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Towards a carbon footprint analysis as an extended environmental indicator for roadside maintenance strategies: a multi-scale perspective

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Abstract—Within the framework of the bio economy, a supply chain resulting from the valorization of grass roadside verges maintenance activities is currently emerging. It represents a potential sink of biomass which could be valorised as a source of energy (heat or electricity) or other applications, thanks to the availability of technologies and the growing biomass demand. However, the assessment of these emerging activities could not any longer be made exclusively under technical and economic considerations. As a consequence, there is an urgent need to evaluate these new activities from a more holistic way, especially regarding their environmental impact. The present paper aims to introduce the carbon footprint analysis as an environmental indicator for establishing the relevance of the maintenance strategies with and without biomass recovery. Results show that the carbon footprint of this emerging valorization value chain could be positive, compared to the traditional maintenance strategy when including the valorization activities.

Keywords—*multi-scale assessment, carbon footprint, environmental assessment, roadside management*

I. INTRODUCTION

Finding more resilient and symbiotic relation of human activities with the environment is a priority today. As mentioned in Rifkin (2022) [1] “rural regions surrounding urban and suburban corridors will increasingly be the front line in both restoring the earth’s ecosystems and reimagining civilization.” Roadside verges are at the interface of these ecosystems (agricultural, natural and urban) all across the territories in most of the countries. Moreover, several studies have shown, when properly managed could mitigate negative impacts but also generate positive impacts to the environment (namely ecosystem services) [2], [3]. One of these potential positive outcomes is the energy production from the collected biomass resulting from the maintenance grass cut campaigns. The growing demand for biomass [4] coupled with recent innovations in roadside maintenance machinery, biomass hoover especially, and the local development of biomass recovery structures are all opportunities for emerging sustainable value chains. However, the assessment of these emerging activities could not any longer be made exclusively under technical and economic considerations for informed decision-making of the whole set of stakeholders (*i.e.* policy makers, industrialist, territory planners and operators). As a consequence, there is an urgent need to evaluate these new

activities in a different way, especially regarding their environmental impact. The present paper aims to introduce the carbon footprint analysis as an environmental indicator for establishing the relevance of roadside maintenance strategies. Hence, the objective of this research is twofold. Firstly, to compare the greenhouse gas emissions (GHG) of roadside maintenance with and without biomass recovery in order to propose a broader and sustainable analysis of these new practices within the French context. Second, to show the interest of a multi-scale analysis in the evaluation of roadside management strategies. The remainder of the present paper is as follows: Section II presents a dedicated literature review on the topic, followed by the proposed Methodology in Section III. In Section IV, we present the results based on a case study before ending with conclusions, limitations and future perspectives for our work in Section V.

II. EXISTING THEORIES AND PREVIOUS WORK

A. Roadside maintenance with biomass recovery: the challenge of mowing from a local to a meso scale

The emergence of sustainable development led to a change in the management of roadsides during the 1990s, leading to a de-intensification of practices in favour of biodiversity, a rationalization of the means allocated to management, a better perception of these spaces by the public and a late mowing [5]. Roadside grass is usually not used but cut and left to decompose *in situ*. However, recent technological developments (mowing tools equipped with aspirators) and research on the quality of roadside biomass [6] are encouraging the emergence of new practices aimed at recovering biomass and valorising it in adapted supply chain, mainly in the energy sector [7]. These changes in practice are not without consequences in terms of impacts; sustainable roadside management depends on the context and political objectives and is the result of a combination of several decisions [3]. These authors have shown that maintenance without biomass recovery seems to be the most suitable strategy to limit maintenance costs, even if the energy use of this biomass could lead to improved profitability of export maintenance activities by reducing energy costs for communities or by generating additional income.



