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Economic Assessment of the Impact of the Sugarcane Industry: An Empirical Approach with Two Focuses for San Luis Potosí, México

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Abstract: The sugarcane industry has a high environmental impact. In countries such as Mexico, cultivation and harvesting practices consume and pollute many ecological resources. However, quantifying these impacts is difficult due to their diverse nature and different units of measurement. In this study, an approach with two focuses was taken to assess the environmental costs of the sugarcane industry in San Luis Potosí, México. The first focus is human health costs related to air pollution (black carbon) and the second one is a lifecycle assessment applied to the production phase. In the first case, four scenarios, with different concentrations and populations, were projected. Costs of 516.8 thousand USD were estimated for a scenario in which black carbon concentrations exceeded the WHO reference by one unit for the total population. In the second case, costs of 642 million USD were estimated for the impairment of seven ecosystem-based services. These estimates may vary due to the source and specificity of the information provided, but nevertheless are considered an appropriate approximation of the cost of environmental damage. It is recommended that first-hand information be collected and systematized to improve the certainty of the estimates and that changes to sugarcane agrifood systems be considered to reduce environmental costs.

Keywords: pollution; indiscriminate use of resources; harmful practices; valuation

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1. Introduction

The impact of human activities on the planet can profoundly affect its ecosystems. Climate change, ocean acidification, permafrost thaw, habitat loss, eutrophication, storm water runoff, air pollution, and invasive species are just some of the problems they cause [1]. Their cumulative impacts and other pressures can have serious consequences for ecosystem functions and for the provision of goods and services [2]. All of these impacts impose costs that should be borne by polluters to reduce or repair the environmental damage caused by their activities [3].

Agriculture is a particularly vulnerable industry because it must feed a growing population in an adverse climatic environment while trying to minimize environmental and human health impacts [4]. However, to date, environmental impacts have been significant: food production accounts for more than one-third of global greenhouse gas (GHG) emissions, which includes emissions from agriculture, land use change, and the supply chain (transportation, packaging, food processing, retail, cooking, and waste) [5].

Emissions are quantified based on food production, not consumption. This means that they do not consider international trade. Half of all habitable land and 70% of the fresh water drawn are used for agriculture and cause 78% of the world's ocean eutrophication. Similarly, livestock accounts for 94% of non-human mammal biomass [6].

Some products have a particularly high environmental impact, such as meat and dairy products, which have the largest carbon footprint. Among agricultural products, dark chocolate, coffee, oils, rice, peanuts, and sugarcane stand out as having the highest GHG emissions [7].

The current market for goods and services does not reflect the true value of the resources used to produce them. In other words, the market does not allocate resources efficiently because it does not consider the value of the environment. This represents a market failure and results in external costs incurred in the value chain of a product not being reflected in its final price and becoming negative externalities [8].

The reason why environmental assets are not properly valued is mainly because they are not privately owned, so there is no defined market for their transaction, as no one would be willing to pay for something they could get for free. However, the valuation of natural resources is one of the goals of sustainable development, suggesting that the environment is not a free good and its level of use is measured by indicating the scarcity of resources [9].

This problem of common or free goods, known as "The Tragedy of the Commons," was first identified by Hardin [8]. In the case of goods that have no distinct or private owner, anyone can make use of them, but no one is responsible for their care and protection, which leads to their destruction if no limits are placed on their use.

There are various methods and approaches that attempt to monetarily estimate the impact of anthropogenic activities, not only productive activities, but all activities that affect the environment [10], with quantitative physical and mathematical models being the most objective, as they relate the reduction or loss of ecosystem services to losses in productivity, human health, biodiversity, or climate, to name a few [11].

The environmental costs of human activities are estimated to exceed USD 6.6 trillion annually, equivalent to 11% of 2008 global gross domestic product (GDP), and are projected to reach USD 28.6 trillion, equivalent to 18% of GDP in 2050. One-third of these costs are attributed to the damage caused by the three thousand largest publicly traded companies. GHG emissions and their climate impacts represent a large and growing share of environmental costs, projected to rise from 69% (4.5 trillion USD) in 2008 to 73% in 2050 (21 trillion USD), and it would be much cheaper to prevent them than to fix them [12].

In addition, more than 12 million people worldwide die each year from exposure to pollutants in air, water, soil, food, and materials in their homes and/or workplaces [13]. This exposure causes health problems such as respiratory disease, heart disease, and some types of cancer. Low-income populations are more vulnerable to living in these areas, with children and pregnant women at the highest risk for pollution-related health problems [14]. In 2019, air pollution from fine particulate matter ($PM_{2.5}$) caused 6.4 million premature deaths, 93 billion days of illness, and 8.1 trillion USD in losses, equivalent to 6.1% of GDPG [15].

Black carbon (BC) is an air pollutant contained in PM2.5 particles that results from the inefficient and incomplete combustion of fossil fuels and biomass and is known to have various impacts on human health and global warming, which is why it is considered one of the most important indicators of air quality [16].

Most of the world sugarcane industry, including in Mexico, undertake in its production and industrialization process activities that have a high impact on the environment and human health. Polluted air by pollutants such as BC causes short- and long-term health effects in humans, such as chronic obstructive pulmonary disease (COPD), asthma, respiratory mortality, cancer, and cardiovascular mortality, to name a few [17].

In addition, they lead to soil and water depredation and degradation, air pollution, and impacts on human health and biodiversity, with effects such as global warming, among others [18–22]. In this regard, there are many advances that have addressed this problem in terms of its identification and quantification.

Mexico is the sixth-largest sugarcane producer in the world [23]. Its sugarcane cultivation area covers 15 states; San Luis Potosí is part of the northeastern sugarcane region. During the 2021–2022 harvest, the state produced 5 million 620 thousand tons of sugarcane on 103 thousand hectares [24], making it the fourth most important agricultural product in the state in terms of harvested area and the second most important in terms of value of production [25]. These figures show its economic and social importance, but also the extent of its impact.

This is a clear example of a case in which government intervention is needed to regulate a sector that, although of great socioeconomic importance to a large part of the population of the country, also has effects whose costs have not been internalized through public policies, as envisaged by the Coase theorem [26].

