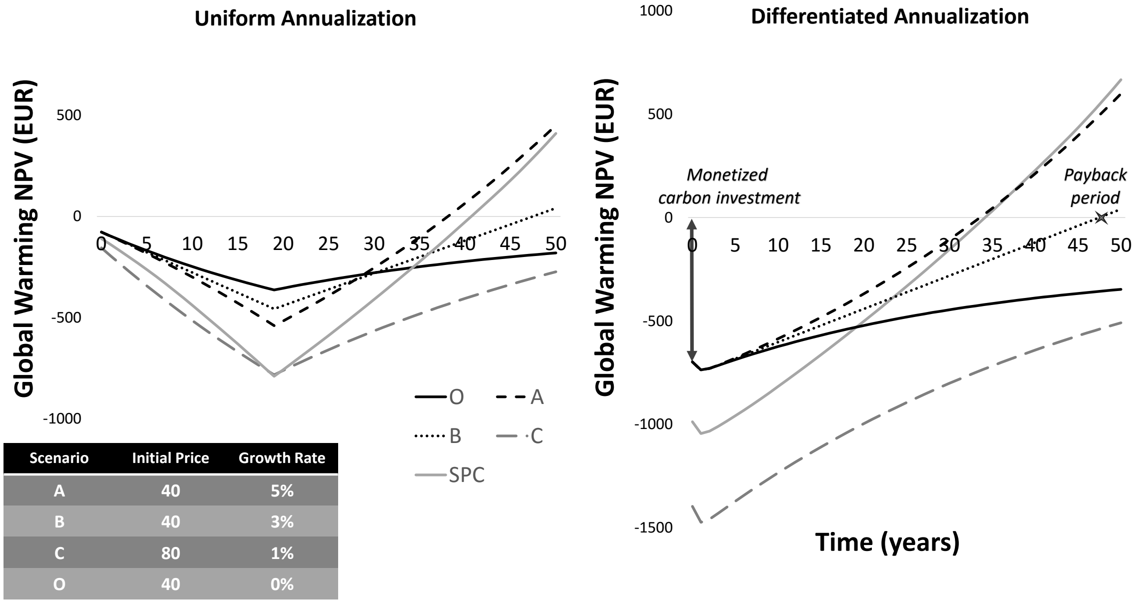
[35] Who argues for a 1.4% discount rate in his report.

[36] 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 which allows for "GHG refunding" starts at $t = 1$.

is "refunded" later in the future. The cross in Figure 8 illustrates the payback period of this carbon investment for Scenario B. The differentiated annualization provides clear information about the carbon investment initially made compared to the uniform annualization.



Scenario	Initial Price	Growth Rate
A	40	5%
B	40	3%
C	80	1%
O	40	0%

Figure 8: Monetized carbon investment payback periods across different carbon price scenarios and time distributions

Table II reports these *carbon profitability* payback periods under different carbon price scenarios and across the two time distributions.[37] Carbon profitability becomes positive (at the payback period) when a biofuel project starts to be environmentally profitable, that is when net GHG savings start to be effective in monetary terms. Such a payback period is important in that it can be compared to a payback period threshold defined either on a political or economic ground.[38] In scenarios A and SPC, the payback period is greater in the uniform than in the differentiated approach. The higher the growth rate of the carbon price, the shorter the payback period. In other words, the faster the price of carbon grows, the stronger the value signal and the more stakeholders are likely to invest in clean projects. Scenario B illustrates an equality between the uniform and the differentiated payback periods because of the underlying Hotelling approach (both the discount rate and the carbon price growth rate are equal to 3%). Scenario C is particular because the initial carbon price is very high: the value signal being

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[37] A discount rate of 3% is again assumed.

[38] Nowadays, the usual concept is the carbon debt which is exclusively physical. A payback period, as introduced in this paper, which is linked to monetary terms could constitute an additional signal, possibly more incentive-compatible, for firms to reduce emissions.

Table II: 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	$\{80, 1\%\}$	80	>100	-
O	$\{40, 0\%\}$	>100	>100	-
SPC	Quinet (2009)	41	35	17.14%

strong immediately, projects which involve a large amount of emissions cannot reach a carbon profitability within a reasonable period of time. Note that the payback period is this time greater in the differentiated than the uniform annualization. This is due to the discounting effect which dominates the carbon price effect in contrast to Scenarios A and SPC. This situation is in favor of the prevention of abrupt climate change (Stern, 2008): the stronger the initial carbon value signal, the higher the potential to prevent catastrophes due to climate change.