Fig. 1. Roadside maintenance with biomass recovery: the challenge of moving from a local to a meso scale

This openness to the merchandizing of roadside biomass leads to an analysis of roadside management on two scales: a micro scale (that of the roadside) and a meso scale (that of the supply chain). The meso level is an intermediate level between that of the product/service and that of the economy, integrating groups of related products and technologies, companies and communities [8]. In their article, these authors illustrate this level by introducing biomass as an automobile fuel, which is close to our case study. The challenge of transforming the roadside maintenance strategy lies in the ability of territories to tackle this multi-scalability, *i.e.* to organize the maintenance of these areas to supply energy sectors (Fig. 1). However, the economic analyses of this transformation reveal the additional cost of such a transformation with few benefits. Hence, it may be interesting to complete these economic analyses with environmental analyses, carbon footprints especially, to study the viability of such an approach.

B. LCA as a tool for multi-scale assessment of the carbon footprint of roadside management

The carbon footprint (CF) is an integrated and unified indicator for environmental management and assessment, used to measure direct and indirect greenhouse gas (GHG) emissions during production and consumption [9], [10]. One of the mainstream approaches to CF research is life cycle assessment (LCA) [11], that is a well-established methodology for assessing the environmental impacts of a product, a process or a service throughout its life cycle [12] which can then support decision-making to improve the environmental performance of future policies [13]. The LCA is relevant for our study as it allows a comparison of alternatives in a global perspective [14]. LCA incorporates a wide variety of environmental impacts and indicators, especially CO₂ emission. This research compares roadside maintenance with or without biomass recovery in terms of CO₂ emissions. Unlike other environmental assessment tools (*e.g.* carbon footprint or energy balance), it allows the impacts of a product or service to be quantified throughout its life cycle (from the extraction of raw materials, to its production, distribution, use and disposal) [15].

III. METHODS

In this study, two roadside maintenance strategies are described and compared to illustrate the importance of multi-scale studies in the evaluation of land management practices.

The comparison is based on methodological phases of the LCA standardized framework: *(i)* definition of the objectives and scope of the study, *(ii)* life cycle inventory, *(iii)* assessment of life cycle impacts and *(iv)* interpretation of the study results [16], [17]. In this paper, the research applies a mixed method approach [18] where data is collected on the basis of quantitative and qualitative data gathered from various sources (interview, experimentation, scientific literature, Base Carbone¹ database ...).

A. Step 1. Objectives and scope of the study

This step involves defining the objectives of the study and the functional unit in order to select the boundaries of the system. The functional unit is a metric used to assess the service provided by the product or the service and provides a reference against which inputs and outputs will be defined and standardized to ensure the comparability of LCA results on a common basis [16], [17].

B. Step 2. Life cycle inventory

This step aims to collect the environmental flows related to the processes and activities included in the system boundaries. The inventory is therefore an analytical accounting of flows. For this purpose, two types of data are collected: activity factors such as kilowatt hours consumed, kilometres travelled, tons transported and emission factors [16], [17]. An emission factor is a typical amount of greenhouse gases released into the atmosphere per unit of activity. The GHGs to be considered when assessing emissions are carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), sulphur hexafluoride (SF₆), nitrogen trifluoride (NF₃), the hydro fluorocarbon (HFC) family and the per fluorocarbon (PFC) family [19].

The activity factors were collected through interviews with machine manufacturers, roadside maintenance supervision platform providers and local authorities.

C. Step 3. Assessment of life cycle impacts

This step aims to convert the environmental flows of the previous step into potential environmental impacts [16], [17]. This conversion aims at calculating GHG emissions through *(i)* the collect of data related to the different activities (operations) related to the operation and end-of-life phases of the project and *(ii)* the evaluation of the quantities of GHG produced for each operation [19].

