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# COST-BENEFIT ANALYSIS OF FIRST- AND SECOND-GENERATION BIOFUELS BASED ON AN ECONOMIC VALUATION OF LIFE-CYCLE IMPACTS

Benoît Gabrielle<sup>1,\*</sup>, Yuanzao Zhu<sup>1</sup>, Stephan Marette<sup>2</sup>, Vincent Martinet<sup>2</sup>

1: AgroParisTech, INRA, UMR EcoSys, Université Paris-Saclay, Thiverval-Grignon, France.

2 : Economie publique, AgroParisTech, INRA, Université Paris-Saclay, 78850, Thiverval-Grignon, France.

\* corresponding author:

INRA, AgroParisTech UMR EcoSys, F-78850 Thiverval-Grignon, France.

E-mail: Benoit.Gabrielle@agroparistech.fr Phone: (+33) 1 30 81 55 51 Fax: (+33) 1 30 81 55 63

**ABSTRACT:** In the face of the current push for liquid biofuels worldwide, the design of policies compatible with sustainable development requires a careful and comprehensive analysis of their respective benefits and drawbacks. The environmental impacts of biofuels are usually quantified with life-cycle assessment (LCA), which provides indicators for a suitable range of impacts but leaves their prioritization up to decision-makers. Cost-benefit analysis (CBA) may be used to aggregate these impacts through an economic valuation of positive and negative effects on the environment. Here, we propose a simplified and ad hoc framework to combine LCA with CBA based on different valuations found in the literature, and apply it to a case-study comparing first- and second-generation biofuels in the Picardy region (northern France). The results were compared to 2 other methods already used to monetize externalities: the Eco-Cost method, and a method developed as part of the European Nitrogen Assessment.

In terms of LCA, 2G bioethanol from miscanthus emitted 30 to 90% less pollutants than its 1G counterpart from sugar-beet, due to its lower requirements in agricultural inputs. This was directly reflected in the ad hoc CBA results, with a 3 to 6-fold decrease between the external costs of sugar-beet and miscanthus ethanol for the 4 impact categories monetized. There was a large variation between the valuation methods, which varied within an order of magnitude. For instance, the eutrophication costs associated with sugar-beet ethanol varied from  $4 \cdot 10^{-4}$  to  $4 \cdot 10^{-3}$  €/MJ of biofuel. Compared to fossil fuels, miscanthus-based ethanol incurred an overall net positive externality of 0.1€/MJ of biofuel, which is on a par with the tax exemption level put in place by the French government for 2<sup>nd</sup> generation biofuels.

**Keywords:** biofuels, cost-benefit analysis, life-cycle assessment, miscanthus, sugar-beet, sustainability assessment, environmental externalities

## 1 INTRODUCTION

In the face of the current push for liquid biofuels worldwide, the design of policies compatible with sustainable development requires a careful and comprehensive analysis of their respective benefits and drawbacks. The environmental impacts of biofuels are usually quantified with life-cycle assessment (LCA), which has the advantage of providing indicators for a suitable range of impacts. In terms of decision-making, this raises the issue of how to aggregate across impact indicators to select among candidate chains. Cost-benefit analysis provides an interesting framework to address the multi-dimensional impacts of biofuels through an economic valuation of positive and negative effects on the environment [1].

There is currently a range of methodologies available to value the services provided by environmental goods. Some of these methods are indirect and use proximate values for environmental goods, other are direct but may present sampling biases and their results may not be easily transferred from one case-study to the next [2]. Based on *stated preferences*, contingent valuation and choice experiments seek to elicit willingness-to-pay (WTP) for non-market goods, generally through surveys [3]. These methods are prone to upward biases for WTP, since choices are hypothetical and not consequential with real payments. Other methods are based on *revealed preferences*. They include evaluation of damage costs, protection costs, transportations costs, or hedonic prices, establishing a link between actual economic behavior and prices (e.g., real estates prices for the hedonic prices method) and the environment. Even if economists prefer revealed preferences, the imperfect knowledge of consumers regarding environmental issues and the complexity of these issues impede the determination of

preferences and their internalisation via the market and the prices. Lastly, a single method cannot cover all the categories of impacts assessed with the LCA, ranging from ozone formation potential in the atmosphere to eutrophication of aquatic ecosystems through the depletion of abiotic resources [4].