Some policy implications can be derived from the borrowing effect. Considering Scenario A, the project may pass the cost-benefit analysis test under the differentiated approach whereas it would not under the uniform annualization[39], which would penalize projects. Now considering Scenario C which accounts for uncertainty of climate change damages, a project assessed through the uniform approach in this case could pass while it would not under the differentiated approach. This is an important issue as it may be potentially harmful to the primary objective of cutting emissions.

A limit to the borrowing effect as studied here though is that potential scale effects regarding biofuel production are not considered. Indeed, the borrowing effect also involves non-LUC emissions from the process of production, thus it is subject to economies of scale. Intuitively, taking those into account should shorten the estimated payback periods for both time distributions since economies of scale would induce more energy efficiency in producing biofuels thus faster net GHG savings on the whole project time horizon. Nevertheless, nothing would change regarding the comparison between the uniform and the differentiated annualizations (over- *vs.* underestimation).

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[39] This would imply that a political or economic threshold is fixed at, say, 35 years.

5 Conclusions

At the very least, this paper warns about the LUC time-accounting failure in internalizing GHG impacts in economic appraisal of projects by policy makers. I put forward two arguments from two different literatures. First, when dealing with global warming, a departure from the widespread Hotelling rule regarding carbon prices is necessary. Indeed, the natural absorption of carbon tends to raise the carbon price growth rate above the discount rate whereas the uncertainty surrounding climate change tends to the reverse. Second, LUC impacts decrease over time by contrast to the uniform time-accounting employed by policy makers. This is largely supported by the biology literature.

These two arguments are strongly intertwined. Studying the crossover between these two considerations, I provide evidence that the uniform annualization has knock-on effects on cost-benefit analysis outcomes: either an upward or downward bias of projects' NPV depending on *(i)* whether the project entails net emissions or sequestrations and *(ii)* whether the carbon price grows slower or faster than the discount rate. This is all the more important when the project entails net emissions thus can be harmful to the climate. It may lead to the implementation of a project which does not complete the environmental criteria initially imposed by policy makers (case of a slower carbon price increase than the discount rate), or the non-implementation of projects which actually satisfy these criteria (case of a faster carbon price increase). To deal with such a situation, I suggest policy makers use two very simple tools. First, in the case of an unavoidable use of the uniform approach, policy makers should estimate the compensatory discount rate which allows one to determine whether an outcome is upward or downward estimated. The second is the carbon profitability payback period. This may constitute a criterion for decision making regarding the implementation of a project. Also, in the future when carbon pricing will be completely part of private decision making, it may create an interesting means to incentivize firms to reduce emissions or increase sequestrations since it is a monetary-based concept. The general message for policy makers in this area is to substitute the uniform annualization method for the differentiated one since most GHG impacts occur right after land conversion. Therefore, it is necessary to change this accounting method within the LCA models which support (upstream) policies.

Regarding the case of bioethanol in France, only direct LUC has been treated so far in this paper but the philosophy behind the model can apply to any phenomenon which entails carbon dynamics. It is worth emphasizing that the magnitude of the bias must increase with the accounting of indirect LUC which is currently a central issue. It may even be greater if one considers time lags of indirect LUC materialization as stated by Zilberman et al. (2013) and empirically put forward by Andrade De Sá et al. (2013).

So far, the results of this paper are founded on a very simple model which in particular entails constant discount rates and growths of the carbon price. It would be interesting for future research to estimate these biases under hyperbolic discounting which is currently the trend in the climate change debate around discounting (Arrow et al., 2013).

Appendices

A Proof of Proposition 1

$$\begin{aligned}
\Delta NPV &= p\left(\frac{z_0+z_1}{2}+\frac{z_0+z_1}{2(1+r)}-z_0-\frac{z_1}{1+r}\right) && (4)\\
&= p\frac{(z_0+z_1)(1+r)+z_0+z_1-2z_0(1+r)-2z_1}{2(1+r)} && (5)\\
&= p\frac{z_0(-r)+z_1r}{2(1+r)} && (6)\\
\Delta NPV &= \frac{p\,r(z_1-z_0)}{2(1+r)} && (7)
\end{aligned}$$

$$\frac{\partial \Delta NPV}{\partial r}=\frac{p(z_1-z_0)}{2}\frac{1+r-r}{(1+r)^2}=\frac{p(z_1-z_0)}{2(1+r)^2} \qquad (8)$$

Assumption 1 leads to $\Delta NPV > 0$ hence $NPV_u > NPV_d$ and $\frac{\partial \Delta NPV}{\partial r} > 0$ for emissions and $\Delta NPV < 0$ hence $NPV_u < NPV_d$ and $\frac{\partial \Delta NPV}{\partial r} < 0$ for sequestrations.