¹ <https://bilans-ges.ademe.fr/>

For a specific operation, the emissions are the product of an activity data, expressed in a unit of work characterizing the activity of the emission item, and an emission factor which is the expression of unit emissions per functional unit [19]. The following equation is used:

$$GHG\ emissions = activity\ data \times emission\ factor \quad (1)$$

This research is based on the emissions factors in the Base Carbone®, which is a public database of emissions factors, necessary for the realization of a greenhouse gas emissions assessment and more generally any carbon accounting exercise. Their emissions factors are constructed in a “life cycle” perspective. This integrates the different phases linked to the activity associated with the emissions factor. For example, the combustion of a litre of petrol includes both the emissions linked to the combustion of this petrol, but also those linked to its upstream (extraction, refining, transport and distribution) [19]. Waste can be recovered at the end of its life in different ways: energy recovery (electrical or thermal) in incinerators and landfills, recovery as a soil improver for composting (and for anaerobic digestion), recovery of biogas for anaerobic digestion and recycling [19].

D. Step 4. Interpretation of the study results

The results are interpreted according to the objectives and scope of the study [19]. It is therefore a matter of analysing the results obtained, the relevance of the data collected, and the relevance of the hypotheses adopted regarding the boundaries of the system [20].

IV. FINDINGS

A. Step 1. Objectives and scope of the study

Our study seeks to compare two scenarios, focusing on roadside maintenance and the future of herbaceous vegetation, through a multi-scale analysis including a roadside scale and a supply chain scale.

From a life cycle perspective, the roadside scale focuses on all roadside maintenance practices of the roadside biomass.

Roadside maintenance aims to keep the road annexes in a good condition to guarantee the safety of the drivers [21]. It includes several activities: mowing with or without biomass removal and routine maintenance (ditch cleaning, roadside dismantling among others). All work sites are secured. Scenario 1 presents roadside maintenance as it is currently carried out. Thus, this scenario involves mowing activities without removal of biomass. Scenario 2 presents roadside maintenance as a biomass source within the energy supply chain, through a methanisation process. Thus, it includes mowing activities with biomass removal and transport.

The supply chain scale focuses on biomass recovery activities. Anaerobic digestion is the biological conversion of organic matter into biogas under oxygen-free conditions [22]. It produces biogas, consisting of approximately 60% CH₄ and 40% CO₂. The biogas can be burned to produce heat and/or electricity [23]. This anaerobic digestion process also produces digestate, *i.e.* the material that is not converted into biogas. The digestate contains the majority of the nutrients in the feedstock and can be used as a bio-fertilizer [24]. The electricity and heat produced from the methanisation of mown grass can replace the energy produced in the grid, mainly in a “non-renewable” way². Therefore, scenario 1 integrates the production of electricity, heat and fertilizers with “traditional” modes, whereas scenario 2 integrates the production of electricity, heat and digestate by methanisation. Our study considers that the use of energy generated in each scenario is the same, so it is not necessary to compare them. However, particular attention will be paid to the use of fertilizers and digestates. Fig. 2 summarizes each scenario considered in our article.

To consider all significant greenhouse gases, they are converted to CO₂ equivalents (CO_{2e}) using the “global warming potential” (GWP), which determines the relative contribution of a gas to the greenhouse effect [25]. Hence, in this study, the focus is on GHG emission for one kilometre of roadside maintenance, *i.e.* kilogram CO_{2e} per unit kilometre of roadside maintained.