The objective of this study was to determine the impact of the sugarcane sector on ecosystem services and to formulate an approach to their economic quantification using two focuses, using the sugarcane zone of San Luis Potosí, México as an example.

2. Materials and Methods

2.1. Study Area

The sugarcane area of San Luis Potosí is part of the northeastern sugarcane region of Mexico, the second largest in the country [27]. There are four mills operating in the state that process sugarcane for industrial purposes, all in the Huasteca region: Plan de Ayala and Plan de San Luis in Ciudad Valles, Alianza Popular in Tamasopo, and San Miguel del Naranjo in El Naranjo. The main access road to the area is Federal Highway 70, which crosses the state horizontally and connects the capital to the Port of Tampico. The region is also crossed vertically by Highway 85 (Mexico–Nuevo Laredo).

Its physiography is varied and consists of plateaus, valleys, plains, mountains, and lomeríos in the three sub-provinces that comprise it: Plains and Lomeríos, Carso Huasteco, and Gran Sierra Plegada. It has a warm climate, but also a semi-warm and even a temperate climate, with rainfall ranging from 1200 mm to 3500 mm per year. This region, composed of four watersheds, is located in the hydrologic region of the Lower Pánuco River, which has significant runoff due to the extensive river network that flows into it [28].

This area was chosen as an example of one approach to assessing ecosystem services affected by the sugarcane industry (Figure 1).

2.2. Model of Costs

With the models developed, the attempt was made to predict what would happen before certain changes in the variables considered, ceteris paribus (assuming no changes in the other variables), in order to simplify the analysis, while understanding that in reality, variations do not occur in isolation.

For this purpose, simplifications had to be made and information taken from other related studies in this initial approach to assessing the environmental impact of sugarcane–sugar activity in the state of San Luis Potosí, Mexico, particularly in Ciudad Valles.

2.2.1. Model of Costs Associated with Human Health Due to Exposure to Air Pollution

For this study, we used a model of costs associated with illnesses caused by the exposure of the population to polluted air [18,29,30], taking as an example the case of black carbon (BC) in Ciudad Valles, San Luis Potosí.

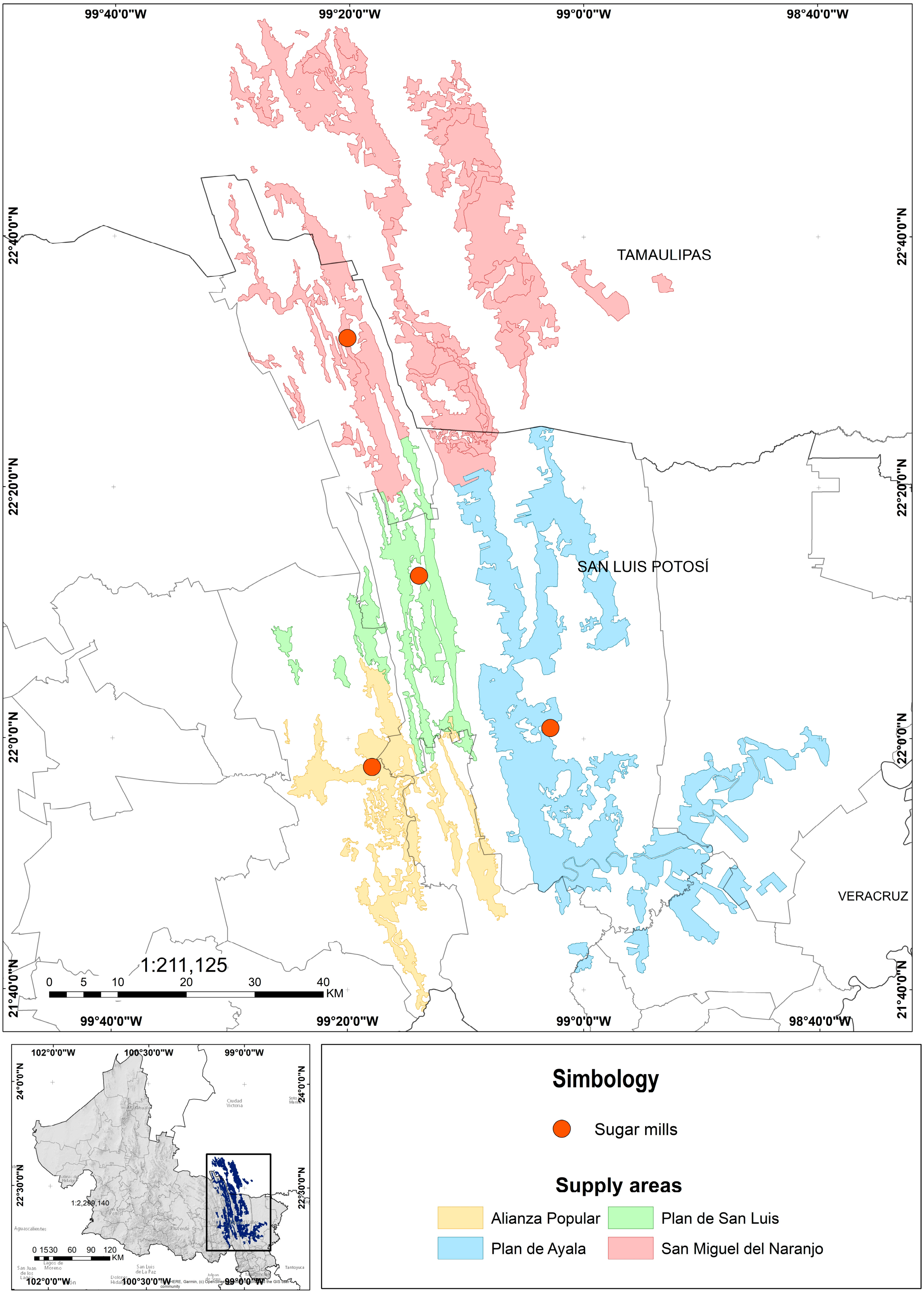

Figure 1. Location of supply areas, sugarcane, and sugar mills in San Luis Potosí.