Linking LCA impacts and economic valuation methods raises further challenges. First, LCA impact indicators are of a different nature than the drivers used in the economic valuation methods: they are expressed as the flux of a reference substance per functional unit (eg, the amounts of nitrates emitted throughout the production of one MJ of biofuel - [4]), whereas economic valuation methods are usually based on the consequences of the emissions. The latter, depend on the concentration changes induced by the total production in a given environmental compartment (such as water bodies), resulting in a potential damage (eg on the drinkability of water - [1]). Deriving an impact from an emission flux requires the estimation of several nested relationships linking emissions to concentrations and their consequences. Figure 1 presents conceptual relationships between these variables: impact indicators output by LCA should be related to a change in the state of an environmental compartment (soils, water, or air), translated into a perceived change in the properties of this compartment (eg, water visibility), which can be monetized using valuation methods.

Such links have not been formally established yet, although economic valuation of LCA impacts has already been reported. For instance, the Eco-Costs method directly translates mid-point impact indicators output by LCA into costs, based on marginal abatement costs [5] (mid-point indicators are impacts estimated at an intermediate point between the emission sources and the

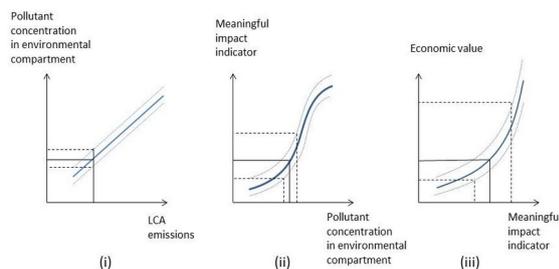


Figure 1. Conceptual relationships between (i) the life-cycle emissions of a pollutant (eg, nitrate) and its concentration change in a particular environmental compartment (eg, water bodies), (ii) this concentration and an indicator usable for economic valuation (eg, visibility), and (iii) this indicator and the economic value or cost in euros. Error bands around illustrate the uncertainty around the mean data points of the relationships, and its propagation through the chain.

ultimate damages caused by the substances released). Thus, Eco-Costs considers that the equivalence factors between substances involved in the same impact category as correct proximates of their relative costs compared to the reference substance of the characterization method, which is questionable. The EcoValue makes a similar assumption but relies on a wider range of valuation methods (involving also travel costs and restoration costs), some of which are difficult to transfer outside of the particular context of this study, in Sweden [6]. Other valuation methods only apply to a particular set of impacts (eg air pollution), or compounds (see [7] for reactive nitrogen – a method referred to as the European Nitrogen Assessment method - ENA). Lastly, the StepWise method was proposed recently to harmonize all externalities via the 'budget constraint', in which all impacts are referred to the value of one year of life for a healthy human being [8]. It has the advantage of using only a single value (corresponding to one month of life), but the equivalence factors on which to relate all impact categories of LCA appear difficult to apply in a wide range of contexts.

The variability of local contexts is an the reason why only a spatially-explicit and dynamic framework can accommodate the theoretical relationships presented on Figure 1 to link emissions to concentrations in an environmental compartment. These relationships depend on local environmental conditions and the biophysical processes governing the fate and impacts of the substances emitted by a particular value chain [9].

Here, we developed such an integrated approach combining ecosystem modelling, life cycle assessment, and monetary valuation of environmental externalities. We applied this generic framework to the assessment and comparison of first-generation biofuels (ethanol from sugar beet) and second generation biofuels (cellulosic ethanol from miscanthus) in the Picardy region in Northern France. The environmental externalities considered were climate change, as related to the emissions of greenhouse gases (GHG), eutrophication due to the leaching of nitrates to groundwater and to surface water bodies, photo-chemical ozone formation and human health.