B Proof of Proposition 2

$$\Delta NPV = p_0\frac{z_0+z_1}{2} + p_1\frac{z_0+z_1}{2} - p_0z_0 - p_1z_1 \tag{9}$$

$$= \frac{p_0z_1 + p_1z_0 - p_0z_0 - p_1z_1}{2} \tag{10}$$

$$\Delta NPV = \frac{\Delta p(z_0 - z_1)}{2} \tag{11}$$

$$\frac{\partial \Delta NPV}{\partial \Delta p} = \frac{z_0 - z_1}{2} \tag{12}$$

Assumption 1 leads to $\Delta NPV < 0$ hence $NPV_u < NPV_d$ and $\frac{\partial \Delta NPV}{\partial r} < 0$ for emissions and $\Delta NPV > 0$ hence $NPV_u > NPV_d$ and $\frac{\partial \Delta NPV}{\partial r} > 0$ for sequestrations.

C Proof of Propositions 3 and 4

$$\Delta NPV = NPV_u - NPV_d \tag{13}$$

$$= p_0\frac{z_0+z_1}{2} + p_1\frac{z_0+z_1}{2(1+r)} - p_0z_0 - p_1\frac{z_1}{1+r} \tag{14}$$

$$= \frac{p_0(z_0+z_1)(1+r) + p_0(1+r_p)(z_0+z_1) - 2p_0z_0(1+r) - 2p_0(1+r_pz_1)}{2(1+r)} \tag{15}$$

$$= \frac{p_0}{2(1+r)}\left(z_0(r_p - r) + z_1(r - r_p)\right) \tag{16}$$

$$\Delta NPV = \frac{p_0}{2(1+r)}(z_0 - z_1)(r_p - r) \tag{17}$$

Relying on Assumption 1, the sign of ΔNPV only depends on the sign of $r_p - r$.

D Land use change impacts time profile: 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 Section 4.

Let's denote by SOC and VGC the carbon stocks respectively in soil and vegetation expressed in tonnes of carbon per hectare. $\Delta SOC = SOC_F - SOC_I$ and $\Delta VGC = VGC_F - VGC_I$ are then the carbon stock differences between land conversion and equilibrium achievement where the indices I and F respectively refer to initial (before conversion) and final (after conversion) lands. z_t is expressed in tonnes of CO_2 per unit *e.g.* hectare or tonne of ethanol, per year. It is decomposed into z_t^s and z_t^v the respective annual LUC impact from soil and vegetation which are spread out over T^s and T^v, their respective time horizons. ω_s and ω_v are introduced as the respective shares of soil and vegetation carbon which are converted into CO_2 impacts.[40] A is a constant which at least includes the coefficient of conversion of carbon into CO_2.[41]

Definition 1 (Uniform annualization) *LUC impact flows are uniformly annualized when* $T^v \leq T^s$ *and impacts on soil and vegetation are respectively constant over time i.e.* $z_t^s = z_{t+1}^s \ \forall t \leq T^s$ *and* $z_t^v = z_{t+1}^v \ \forall t \leq T^v$*. The total annualized LUC impact is then:*

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

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

Definition 2 (Differentiated annualization) *LUC impact flows are differentiately annualized when* $T^v \leq T^s$, $z_t^s \neq z_{t+1}^s \ \forall t \leq T^s$ *and* $z_t^v \neq z_{t+1}^v \ \forall t \leq T^v$*. The total annualized LUC impact is then:*

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

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

f^s *and* f^v *are continuous and monotonic functions of time which underlie the carbon response of respectively soil and vegetation to LUC.*

For a grassland or a forestland converted into a cropland, the SOC dynamic follows an exponential decrease according to the meta-analysis of Poeplau et al. (2011).[42]

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

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

[42] 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 is effective at $t = 0$.