To evaluate the negative externalities, i.e., the monetary burden of health risks, Value of Statistical Life (SVL), Cost of Illness (COI), and Disability-Adjusted Life-Years (DALY) methods are used for the criteria of mortality and morbidity, which are evaluated separately. Mortality is assessed using SVL, which is generally available for each country and is based on estimates for labor wages or insurance completions.

The total costs by exposure to air pollution are calculated with Formula (1).

$$\text{Total USD Costs} = MBC + MTC \quad (1)$$

where MBC is the total morbidity costs and MTC is the total mortality costs.

All formulas, procedures, and specifications for calculating total cost are provided in Appendix A.

It was noted that in reality, it is very unlikely that there are isolated variations in variables such as BC concentration, concentration fraction of BC in $PM_{2.5}$ particles, percentage of exposed population, wind direction and speed, topography of the area, and composition of BC itself (BC from fossil fuels + BC from biomass), and that by combining all the changes in these variables, there are infinite possibilities of influence and associated costs.

This assessment method proposed scenarios in which only one of the factors that can influence the impact were varied, based on the critical variable regulated at the national and international level for human health impacts: the BC concentration, measured indirectly through the concentration of $PM_{2.5}$ particles.

In evaluating the case of México taking as example the sugarcane industry of the state of San Luis Potosí, the following considerations were taken:

- Ciudad Valles is a small city located in a valley with an approximate territorial extension of 9 km from east to west and 9 km from north to south.
- Maximum average wind speed is 1.9 m/s, but it occurs occasionally during the summer, while the period with lower wind speeds occurs during the sugarcane harvest in November to May (winter and spring). According to the data obtained in the field, the average wind speed in the period from December 2020–May 2021 was 0.25 m/s.
- Monitoring in the field showed that the average daily concentration of BC during the harvest was 0.9 $\mu g/m^3$, and after the completion of the harvest, it decreased to values close to zero, corresponding to about 16 $\mu g/m^3$ of $PM_{2.5}$ particles according to the literature consulted. Based on this information, the first scenario was proposed.
- Although BC concentration is highest in winter, when dispersion is lowest due to low wind speed, it has been observed that BC concentration is directed towards the city due to the valley–mountain effect, so it can be assumed that a significant part of the population may be affected by this pollution.
- In fact, the general public also has different cleaning habits during this time of year. The image inserted in the article shows the spread of pollution caused only by the mill, without considering that the areas where the sugarcane is burned, which is also a source of emissions, surround a large part of the city.
- The second scenario is due to the daily limit of the Mexican standard NOM 025 SSA1-2021 [31], which associates this $PM_{2.5}$ concentration with poor air quality and high health risk.
- The third scenario follows a critical concentration level and is associated with a high and very high health risk according to the 172 SEMARNAT-2019 standard [32] for determining and announcing the air quality and health risk index.
- The exposed population (N) was assumed to be the population of Ciudad Valles, San Luis Potosí, located near the Plan de Ayala sugar mill and part of the area served by the mill. According to the Censo de Población y Vivienda [33], this city has about 137 thousand inhabitants.
- Since WHO does not have reference values for BC, the values established for PM2.5 were used. It was assumed that BC represents about 11–12% of PM2.5 [34], so at the

end of the calculation the corresponding interpolation was performed to estimate the value for BC, with other three scenarios where we variated the proportion of BC in PM2.5, in a range of 5%, 12% and 20%.

- A VSL value recently estimated for Mexico by Rojas and Montero [35] was used. The VSL calculated by these researchers was USD 416,096 for 2018 and its updated value for 2023 is USD 488,580.
- According to World Bank (WB) [36], the Mexican GDP per capita was USD 10,045.7 for 2021, so this data was used for the calculation.
- In the cases where was necessary the exchange dollars-mexican pesos or vice versa, the peso-dollar parity for 2 March 2023, was considered, which was 18.1149–1.0000 [37].
- For this study, an estimated COI for Mexico was considered, which refers to diseases caused by air pollution. The COI for the general population is USD 30,725 per case in 2010, converted to 2023 prices [38].

2.2.2. Assessing the Impact of Sugarcane on Ecosystem Services

The second focus is part of the methodologies have emerged that attempt to capture a larger number of elements that allow for a more comprehensive and holistic assessment of impacts, including environmental and human health impacts, on soil, air, and water resources. Most of these proposals are based on lifecycle assessment (LCA).

The lifecycle of a product or service is the chronological process from extraction and processing of raw materials, production, transportation and distribution, use, maintenance, reuse, recycling, and disposal to end-of-life [39].

The LCA is a standardized method that allows the objective assessment of the impact of a product on the environment at all stages of its lifecycle (discharges, waste, atmospheric emissions, raw material, and energy consumption) [40]. The impacts generated are of different nature and therefore quantified in different units. One of the basic tasks of LCA is to unify impacts into usable numbers by categorizing different activities that generate the same impact.

In 2012, the European Union (EU) published the EN15804 standard, which sets guidelines for environmental product declarations (EPDs) by companies to ensure their transparency and comparability and to enable sustainability assessment. This standard classifies environmental impact in 15 categories (Table 1) [41]. To facilitate the quantification and comparison of environmental impacts, aggregated metrics known as Environmental Cost Indicators (ECIs) have been created to estimate the shadow price of products.

Table 1. Impact categories, according to EN15804 [41].

Impact Category/Indicator	Unit	Description
Climate change: total, fossil, biogenic, and land use	kg CO^2-eq	Indicator of global warming potential due to greenhouse gas emissions to the atmosphere. It is divided into 3 subcategories depending on the emission source: (1) fossil resources (2) bio-based resources (3) land use change
Ozone depletion	Kg CFC-11-eq	Indicator of atmospheric emissions causing stratospheric ozone layer depletion.
Acidification	kg mol H+	Indicator of potential acidification of soils and waters due to release of gases such as nitrogen oxides and sulfur oxides.
Eutrophication—freshwater	kg PO-eq	Indicator of enrichment of the freshwater ecosystem with nutrients due to the emission of compounds containing nitrogen or phosphorus.
Eutrophication—marine	kg N-eq	Indicator of enrichment of the marine ecosystem with nutrients due to the emission of nitrogen compounds.