## 2 MATERIALS AND METHODS

For the application of the proposed evaluation framework, we consider two bio-ethanol chains representative of the 1st and 2nd generation technologies, respectively, in the Picardy region (northern France). The first-generation chain is based on sugar-beet, for which Picardy is a major production area, while the 2nd generation one is based on miscanthus, a perennial grass with C4 photosynthesis. The idea is to compare the first generation chain biofuel situation with a hypothetical second generation chain biofuel situation (miscanthus being still in development). In the present situation, using 50 000 ha of arable land cropped to sugar-beet (a third of the total sugar-beet acreage of the region) for energy purposes would produce 0.5 Mt of bioethanol. Converting the same area to miscanthus would result in the production of a similar amount of bioethanol with the prospective 2nd generation technology [9].

The LCAs of the 2 biofuel chains are based on ref. [10], and are briefly summarized below, following the ISO standards. The functional unit was 1 MJ of biofuel energy content (lower heating value), with system boundaries correspond to a Well-to-Tank system, i.e. including all flows of resources, energies and pollutants from the extraction of raw materials up to ethanol dehydration. Indeed, since the focus was the impacts of the fuel production and more specifically of the agricultural production, we did not include the steps of fuel blending and distribution to the service station. Energy embedded in farm machinery and capital equipment was included.

The system was extended to take into account savings due to the substitution by co-products. Considered co-products of the sugar beet ethanol were pulps, lime-carbonation residue, vinasses and sugar. For each of these co-products an alternative product chain was designed according to local practices and based on the expertise of professionals from the region. For sugar, we used mass-baes allocation since a local substitute product would lead to consider the same sugar beet chain. The miscanthus conversion unit was based on a grass conversion to ethanol, used both substitution and economic allocation for the various co-products. Substitution concerned the energy costs avoided thanks to biogas production from vinasses. Economic allocation factors were then used for fibres and proteins from the biomass waste.

The link to CBA was developed for mid-point impacts of the LCA, characterized with the CML2 [4] – the latter is no longer up to date but was relied on in the economic valuation methods reported in the literature, and was thus used for comparison. Implementation of the framework proposed on Figure 1 was illustrated via an ad'hoc method based on different valuation approaches was applied to the case-study area (based on refs [11] and [12]). Four impact categories were considered in this study: eutrophication, human health (related to the presence of nitrate in drinking water), acidification and global warming. The valuation of impacts incurred by persistent organic pollutants and heavy metals was deemed too uncertain to be included in this analysis [12].

. Note that for human health only the impacts related to the losses of reactive nitrogen (Nr) were assessed here.

The framework proposed on Figure 1 was applied to a particular case-study in the Bay of Somme (Northern France), focusing on the emissions of nutrients (N and P).

An in-depth analysis on the field was beyond the scope of this paper which aims at illustrating a simple example of linking LCA with CBA, as related to water quality. The replacement of the sugar beet by the miscanthus in the area when switching from 1G to 2G biofuels may be expected to reduce water pollution of surrounding rivers and eventually of the Bay of Somme. We present a possible monetary benefit of the water improvement, as reflected by the turbidity of surface water at the outlet of the Somme river.

The monetary benefit B over a year linked to water improvement is computed as follows:

$$B = \Delta S / S \times T \times I \times P. \quad (1)$$

where  $\Delta S$  is the variation of the Secchi visibility, a measure of water turbidity, arising from the cropping of the sugar beet or miscanthus compared to the baseline land-use and visibility (S, in m). T is the number of tourists visiting the Bay of Somme over a year, and I is the average monthly income in France (€). We consider the monthly income related to visits during vacations. P is the proportion of income that citizens are ready to pay for an improvement of water. This proportion is coming from a literature review of papers using the travel cost methods and will consider several values because of the fragility of such figures.