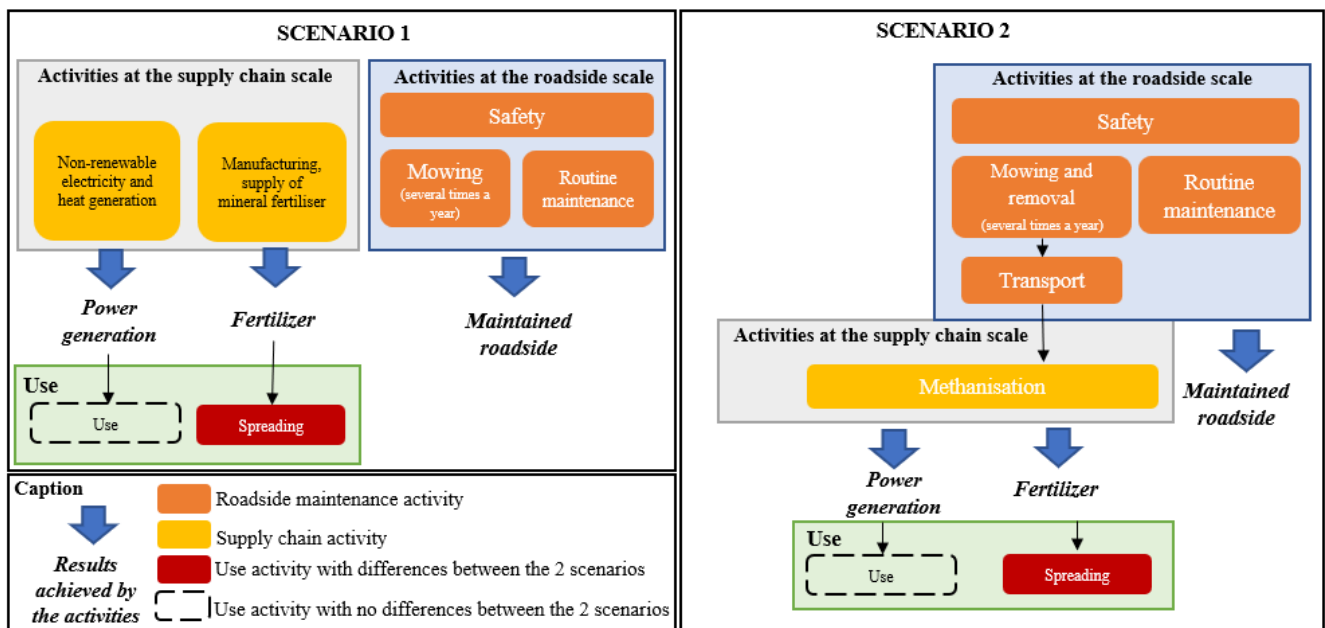


Fig. 2. Presentation of each scenario

² nuclear energy, natural gas, coal...

B. Step 2. Life cycle inventory

The assessment of greenhouse gas emissions for each mowing scenario includes emissions related to roadside maintenance (mainly related to the consumption of machinery) and emissions related to the use of biomass (related to the production of energy, heat and land applications).

1) Activities at the roadside scale

The analysis at the roadside scale depends on the activities performed. This section will present the assumptions and choices made in this study.

a) Safety

The use of mobile maintenance equipment on the road requires to establish security perimeters both for the workers and for the drivers. The safety of maintenance activities requires a motorized vehicle. To facilitate the GHGs emissions assessment, two approximations can be made: (i) all maintenance activities are secured and (ii) the speed of progress of the securing activity is identical to that of the secured activity. Note that the main difference is that the speed of securing a mowing site with removal is slower than a mowing site without removal.

b) Mowing

The differences between the two maintenance scenarios lie mainly in mowing because of the additional removal activity in scenario 2. Emissions related to mowing depend on the frequency of maintenance per year and the width maintained. Biomass removal will have an impact on the consumption of the machine, the speed of the work.

One assumption, valid for both scenarios, is made. Three mowing campaigns can be carried out each year, using different tool widths. One implement width corresponds to one pass of the work site along the roadside. For the scenario, we can note that the volume of grass harvested per kilometre differs according to the width maintained.

The information related to the work site differs according to the scenarios. TABLE I relates to the work site data used in

TABLE I. DATA RELATED TO BIOMASS TRANSPORT OPERATIONS IN ALL SCENARIOS

Data related to transport operations		All scenarios
Vehicle dedicated to transport	Forward speed of biomass transport	40 km/h
	Fuel consumption	12 L/h