Table 1. *Cont.*

Impact Category/Indicator	Unit	Description
Eutrophication—terrestrial	mol N-eq	Indicator of enrichment of the terrestrial ecosystem with elements containing nutrients due to the emission of nitrogen compounds.
Depletion of abiotic resources: minerals and metals	kg Sb-eq	Indicator of depletion of non-fossil natural resources.
Depletion of abiotic resources: fossil fuels	MJ, net calorific value	Indicator of depletion of natural fossil fuel resources.
Human toxicity: cancer, non-cancer	CTUh	Effects on humans of toxic substances released into the environment. Subdivided into carcinogenic and non-carcinogenic toxic substances.
Ecotoxicity (freshwater)	CTUe	Effects of toxic substances released into the environment on freshwater organisms.
Water use	m^3-eq of deprivation	Indicator of the relative amount of water used, based on regionalized water scarcity factors.
Land use	Adimensional	Measure of changes to soil quality (biotic production, erosion resistance, mechanical infiltration).
Ionizing radiation, human health	kBq U-235	Damage to human health and ecosystems associated with to radionuclide emissions.
Particulate matter emissions	Disease incidence	Indicator of potential incidence of diseases due to particulate matter emissions.

Currently, there are no comparable standards for categorizing effects, so it is assumed that several of the categories defined in the EN15804 standard are derived from extensive and reputable experimental studies and were used as a reference for this study.

To estimate the costs associated with impacts on ecosystem services, calculation factors were created that assign a monetary value to each unit of impact; the cost estimate is then the product of this factor and the units. This is known as the shadow price of environmental impacts and is an issue on which EU countries have made significant progress, even developing specific methodologies for different economic sectors [42,43].

In the Netherlands, for example, environmental costs measured by an ECI are used as selection parameters for public projects that are put out to tender [44]. The weighting factors considered for these projects using the 2019 Milieu Cost Indicator (MKI) are listed below. To estimate weighting costs for Mexico, prices were converted to MXN at the 3 March 2023, exchange rate [37] and updated through 2023 (Table 2).

Table 2. Weighting of environmental impacts based on calculation factors, converted to MXN, updated to 2023 prices.

Impact Category	Unit	Weighting Factor (WF) (€/Unit)	WF (USD/Unit)	Updated WF for Mexico (USD/Unit)
Global warming	kg CO-eq_2	0.05	0.045	0.055
Ozone depletion	kg CFC-11-eq	30.00	26.798	32.940
Soil and water acidification.	kg SO_2-eq	4.00	3.573	4.392
Eutrophication	kg $PO_4{}^3$-eq	9.00	8.039	9.882
Depletion of abiotic resources elements	kg Sb-eq	0.16	0.143	0.176
Depletion of abiotic resources: fossil fuels	kg Sb-eq	0.16	0.143	0.176
Human toxicity	kg 1.4 DB-eq	0.09	0.080	0.099
Ecotoxicity (freshwater)	kg 1.4 DB-eq	0.03	0.027	0.033
Ecotoxicity of seawater	kg 1.4 DB-eq	0.00	0.000	0.000
Terrestrial Ecotoxicity	1.4 DB-eq	0.06	0.054	0.066
Creation of photochemical oxidants (smog)	kg C_2H_4	2.00	1.787	2.196

For the LCA of sugarcane, the software Mobius [45] was used, a program capable of evaluating the LCA of different products; it also has a cloud that stores the assessments created, which can be used to start or complete the evaluation of different products. In this case, only the production stage for which there is a developed model was evaluated. As can be seen, sugarcane production affects eight of the fifteen impact categories considered in EN15804.

3. Results

3.1. Economic Valuation of Air Pollution from Population Exposure: The Case of Black Carbon in Ciudad Valles, San Luis Potosí

In applying the above criteria to the model, several findings were made. The first is that the cost is zero if the concentration of the pollutant is equal to the limit set by the WHO, ceteris paribus. On the other hand, negative results are obtained when the concentration of the pollutant is below the limit set by the WHO.

Tables 3–10 show examples of what happens to the health costs related to BC exposure when the $PM_{2.5}$ reference concentration (15 μg/m^3) is exceeded by 1 mg for the entire population of Ciudad Valles, San Luis Potosi.

Table 3. Rr_m due to the exposure to the average concentration of the pollutant.

Mortality and Morbidity in the Short Term	C_p	C_m	Rr	Rr_m
	Average 24-h Mean Data (μg/m^3)	**WHO Standard (μg/m^3)**	**Relative Risk to the Pollutant**	**Relative Risk**
Total mortality	16	15	1.015	1.0015
Respiratory disease	16	15	1.022	1.0022
Cardiovascular disease	16	15	1.013	1.0013
Asthma attack	16	15	1.021	1.0021
Chronic bronchitis	16	15	1.029	1.0029

Table 4. Population Attributable Risk (PAR).

Rr_m	Population Exposed to the Poullant p (c)	Rr_m-1	Rr_m-1 (p (c))	PAR
1.0000	1.00	0.0015	0.0015	0.0099
1.0000	1.00	0.0022	0.0022	
1.0000	1.00	0.0013	0.0013	
1.0000	1.00	0.0021	0.0021	
1.0000	1.00	0.0029	0.0029	
Σ			0.0100	

Table 5. Estimated number of cases (I_{ne}).

Concept	I_e (10^5)	N	I_e	I_{ne}
Total mortality	543.5	136,351	0.00544	7.34
Respiratory disease	550.9	136,351	0.00551	7.44
Cardiovascular disease	546	136,351	0.00546	7.37
Asthma attack	940	136,351	0.00940	12.69
Chronic bronchitis	694	136,351	0.00694	9.37

Table 6. Value of a Statistical Life (VSL).

Year	Value
2018 (USD) [1]	416,096
2023 (USD) [2]	488,550

[1] [35]. [2] Considering IR of 27.42%.

Table 7. Mortality costs.