Table 1 lists the different parameters of eq. (1) in the first column and the related values in the second column. Variations in Secchi disc visibility (S, in m) are related to the emissions of eutrophication compounds output by the LCA in nitrate equivalents (EP, in g NO<sub>3</sub> eq./MJ biofuel), through the following relationships:

$$NO_3^- = \sum EP * A_{bf} * Y_{MJ} * FF / DR \quad (2)$$

$$S = \exp \left[ 5 - 0.894 * \log \left( NO_3^- * 1000 \right) \right] \quad (3)$$

where NO<sub>3</sub><sup>-</sup> is the increase in nitrate concentration related to the cultivation of feedstock, A<sub>bf</sub> is the area cropped to biofuel feedstock (sugar-beet or miscanthus; ha), Y<sub>MJ</sub> is the amount of biofuel produced per ha of crop (in MJ/ha/yr), and DR is the discharge rate of the Somme river (~10<sup>9</sup> m<sup>3</sup>/yr). Parameter FF is an unitless fate factor accounting for the fact that only part of the nitrates leached below the root zone of crops actually reaches the river's outlet. It was set to 50% based on a study in Brittany (Western France – [13]).

Table 1 gives several estimations of the willingness to pay of people visiting the Bay of Somme. A conservative cost-benefit analysis tends to consider the lower estimate of the monetary benefit B.

An alternative method was used to monetize the impact of crops on surface waters, based on the relationship to real-estate pricing [12]. Two methods were also used to evaluate the impacts of nutrient losses to groundwater and its drinkability, based on water pricing and human capital [12]. Lastly, a shadow value of 32 € per tonne of CO<sub>2</sub> eq. emitted was used as recommended from a recent report in France [14].

Parameters	Values
Variation of the Secchi visibility <sup>a</sup>	1-15 cm
T, number of tourists over a year <sup>b</sup>	952 000
I, average monthly income <sup>c</sup>	€ 1629
P, the proportion of income <sup>d</sup>	
$P_{Min}$	0.005
$P_{Average}$	0.01
$P_{Max}$	0.018

<sup>a</sup> Authors' estimation.

<sup>b</sup> Tourist office of the Bay of Somme.

<sup>c</sup> French Statistics Yearbook (INSEE)

<sup>d</sup> Compilation of literature references [12]

Table 1. Numerical values and sources of the parameters of the equation expressing the benefits of producing biofuels on water quality in the Bay of Somme in Picardy (eq. (1) in text).

For comparison with previous work on LCA and externality valuation, two other methods were used to monetize environmental externalities: the Eco-Cost method [5], and the 'ENA' method developed as part of the European Nitrogen Assessment [7].

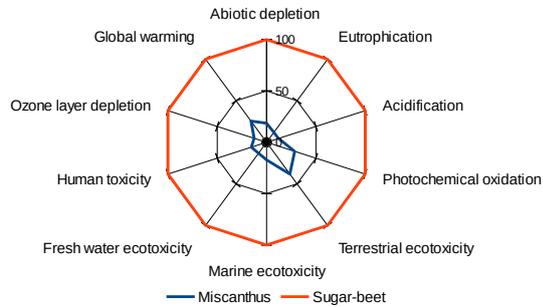
Table 2 summarizes the principles and the economic values associated with these two methods.

Impact category	Substances involved	Valuation method	Value	Ref.
Acidification	SO <sub>2</sub> eq.	Abatement costs	8.25 €	EC
Eutrophication	PO <sub>4</sub> <sup>3-</sup> eq.	Abatement costs	3.90 €	EC
	N <sub>r</sub> in water	Treatment costs, willingness to pay, productivity loss	5-20 €	ENA
	NH <sub>3</sub> -N, NO-N in air	Same as above	2-10 €	ENA
Human health	N <sub>r</sub> in water	Same as above	0-4 €	ENA
	NH <sub>3</sub> -N, NO-N in air	Same as above	2-20 €	ENA
	C <sub>2</sub> H <sub>4</sub> -eq.	Prevention costs	9.7 €	EC
Global warming	CO <sub>2</sub> eq.	Prevention costs	0.135 €	EC
	N <sub>2</sub> O-N	Productivity loss	5-15 €	ENA

Table 2: Impact categories assessed and valuation methods used for the case-study with the Eco-Cost method (EC; [5]) and the European N assessment (ENA) method [7]. Values are expressed per kg of substance contributing to the impacts.