TABLE II. DATA RELATED TO ROUTINE MAINTENANCE OPERATIONS IN ALL SCENARIOS

Data related to routine operations		All scenarios
Vehicle dedicated to ditch cleaning	Forward speed of ditch cleaning	0.3 km/h
	Fuel consumption	13 L/h
Vehicle dedicated to securing ditch cleaning sites	Forward speed of safety operation for ditch cleaning	0.3 km/h
	Fuel consumption	2.6 L/h
Vehicle dedicated to roadside dismantling	Forward speed of roadside dismantling	0.2 km/h
	Fuel consumption	13 L/h
Vehicle dedicated to securing roadside dismantling sites	Forward speed of safety operation for roadside dismantling	0.2 km/h
	Fuel consumption	2.6 L/h

our research are provided by manufacturers or by communities in interviews.

c) Transport of biomass

The transport of herbaceous biomass only concerns scenario 2. These GHG emissions depend on the amount of grass collected. Former experiments carried out in the French department of Mayenne and Vosges identified key information concerning the transport of biomass for recovery purposes. Another study showed that 50 kilometres of mown road corresponds to approximately 100 tons raw material of grass to be recovered, which is equivalent to 2 tons raw material of grass per kilometre [6]. Another French study estimates that the average yield of collected biomass observed on the sites is 0.8 tons of raw material per kilometre, with variations from one site to another (depending on the date of intervention, the type of surface etc.) [26]. These values are consistent, for this study we consider thus, a yield of 0.8 tons per kilometre.

The biomass is collected in boxes with a storage capacity of 4 tons [6]. Once filled, these boxes are transported from the mowing plant to the transport trucks. We assume that emissions related to the loading/unloading of the boxes are negligible as this transfer takes little time and energy. Therefore, GHG emissions are mainly related to the transport of biomass from the sites to the recovery sites. The latter are usually located 20 kilometres from the sites [6]. Note that the transport activity does not require special securing measures. TABLE II relates to the work site data used in our research are provided by manufacturers or by communities in interviews.

d) Routine maintenance

Routine maintenance includes roadside dismantling and ditch cleaning activities, carried out with a mechanical shovel. The work site data do not differ between the scenarios. TABLE III relates to the work site data used in our research are provided by manufacturers or by communities in interviews.

According to experiments carried out in the Mayenne department, the frequency with which these activities carried out would differ according to the scenario, *i.e.* the removal of biomass would change the maintenance cycles [27], [28] because the biomass left on the ground raises the level of the

TABLE III. FREQUENCY OF ROUTINE MAINTENANCE ACTIVITIES ACCORDING TO THE SCENARIOS

Frequency	Scenario 1	Scenario 2
Maintenance cycle of ditch cleaning	15 years	20 years
Maintenance cycle of roadside dismantling	15 years	20 years

TABLE IV. DATA RELATED TO MOWING OPERATIONS IN ALL SCENARIOS

Data related to mowing operations		Scenario 1	Scenario 2
Vehicle dedicated to mowing	Forward speed of mowing operation	6 km/h	3 km/h
	Fuel consumption	15 L/h	20 L/h
Vehicle dedicated to securing mowing sites	Forward speed of safety operation	6 km/h	3 km/h
	Fuel consumption	2.6 L/h	

roadside and the bottom of the ditch and complicates the flow of water from the road. TABLE IV relates to assumptions made by this study on the routine maintenance frequency according to the scenarios.

Each of the above activities uses machinery powered by fuel, with an emission factor of 3.1 kilogram CO_{2e} per litre [19].

2) Activities at the supply chain scale

For a reminder, scenario 1 integrates the quantities of CO_{2e} emitted for the production of electricity, heat and fertilizers with “traditional” modes, whereas scenario 2 integrates the quantities of CO_{2e} emitted for the production of electricity, heat and digestate by methanisation (Fig. 2).

The amount of energy that can be recovered from the methanisation of biomass from mowing (biogas) represents 44,5% of the primary energy [6]. The rest of the primary energy is either used to fuel the anaerobic digestion and cogeneration process (heating of digesters, consumption within the anaerobic digestion or cogeneration process, etc.) or dissipated during cogeneration (unused heat, waste energy) [6]. The transformation of grass into methane generates 22.4 kilograms CO_{2e} per ton of raw material³ (methane emissions from the process, leakage and amortization induced by the methanisation).