Concept	Value
I_{ne}	7.34
VSL (USD)	3,584,640

Table 8. Morbidity costs.

Concept	Value
Ine per total morbidity	7.44
DALY	7.4
GDP per capita in Mexico (USD)	10,045.68
Morbidity losses (USD)	552,867

Table 9. Air pollution COI.

Concept	Value
COI (2010)	30,725
Total morbidity Ine	7.44
Exchange rate	18.1149
IR (2010–2023)	0.7403
COI (USD)	169,165

Table 10. Total health costs associated with air pollution with three proportions of BC in $PM_{2.5}$, (a) 5%, (b) 12%, (c) 20%.

Concepts	PM2.5	BC		
		a	b	c
Mortality costs	3,584,640	179,232	430,157	716,928
Morbidity costs	722,032	36,102	86,644	144,406
DALY losses	552,867	27,643	66,344	110,573
COI losses	169,165	8458	20,300	33,833
Total Costs	4,306,671	251,435	603,444	1,005,741

The assumption that the entire population is exposed to BC air pollution is not so far-fetched, because both the mill and the sugarcane zone are located around Ciudad Valles, so any harvest time, smoke and BC deposition can be observed over a large part of the city (Figure 2).

Similarly, it can be seen that 82% of the costs are due to premature mortality from direct exposure to polluted air, while 13% are due to health problems or disability from the same cause.

In addition, Table 11 shows that each unit increase in the concentration of the pollutant (in this case $PM_{2.5}$) increases the risks of mortality and morbidity by 1 to 3%. However, considering that only 11% to 12% of $PM_{2.5}$ is attributable to BC, the increase in human health impacts due to this pollutant would be between 0.1% and 0.3%.

Table 11. Rr_m due to the exposure to the average concentration of $PM_{2.5}$ and BC.

Mortality and Morbidity	C_p	C_m	Rr	Rr_m $PM_{2.5}$	Rr_m BC
Total mortality	16	15	1.015	1.5	0.2
Respiratory disease	16	15	1.022	2.2	0.2
Cardiovascular disease	16	15	1.013	1.3	0.1
Asthma attack	16	15	1.021	2.1	0.2
Chronic bronchitis	16	15	1.029	2.9	0.3

Figure 2. Black carbon from Ingenio Plan de Ayala in Ciudad Valles, San Luis Potosí.

Likewise, it can be seen that 82% of the costs are due to premature mortality from direct exposure to polluted air, while 13% are due to health problems or disability from the same cause.

First, four scenarios were created, varying the concentration of the pollutant and the proportion of the population exposed to it. For the scenarios, the concentration of $PM_{2.5}$ was varied between 16 µg/m^3 and 19 µg/m^3, with changes of one unit; the exposed population changed in a range from 25% to 100%, with changes of 25%.

The results showed that a 25% change in the exposed population has a similar impact on costs as a change of one additional unit above the reference value from the WHO. Likewise, a higher proportion of BC composition in $PM_{2.5}$ leads to an increase in costs attributable to the former (Table 12).

Table 12. Economic cost scenarios caused by exposure to black carbon (BC) of the population of Ciudad Valles, S. L. P. (USD), varying pollutant concentration and exposed population.

Variable	Scenario			
	a	**b**	**c**	**d**
Concentration (µg/m^3)	16	18	17	19
Exposed population (%)	100	50	75	25
Mortality cost	430,157	642,057	642,057	430,157
Morbidity cost	86,644	129,325	129,325	86,644
Morbidity losses	66,344	99,026	99,026	66,344
Cost of treatment	20,300	30,300	30,300	20,300
Total cost	516,801	771,382	771,382	516,801

Then it was assumed that half of the population is constantly exposed to pollution, but $PM_{2.5}$ concentrations and BC content in $PM_{2.5}$ varies as follows: (a) 16 µg/m^3, assuming a one-unit increase over the WHO reference; (b) 45 µg/m^3, implying an approximate concentration of 5 µg/m^3 BC, the maximum concentration detected in field monitoring in Ciudad Valles, San Luis Potosi, during the 2020–2021 harvest; (c) 100 µg/m^3, corresponding to approximately 12 μg/m^3 BC, which is the concentration detected in previous studies at some highly polluted sites.

Moreover, the BC content in $PM_{2.5}$ was suggested to be 5%, 12% (as reported in the literature), and 15%.

With these variations, nine scenarios were generated in which the increase of BC content in $PM_{2.5}$ was found to have a proportional effect on the increase of costs. On the other hand, it was found that the more the pollutant concentration increases, the more exponential the effect on the total cost becomes.

Thus, a change from 15 μg/m^3 to 45 μg/m^3 triples the cost, but if the $PM_{2.5}$ concentration increases from 16 μg/m^3 to 100 μg/m^3 (525% change), the cost increases from 126,343 USD to 7.57 million USD, which represents a change of 5895% (Figure 3).