### 3 RESULTS AND DISCUSSION

#### 3.1 Life-cycle assessment



**Figure 2.** Relative life-cycle impacts (in %) of the production of one MJ of bioethanol from sugar-beet and miscanthus in Picardy.

On a hectare basis, miscanthus fields emitted 4 times less nitrate and 25% less  $N_2O$  (a potent GHG) than sugar-beet (Table 3). Low levels of  $N_2O$  emissions are generally reported with perennial grasses in field trials, except during the establishment year [15], due to low fertilizer input levels and lack of build-up of mineral N in the topsoil. The same applies for the other losses of reactive N [15, 16], for similar reasons. The CERES-EGC model simulated a net deposition of ammonia on the miscanthus fields due to the assumption of a constant background atmospheric concentration of  $10 \text{ ng NH}_3\text{-N m}^{-3}$  for this gas, which is in the lower range of values reported for France, and the absence of ammonium build-up in the soil under miscanthus.

Figure 2 shows the relative life cycle impacts of both biofuels. On a MJ basis, miscanthus emitted 3 times less GHG and substances contributing to eutrophication. Switching from 1st generation to 2nd generation ethanol would therefore reduce the GHG emissions of the agricultural sector in the Picardie region and improve the quality of water bodies, while other impact categories would be abated by 70 to 90%.

On a MJ basis, Figure 2 shows that 2<sup>nd</sup> generation ethanol generated 80% less impacts than its 1<sup>st</sup> generation counterpart (Figure 2), which is in accordance with recent literature on the LCA of biofuels [17].

	Sugar-beet	Miscanthus
Nitrous oxide	0.48	0.38
Nitric oxide	1.39	0.28
Ammonia	5.53	-2.1
Nitrate	51.8	11.8

**Table 3:** Field emissions of reactive N under sugar-beet and miscanthus ( $\text{kg N ha}^{-1} \text{ yr}^{-1}$ ), as averaged over the Picardie region.

#### 3.2 Economic valuation

The second step to apply the monetization framework of

Figure 2 consisted of estimating the variations in Secchi disk visibility (S) with the 1G and 2G biofuel scenarios. The latter decreased by 15 and 1.5 cm with the sugar beet and miscanthus scenarios, respectively, in response to the 50 000 ha of crops established. Based on the hedonic costs method proposed here, and the parameters listed in Table 1, this lead to median externalities of  $3.02 \cdot 10^{-4}$  and  $2.36 \cdot 10^{-4}$  €, respectively (Table 4) - hence a 10-fold difference between both biofuels. The alternative method based on real-estate prices resulted in a similar gap, which may be expected since both valuations respond linearly to changes in nitrate concentrations in surface water. Interestingly, both methods yielded similar orders of magnitude, despite based on completely different variables. Note that the values used in the relationship between water quality (S) and real-estate prices were derived from a set of studies in regions possibly far remote from Picardy (the USA in particular -[12]).

Similar differences in the environmental performances of the 2 feedstocks and biofuels occurred with the other impact categories, directly reflecting the LCA results. There was 3-fold decrease for global warming between the external costs of sugar-beet and miscanthus ethanol for the 3 impact categories monetized (Table 4).