The CARMEN project, focused on the methanisation of roadside grasses, states that [6]:

- One ton of roadside grass (raw material) produces 0.16-megawatt hours of electricity by cogeneration.
- One ton of roadside grass (raw material) produces 0.103-megawatt hour of heat by cogeneration.
- Fermentation leads to a 10% loss of mass of the biomass, *i.e.* one ton of grass produced 0.9 tons of digestate.

In order to compare the fertilizer obtained by scenario 1 and the digestate obtained by scenario 2, several assumptions were made. Firstly, it was considered that the production of digestate obtained by methanisation avoids the use of synthetic nitrogen fertilizers, which makes it possible to avoid the production emissions of these fertilizers [19]. The estimate of the emissions related to the production of fertilizer depends on (i) the nutrients present in the digestate, (ii) their content in kilograms in the digestate obtained by the methanisation of one ton of grass and (iii) the emissions from the manufacture of synthetic fertilizer equivalents from the Carbon Base®

TABLE VI. ESTIMATION OF THE EMISSION FACTORS RELATED TO THE PRODUCTION OF FERTILIZER WITH THE SAME CHARACTERISTICS AS THE DIGESTATE

Nutrients	Kg nutrients per ton of methanized grass	Manufacturing emissions in synthesis— kgCO _{2e} /kg nutrient	Total item (kgCO ₂ /ton of methanized grass)
Nitrogen (N)	3.6	4,270	15.37
Phosphorus (P ₂ O ₅)	1.16	1.35	1.57
Potassium (K ₂ O)	2.61	0.678	1.77
Total			18.71

TABLE V. SUMMARY OF EMISSION FACTORS USED TO ASSESS GREENHOUSE GAS EMISSIONS FROM BIOMASS RECOVERY

Emission factor			
Scenario 1		Scenario 2	
Non-renewable electricity generation	0.0785 kgCO _{2e} /kWh	Methane emissions during cogeneration	22.4 kgCO _{2e} /ton raw material
Non-renewable heat production	0.243 kgCO _{2e} /kWh		
Manufacturing, supply of mineral fertilizer	18.71 kgCO ₂ /ton	Fuel consumption	3.1 kgCO _{2e} /litre
Fuel consumption	3.1 kgCO _{2e} /litre		

[19]. The composition of nitrogen, phosphorus and potassium in the digestate depends on the biomass used in the methanisation process. Therefore, it is difficult to obtain a precise distribution of the nutrients found in the digestate obtained from the methanisation of roadside grass. Therefore, we assume that the proportion of nutrients in the digestate is approximately the same as in the compost (6.2 kilograms of nitrogen, 2 kilograms of phosphorus and 4.5 kilograms of potassium in one ton of compost) [19]. Analyses carried out in the CARMEN project showed a total nitrogen concentration of 3.6 kilograms of nitrogen per ton of grass [6]. Consequently, according to the same proportions as for compost, the composition of the digestate (for 0.9 tons of digestate following methanisation of one ton of grass) is as follows: 3.6 kilograms of nitrogen, 1.16 kilograms of phosphates and 2.61 kilograms of potassium. Thus, the emission item related to the production of fertilizers used in this study is presented in TABLE V.

Emissions related to the spreading of digestate from mown grass are to be considered, with a consumption of 65 L of fuel for 90 tons of digestate to be spread [6]. The consumption related to fertilization with chemical fertilizers is of the order of half of a digestate application [6].

TABLE VI shows the emission factors from Carbon Base® used to compare the two scenarios [19].

C. Step 3. Assessment of life cycle impacts

1) Activities at the roadside scale

In order to help define the GHG emissions calculation, a list of all required variables is defining (TABLE VII).

Based on the generic equation (1) presented in section III. C, the equation leading to the calculation of GHG emissions from different roadside maintenance activities are as follows.