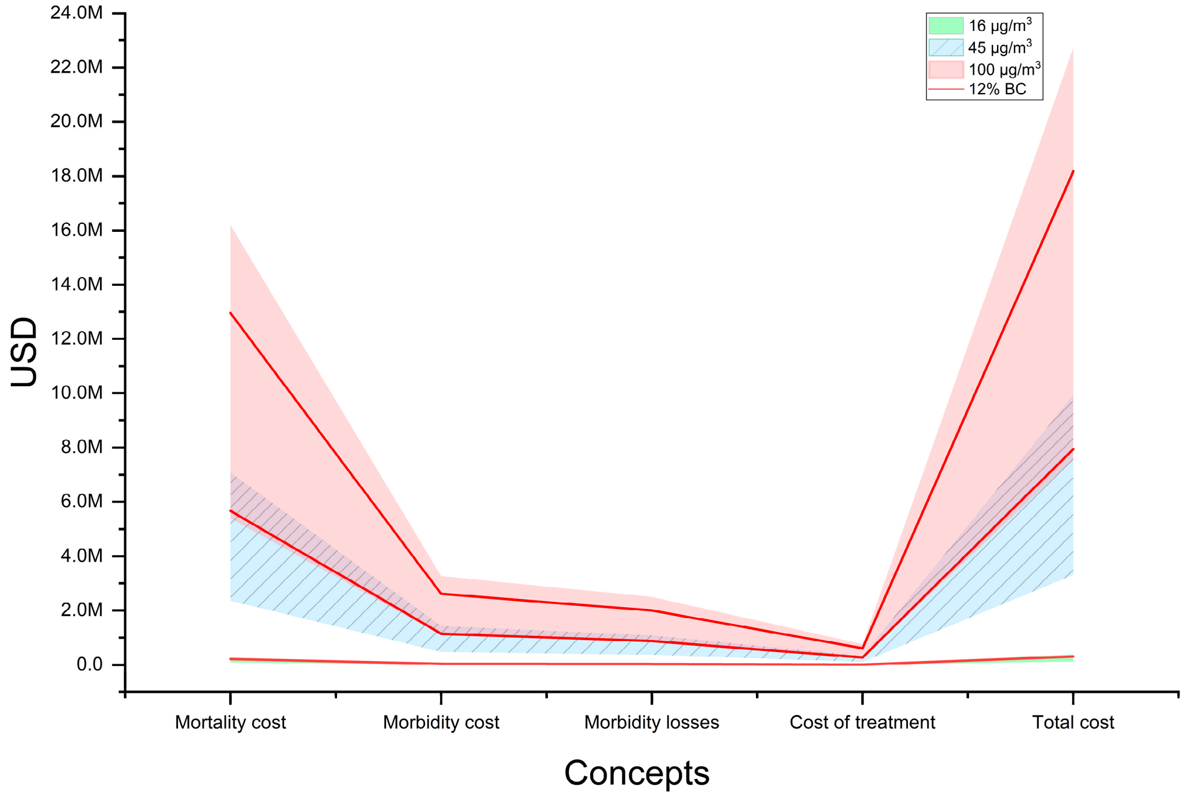

Figure 3. Economic cost scenarios caused by exposure to black carbon (BC) of the population of Ciudad Valles, S. L. P. (USD), varying pollutant concentration and BC content in $PM_{2.5}$.

3.2. Valuation of the Costs of Ecosystem Services Caused by the Sugarcane Sector

Using information from Hillege [44] and Ecochain [45], the second focus of the approach to the economic assessment of sugarcane impacts on ecosystem services was created. According to this model, with the given parameters, the environmental cost of impacts on ecosystem services due solely to sugarcane production reaches 114.2 USD per ton produced, with fossil fuel depletion, human toxicity, and global warming as the items with the highest costs, accounting for 63%, 20%, and 9% of the total costs, respectively (Table 13).

Based on this model and production statistics from CONADESUCA [25], an estimate was made of the cost of sugarcane production in San Luis Potosi and for each of the four sugar mills located in the state during the last completed sugarcane harvest (2021–2022).

It is estimated that the environmental cost for the state of San Luis Potosí was about 642 thousand USD, representing more than 16% of the income of the producers, given a price of 646.5 USD per ton of sugarcane (Table 14). The mill with the highest cost is San Miguel del Naranjo (27%), although the difference between it and Alianza Popular, the mill with the lowest cost, is no more than 4 percentage points (Figure 4).

Table 13. Distribution of costs of ecosystem services affected by sugarcane production in San Luis Potosí by category.

Impact Category	Unit	Impact/kg Sugarcane	Costo/kg (USD)	Cost/ton (USD)
Global warming	kg CO_2-eq	0.16	0.0103	10.3
Soil and water acidification	Kg SO_2-eq	5.96×10^{-4}	0.0031	3.1
Eutrophication	kg $PO_4{}^{3}$-eq	3.18×10^{-4}	0.0037	3.7
Depletion of fossil fuels	MJ	0.35	0.0000	0.0
Human toxicity	kg 1.4 DB-eq	0.20	0.0720	72.0
Ecotoxicity in freshwater	kg 1.4 DB-eq	0.02	0.0231	23.1
Ecotoxicity of seawater	kg 1.4 DB-eq	10.07	0.0008	0.8

Table 14. Distribution of costs of ecosystem services affected by sugarcane production in San Luis Potosí by sugar mill.

Mill	Tons Produced	Environmental Cost (USD/ton)	Total Cost (USD)
Alianza Popular	1,314,400	114.2	150,130,853
Plan de Ayala	1,355,860		154,866,417
Plan de San Luis	1,431,692		163,527,953
San Miguel del Naranjo	1,517,879		173,372,237
Total San Luis Potosí	5,619,831		641,897,459

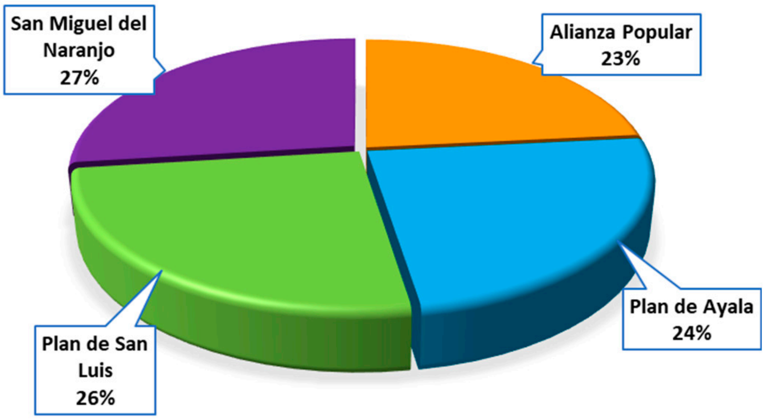

Figure 4. Costs of ecosystem services affected by sugarcane production in San Luis Potosí, proportion by sugar mill.

4. Discussion

Although products derived from sugarcane have diversified, cane sugar production continues to account for the majority of production. This is especially true in countries such as Mexico, which have not achieved such diversification. In any case, new products such as bioethanol are also the result of an industrialization process.

For this reason, sugarcane cultivation is inextricably linked to the associated agricultural industry. The sugarcane industry is thus a long chain of activities, many of which have a high environmental impact. Land clearing, the use of machinery and equipment in cultivation, agrochemicals, and labor with unfair pay and treatment, such as waste disposal and combustion processes, are just some of these activities.