Definition 3 (Declension in weak and strong definitions of LUC time distributions) *The uniform and differentiated annualizations are respectively characterized by the exclusion and inclusion of a carbon stock dynamic. The declension relies on whether* $T^v < T^s$ *or* $T^v = T^s$ *as Table III states.*

Table III: Declension in Weak and Strong Definitions

		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 to categorize energy policies according to the time distribution they consider for LUC impacts. The uniform annualization definition is strong in the sense that it is the extreme case of uniformization: impact flows (from both soil and vegetation) are equal over the same time period. This is the case which is at most a far cry from the real dynamic of LUC. By contrast, the differentiated annualization is strong in the sense that soil and vegetation LUC impacts are distinguished in both their time horizon and their dynamic. The latter case is as close as possible to reality.

The European RED is based on the strong uniform annualization 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 $T^s = 30$. Both though do not account for carbon (hence CO_2) dynamics either in soil or biomass.

E Data

Table IV: 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	-
Inflation rates	Historical rates till 2014	Worldwide Inflation Data
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 justifications in the last section of the paper
Carbon Price Projections	"Home made" Shadow value of carbon in France	See the last section 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 CO_2	Emi: $\omega_s = 30\%$ and $\omega_v = 90\%$ Seq: $\omega_s = 30\%$ and $\omega_v = 100\%$	See the last section of the paper
Non-LUC emissions	Wheat *Miscanthus*	Biograce Hoefnagels et al. (2010)
Gasoline emissions	87.1 g CO_2/MJ	Joint Research Centre (JRC WTT report Appendix 2 version 4a, April 2014)

F Land cover effects

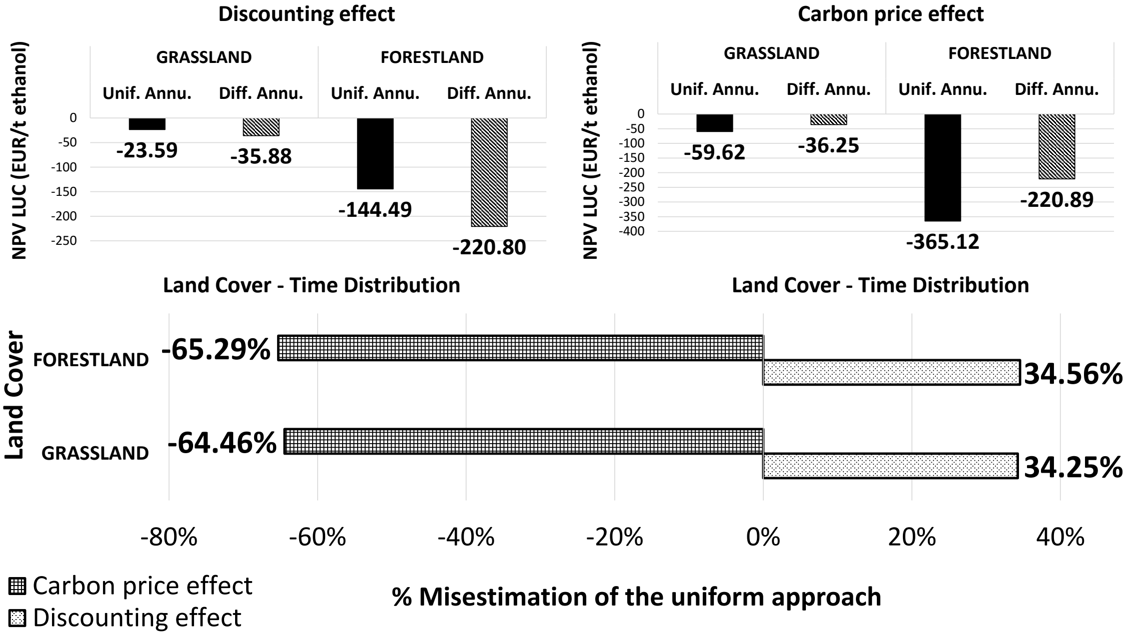

Figure 9: Discounting effects and carbon price effects across land conversions

The conversion either of a grassland or a forestland into an annual cropland is associated with an overestimation of the NPV regarding the discounting effect and an underestimation regarding the carbon price effect. Indeed, since emissions are considered as costs here, the NPVs are negative as shown in Figure 9. However, the negative NPV under the uniform annualization is greater (less negative) than the one under the differentiated approach in the discounting effect case (hence the overestimation). Similarly, the NPV under the uniform annualization is smaller (more negative) than the one under the differentiated approach in the carbon price effect effect case (hence underestimation). The combined effect results in around 30% for the two land conversions so the bias is even greater than in the net sequestration case illustrated in the last section of the paper.

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