Impact category	Pollutants involved	Valuation method	Costs for 1G ethanol €/MJ	Costs for 2G ethanol €/MJ
Global warming	Greenhouse gases	Shadow price of $CO_2$	$1.82 \cdot 10^{-3}$	$5.44 \cdot 10^{-4}$
		Hedonic pricing	$3.02 \cdot 10^{-4}$ ( $1.46 - 5.25 \cdot 10^{-4}$ )	$2.82 \cdot 10^{-5}$ ( $1.37 - 4.92 \cdot 10^{-5}$ )
Eutrophication	Nitrates into surface water	Real-estate pricing	$5.90 \cdot 10^{-4}$	$5.55 \cdot 10^{-5}$
		Human health	Nitrates into ground water	Water pricing
		Human capital (wage)	$1.92 \cdot 10^{-2}$	$9.68 \cdot 10^{-3}$

**Table 4:** External costs of sugar-beet and miscanthus ethanol using the coupled LCA - CBA approach developed for Picardie. Two valuation methods were used for the eutrophication and human health impacts.

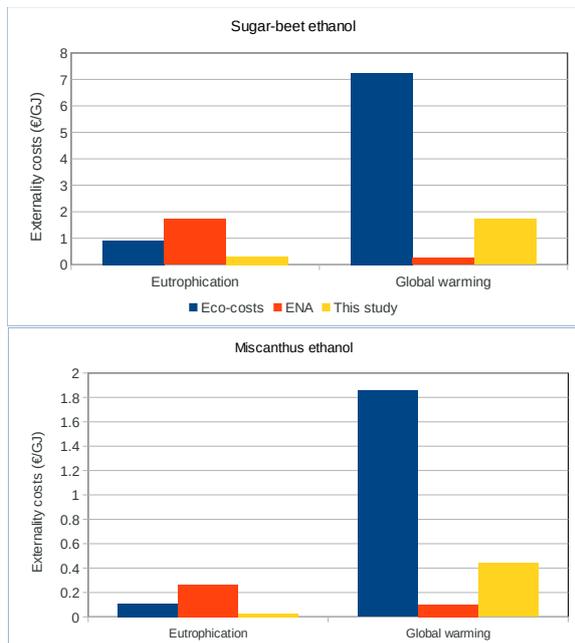


Figure 3. Estimates of costs associated with the production of one MJ of bioethanol from sugar-beet and miscanthus, with 3 valuation methods: Eco-Costs (blue bars), the European N Assessment method (orange), and an ad'hoc method developed for Picardie (yellow).

There was a large variation between the valuation methods, which varied within an order of magnitude (Figure 3). For instance, the eutrophication costs associated with sugar-beet ethanol varied from  $4 \cdot 10^{-4}$  to  $4 \cdot 10^{-3}$  €/MJ of biofuel, ie within one order of magnitude. The ranking of the 3 valuation methods in terms of costs also varied according to the biofuel chain and the impact categories, with no consistent pattern. There were differences in scope between the valuation methods, since for instance the ENA method factored biodiversity impacts in the monetization of eutrophication, which the other methods did not. This may explain the larger costs associated with its estimate compared to the other two methods.

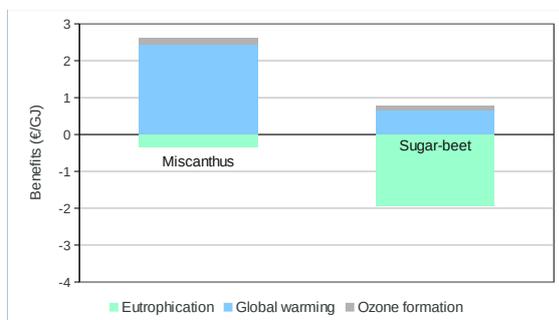


Figure 4: Cost-benefit analysis of substituting gasoline with bioethanol from sugar-beet and miscanthus, with the environmental externalities estimated in the Picardie region using the methodology proposed here.