This is due to the growing debate on the impact of the sugarcane sector on various environmental and socioeconomic aspects [46] but additionally, competition between sugarcane and food crops for land use threatens global food production. In addition, there are the detrimental effects on biodiversity and endemic species due to land use changes [47], as well as negative environmental externalities such as GHG emissions [48]; alteration of physical [49], chemical, and biological soil properties [50], causing nutrient depletion; and acidification and eutrophication potentials [51].

In addition, there is pressure on water resources due to changes in irrigation demand, leading to depletion and degradation of available water [52]. Likewise, there are social impacts from affecting the health and well-being of farmers [53], workers, and settlers in sugarcane areas, including working conditions, land rights, workers' rights, forced labor, and child labor, to name a few [21].

Several of these impacts on ecosystem services of the sugarcane zone and its area of influence in San Luis Potosí have been revealed by several studies [54–56].

Research on the impacts of sugarcane cultivation on ecosystem services began in the early 1960s and has expanded greatly in the last decade [22]. At present, there are very structured methods of estimating the costs of the impacts of the sugarcane value chain or part of it. Some focus entirely on human health impacts [18,30,57], and although they address direct exposure to polluted air, they can serve as indicators of environmental impacts, especially when additional information is not available to build a more complex assessment of impact monetization.

For instance, the method for the economic assessment of air pollution due to population exposure, which was carried out using the example of black carbon in Ciudad Valles, San Luis Potosí, is based on losses in the public and/or private economy resulting from expenditures for the treatment of diseases related to exposure to polluted air and from the disability or premature death of people due to this reason.

This model can be used for pollutants for which there are direct or indirect reference values, such as those of the WHO, as long as any adjustments are made that result from the activity being evaluated and the characteristics of the place where it is carried out.

In addition, the model assumes that the cost of exposure of the population to air pollution begins when the established limits for these pollutants are exceeded, in this case those of [31]. Thus, when a concentration below the established reference levels is considered, the model reports negative costs, and when a concentration equal to the established reference levels is considered, the model reports costs equal to zero.

This does not mean that there is a negative cost to not meeting the WHO concentration limits, nor does it mean that there are any savings. In any case, it could be argued that the model assumes that the costs to the economy are significant only when these limits are exceeded.

This suggests that the proportion of the population exposed has a greater impact on the variation in costs than changes in pollutant concentration, at least in the case of BC.

If BC accounts for 11–12% of $PM_{2.5}$ particles, then if the reference value of WHO is exceeded by 1 $\mu g/m^3$, i.e., at 16 $\mu g/m^3$, the BC concentration would be about 1.75 $\mu g/m^3$. According to the preliminary results of a field investigation conducted in the Plan de Ayala sugar mill area in Ciudad Valles, San Luis Potosi, during the 2020–2021 harvest season, concentrations equal to or above this concentration were reached in at least half of cases. It can be assumed that the sugarcane industry, at least in this part of the sugarcane area of the state, generates a cost to human health costs that should actually be borne by the owners of the sugarcane fields and mills.

It is important to keep in mind that variations in the model parameters, such as the specific parameters of each pollutant to economic variables such as the base year of the estimates, inflation, and the exchange rate, can cause large variations in the results. For example, the estimated cost increase is not derived from worsening air pollution in all cases.

On the other hand, and speaking of the second assessment approach, it is a clear example of the progress that has been made by institutions, companies, and individual researchers who have dedicated themselves to the study of the impact of activities on ecosystem services.

Clearly, industrial activities carried out in cities, have better control and registration systems, so their life cycles and their evaluation are more complete and with more specific information. However, agricultural industries such as sugarcane, which are just as important from an economic and social point of view, also have relevant advances.

For example, for the approximation made in this study for Mexico, taking the sugarcane area of San Luis Potosí as an example, parameters obtained in Brazil [45] were used; however, it was found that the production systems of both countries are similar, so, since there was no information from national sources, it was used for this estimation.

In this case, one of the most relevant variables that cause changes in the environmental costs of sugarcane, associated with the impacts of the ecosystem services affected, is the quantity produced, since the cost is estimated based on total cost per unit produced. Thus, given that the supply areas of the four mills located in the state produce similar quantities of sugarcane, their estimated costs are also similar.

At this point, it is appropriate to highlight the need to have more information about each of the mills not only in San Luis Potosi, but throughout the country, in order to obtain better estimates of their costs, since, as mentioned above, the impact is directly related to the characteristics of the activities carried out, so that a mill that performs irrigation does not have different impacts from one that does not, nor does one that performs green harvesting from one that harvests using the double-burning method, or mills with or without filters in their chimneys, to name a few.

In addition to research on the cost of impacts, there is also research focused on reducing those impacts. One of these came from Brazil's Laboratório Nacional de Ciência e Tecnologia do Bioetanol (CTBE) in 2016, which used the Virtual Sugarcane Biorefinery (VSB) to create scenarios using four management practices to model mass and energy balances in different scenarios: harvesting, tillage, machine traffic, and crop rotation. It was concluded that transitioning to green harvesting, crop rotation with crops such as sunn hemp (*Crotalaria juncea* L.), controlled traffic farming, and adoption of reduced tillage contributed to reducing the economic and environmental costs of sugarcane [58].

5. Conclusions

Agrifood systems are currently facing the complex problem of meeting the demand of a growing population for safe and nutritious food under adverse climatic conditions, without neglecting the obligation to reduce their environmental footprint.

Some of these systems, such as sugarcane cultivation, have particularly strong impact, where some production and industrial practices need to be modified to enable sustainable development. This requires identifying and quantifying their impacts and finding alternatives to reduce them and provide better social and economic options for producers and workers in the sector.

Given the complexity of measuring the impacts of systems as a whole, some researchers have chosen to assess only a portion of the impacts and specialize in that part or section. One example is the assessment of air pollution and its associated health costs. Still within this topic, the study of some pollutants, such as black carbon (BC), is specialized and their results are used as indicators based on their properties.