Mowing, with (2) or without removal (3), depends on the number of passes made in a year, the length of the section maintained, the vehicle’s forward speed, its fuel consumption and its emission factor.

$$E_{GHG_{Mowing\ rec}} = N \times \frac{L}{S_{Vehicle\ of\ mowing\ recov}} \times C \times E_{Fuel} \quad (2)$$

$$E_{GHG_{Mowing}} = N \times \frac{L}{S_{Vehicle\ of\ mowing}} \times C \times E_{Fuel} \quad (3)$$

³ <https://naei.beis.gov.uk/data/>

TABLE VII. LIST OF VARIABLES USED IN THE CALCULATION

Variable	Unit	Description
$E_{GHG_{Maintenance\ Activity}}$	kgCO _{2e}	Emission of a maintenance activity
L	Km	Length of the roadside section
N	/	Number of passes in a year
$\sum T$	h	Sum of activity times
MC	year	Maintenance cycle
$D_{WS \rightarrow BP}$	km	Distance round trip between work site and biogas plant
SC	ton	Storage capacity of the removal box
$Q_{Grass\ or\ Q_{Wood}}$	ton	Quantity of biomass collected
$S_{Vehicle\ dedicated\ to\ Activity}$	Km/h	Forward speed of the vehicle
C	L/h	Fuel consumption
E_{Fuel}	kgCO _{2e} /L	Factor emission of fuel

The transport of biomass (4) considers the number of round trips made by the trucks to transfer the biomass from the mowing site to the biogas plants (amount of biomass transferred depending on the capacity of the box). The calculation also depends on the distance covered by the truck (round trip), its speed of travel, its fuel consumption and its emission factor.

$$E_{GHG_{Transport_{Grass}}} = \frac{Q_{Grass}}{SC} \times \frac{D_{WS \rightarrow BP}}{S_{Vehicle\ transport}} \times C \times E_{Fuel} \quad (4)$$

The equations related to roadside maintenance (ditch cleaning (5) and roadside dismantling (6)) depend on the maintenance cycles, the length of the section maintained, the vehicle's forward speed, its fuel consumption and its emission factor

$$E_{GHG_{Ditch\ cleaning}} = \frac{1}{MC_{Ditch\ cleaning}} \times \frac{L}{S_{Vehicle\ for\ ditch\ cleaning}} \times C \times E_{Fuel} \quad (5)$$

$$E_{GHG_{Roadside\ dismantling}} = \frac{1}{MC_{Ditch\ cleaning}} \times \frac{L}{S_{Vehicle\ for\ ditch\ cleaning}} \times C \times E_{Fuel} \quad (6)$$

Finally, the emissions related to securing the work sites (7) depend on the time spent on other activities, the consumption of the van and its emission factor

$$E_{GHG_{Safety}} = \sum T \times C \times E_{Fuel} \quad (7)$$

On the basis of these equations and identical initial conditions, it is then possible to compare the two scenarios. For this comparison, we have considered 2 initial conditions: (i) a length of road section equivalent to 1 kilometre and (ii) 3 mowing passes per year.

For the first scenario (mowing without biomass removal), mowing represents 43% of the emissions (47.4 kilograms of CO_{2e} per km for mowing). Routine maintenance (including roadside clearance and ditch cleaning) represents 41% of emissions (45.6 kilograms of CO_{2e} per km for all routine maintenance: 27.4 kilograms of CO_{2e} per km for roadside dismantling and 18.3 kilograms of CO_{2e} per km for the ditch cleaning). Securing the site accounts for 16% of the emissions (17.3 kilograms of CO_{2e} per km). For this scenario, total emissions from roadside maintenance amount to 110.4 kilograms of CO_{2e} per kilometre.