### 3.3 Cost-benefit analysis of substituting gasoline

The externalities of the two biofuels were compared to those generated by gasoline, using for this chain the results from a recent LCA study commissioned by the French Environment Agency (ADEME - [18]). Three impact categories were included in the cost-benefit analysis: GHG emissions, ozone formation potential, and eutrophication (Figure 3). Valuation was done with the ad'hoc method proposed here for eutrophication, the Eco-Cost method for ozone formation, and the shadow value estimated for CO<sub>2</sub> in France (Table 2). Indirect land-use change effects related to feedstock production were included for both biofuel pathways based on a recent study reviewing the literature [19]. This resulted in an extra emission of 16 g CO<sub>2</sub>-eq./MJ of fuel for sugar-beet ethanol, and a nil factor for miscanthus.

The two bioethanol chains had lower impacts than gasoline for global warming and ozone formation, while only sugar-beet ethanol incurred a larger eutrophication impact. This resulted in positive externalities for the first two impact categories for bioethanol, and a negative one for the latter. Overall, only the 2G chain appeared to create benefit in terms of environmental externalities, ranging from 2 to 2.4 euros/GJ biofuel. The eutrophication impact generated by sugar-beet prevailed over the benefits from climate change and ozone formation mitigation compared to fossile gasoline, resulting in an environmental cost of 0.2 to 2.7 €/GJ, depending on the WTP value used for the eutrophication impact (Table 1). For comparison, the tax exemption level currently put in place by the French government in 2011 for ethanol is 0.66 €/GJ, which is several-fold smaller than the benefits estimated for miscanthus-based ethanol.

There are many limitations coming from this study and the conclusions that may be drawn from it. First, not all of the environmental impacts quantified with the LCA were considered in the analysis. A complete cost benefit analysis would require the extension of the methodology of Figure 1 to other impacts of sugar beet and miscanthus, namely air pollution (via the ozone formation potential of the LCA), soil pollution, or landscape preferences. Economic parameters, like the price of ethanol, the price of land, the supply chain profits and the employment in Picardie should also be taken into account. All these estimated benefits/costs could be added for being compared to the administrative costs such as the tax credit for promoting miscanthus.

It should be noted again that the way to transform all different impacts in monetary values is extremely fragile. The sub-additivity effect is particularly acute. The sub-additivity effect occurs when the estimated WTP for the improvement of one environmental characteristic plus the estimated WTP for another environmental characteristic is greater than the estimated willingness-to-pay when respondents are asked to value both environmental characteristics together [20]. This effect is particularly important when all the dimensions of the previous sections are considered.

Also, we focused here on impacts of either 1G bioethanol or 2G bioethanol, as if the regulator could impose either only 1G bioethanol or only 2G bioethanol in Picardie. This simplification overlooked the coexistence between both crops, which raises the issue of the farmers' incentives to adopt sugar beet for 1G bioethanol or miscanthus for 2G bioethanol (see [21]). This question also raises the issue of contracts between farmers and the industry, in particular for promoting miscanthus that is a perennial crop.

One extension would consist in organizing long a questionnaire (or even a field experiment) with people from Picardie and asking them about the policy they would prefer. We could present the different impacts of 1G and 2G bioethanol on eutrophication, human health, acidification and global warming (see impacts of Figure 2) and ask them their WTP.

#### 4 CONCLUSION

Although directly relevant to policy-making, cost-benefit analyses (CBA) are difficult to apply to biofuels and bio-based products in general because of the wide span of environmental impacts they should comprehend. The environmental externalities considered are usually restricted to GHG emissions, which are directly output by LCAs. Including other categories is challenging because of the complexity of valuing them and the large variability across estimation methods and geographical areas. Here we attempted to value the effect of producing 1G or 2G biofuels at regional scale in France, by building connections between LCA and CBA. There was a stark (up to 10-fold) variation among the 3 valuation methods used, depending on the impact category considered. Overall, the impacts of water appeared more costly than those on climate. Benefits incurred from substituting fossil gasoline with bio-ethanol were substantial for miscanthus-based ethanol, but less pronounced with sugar-beet. Thus, investing in 2G biofuels appears more sensible both from an environmental and economical perspective.

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