The mathematical model resulting from the applied method evaluates the health costs of a population exposed to a pollutant in terms of costs and losses due to morbidity and early death.

In the case of Ciudad Valles, San Luis Potosí, Mexico, for a 1 $\mu g/m^3$ increase in BC concentration, these costs could reach 516.8 thousand USD if the entire population were exposed to the pollutant. According to the model, costs could change more when the exposed population varies than when concentrations increase. According to preliminary results of a field research, this concentration is reached and exceeded on several days of the approximately six-month harvest each year.

On the other hand, other kind of methods and techniques have emerged that attempt to make an increasingly comprehensive assessment of the impacts of ecosystem services in their entirety for each product created and used by humans. One of the most widely used methodologies is product lifecycle assessment (LCA), which considers the impact of all stages of a product, from the inputs, production, and use to its disposal.

This method has been complemented by others, such as Environmental Cost Indicators (ECI), to determine the shadow price of products, achieving significant progress in the monetary valuation of environmental impacts.

However, not all countries are equally advanced in the development of these issues, and some, such as Mexico, are at Tier Level I or II, especially for chains such as sugarcane. In these cases, it is necessary to use information from other countries which have similar conditions in order to maintain the veracity of the parameters.

In this case, we have only obtained information on the production system, which means that the costs are underestimated because the impacts and costs of the other parts of the sugarcane industry life cycle are not considered.

The cost of the impact of seven ecosystem services was estimated at 642 thousand USD for only this part of the chain, when considering total unit cost (cost per ton), which of course means that the higher cost results directly from higher production; ignoring the differences between the industrial and the production system was necessary because we do not have this kind of specific information.

The challenge, then, is to make progress in obtaining and systematizing first-hand information that is increasingly specific and up to date, in order to improve the certainty of results and provide accurate and timely information that contributes to decision making that promotes the sustainable development of the sugarcane sector and other productive sectors in the country.

At the same time, research based on experimentation or modeling should be advanced with system changes to try to reduce the impact of this industry. It is important to keep in mind that impacts are not limited to environmental issues, but social and economic issues must also be addressed if a real shift toward a truly sustainable industry is to occur.

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Appendix A

Appendix A.1 Morbidity Costs

$$\text{Morbidity Costs(MBC)} = \text{DALY USD losses} + \text{COI USD losses} \quad \text{(A1)}$$

$$\text{DALY USD losses} = I_{ne} \times \text{DALY} \times \text{GDP per cápita} \times \text{ER} \times \text{IR} \quad \text{(A2)}$$

- Estimated number of cases (I_{ne})

$$I_{ne} = I_e \times PAR \times N \quad \text{(A3)}$$

where I_e are the base incidence cases per 10^5 of the population corresponding to mortality/morbidity health impacts, and the total population of the study site (N).

- Population attributable to risk (PAR)

$$PAR = \sum[\{Rr_m - 1\}] \times p(c) / \sum[\{Rr_m - 1\} \times p(c) + 1] \quad (A4)$$

where $p(c)$ is the proportion of the population exposed to pollutant "K" [30].

The fraction of the excess disease rate in each population that can be connected to exposure to a particular air pollutant, assuming a proven causal relationship between exposure and excess disease rate without significant confounding effects on that association.

For the assessment, factors such as the relative risk Rr_m due to the average concentration of the pollutant, the population attributable to the risk (PAR), the reference cases (I_e), and the total population (N) are considered.

- Relative risk (Rr_m) due to the average concentration of pollutants

$$Rr_m = 1 + \left(C_p - C_m\right) \times (Rr - 1)/10 \quad (A5)$$

Relative risk (Rr) is the ratio of the probability of an exposed group developing a disease to the probability of a non-exposed group developing the same disease due to air pollutants.

C_p is the concentration of pollutant "K" in the air; C_m is the allowable standard for pollutant "K" according to the guidelines of WHO [59]; Rr is the relative risk for pollutant "K"; the values of Rr and I_e are given in Table A1.

Table A1. Parameters considered for mortality/morbidity for the pollutant $PM_{2.5}$.

Morbidity Mortality	Relative Risk (Rr)	Reference Incidence (I_e)
Total mortality	1.015	543.5
Respiratory disease	1.022	550.9
Cardiovascular disease	1.013	546
Asthma attack	1.021	940
Chronic bronchitis	1.029	694

- DALY

  The DALY indicates the years of life lost and can therefore be assessed in terms of a person's annual income (GDP per capita). DALY value is estimated for each country and by different causes of affectation. DALY from Mexico was obtained from the Global Health Observatory Data Repository [60] (Table A2).

Table A2. Disability-Adjusted Life Years (DALYs) attributable to ambient air pollution in Mexico, by 2019 [60].

Cause	Per Capita
Total	0.00043
Lower respiratory infections	0.00006
Trachea, bronchus, lung cancer	0.00001
Ischemic heart disease	0.00025
Attack	0.00006
Chronic obstructive pulmonary disease (COPD)	0.00005

- ER is the exchange rate which is used to convert the amounts to a different currency. In this case, the amounts are given in U.S. dollars to provide the reader a better notion of the impact, since this is the most widely used currency in the world.
- IR is the inflation rate in the country, in this case in Mexico, used to update the value.

For this study, we used a model of costs associated with illnesses caused by the exposure of the population to polluted air [18,29,30], taking as an example the case of black carbon (BC) in Ciudad Valles, San Luis Potosí.

$$\text{COI USD losses} = \text{COI} \times I_{ne} \times \text{IR} \quad (A6)$$

Cost of Illness (COI) includes the total costs incurred, such as the cost of drugs, travel, hospitalization, and lost days.

Appendix A.2 Mortality Costs

$$\text{Mortality damages (USD)} = \text{VSL} \times I_{ne} \times \text{IR} \tag{A7}$$

The value of a statistical life (VSL) is a local tradeoff between death risk and money. When tradeoff values are derived from decisions in market contexts, VSL serves as a measure of the population's willingness to pay for risk reduction and the marginal cost of increasing safety. Factors such as income levels and population perceptions determine VSL, so it can reveal important differences across countries [61].

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