Scenario 1 - Mowing without removal (kgCO₂) Scenario 2 - Mowing with removal (kgCO₂)

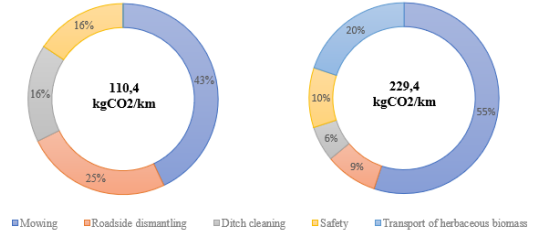


Fig. 3. Distribution of CO_{2e} emissions from each roadside maintenance activity under each scenario

For the second scenario (mowing with biomass removal), mowing with biomass removal represents 55% of the emissions (126.4 kilograms of CO_{2e} per km for mowing). Emissions related to biomass transport amount to 20% (45.5 kilograms of CO_{2e} per km). Routine maintenance of work sites accounts for 15% of emissions (20.5 kilograms of CO_{2e} per km for roadside dismantling and 13.7 kilograms of CO_{2e} per km for the ditch cleaning), while securing work sites accounts for 10% of emissions (23.3 kilograms of CO_{2e} per km). For this scenario, total emissions from roadside maintenance amount to 229.4 kilograms of CO_{2e} per km, which is 108% higher than for scenario 1. The distribution of CO_{2e} per km emissions for each scenario is presented in Fig.3.

2) Activities at the supply chain scale

In order to help define the GHG emissions calculation, a list of all required variables is defining (TABLE VIII).

Based on the generic equation (1) presented in section III. C, the equations leading to the calculation of GHG emissions from recovery activities are as follows.

Emissions from non-renewable electricity production depend on the amount of electricity produced (comparatively the same as from methanisation) and the associated emission factor.

TABLE VIII. LIST OF VARIABLES USED IN THE CALCULATION

Variable	Unit	Description
$E_{GHG_{Supply\ Chain\ Activity}}$	kgCO _{2e}	Emission of a supply chain activity
$Q_{biomass}$	t	Quantity of herbaceous biomass
$Q_{Electricity}$	kWh	Quantity of electricity produced from the collected biomass
Q_{Heat}	kWh	Quantity of heat produced from the collected biomass
$Q_{Digestate}$	t	Quantity of digestate produced for land applications (t)
$E_{NR\ elec\ generation}$	kgCO _{2e} /kWh	Non-renewable" electricity generation
$E_{NR\ heat\ generation}$	kgCO _{2e} /kWh	Non-renewable" heat generation
$E_{Fertilizer\ manuf}$	kgCO ₂ /t	Manufacturing, supply of mineral fertilizer
$E_{Methane\ emissions}$	kgCO ₂ /t	Methane emissions during cogeneration
$C_{Spreading}$	L/t	Fuel consumption per ton of digestate
E_{Fuel}	kgCO _{2e} /L	Factor emission of fuel

$$E_{GHG_{NR} \text{ elec generation}} = Q_{Electricity} \times E_{NR \text{ elec generation}} \quad (8)$$

Emissions from non-renewable heat production depend on the amount of heat produced (comparatively the same as from methanisation) and the associated emission factor.

$$E_{GHG_{NR} \text{ heat generation}} = Q_{Heat} \times E_{NR \text{ heat generation}} \quad (9)$$

Emissions from manufacturing, supply of mineral fertilizers depend on the amount of quantity of biomass and the emission factor of manufacturing and supply mineral fertilizers.

$$E_{GHG_{Fertilizer \text{ manuf}}} = Q_{biomass} \times E_{Fertilizer \text{ manuf}} \quad (10)$$

The equations for methane emissions during cogeneration depend on the associated emission factor and the amount of biomass processed.

$$E_{GHG_{Methane \text{ emissions}}} = Q_{biomass} \times E_{Methane \text{ emissions}} \quad (11)$$

Finally, the consumption related to the spreading of fertilizers and digestate depends on the quantity of digestate, the fuel consumption and the associated emission factor. For a reminder, the consumption related to fertilization with chemical fertilizers is of the order of half of a digestate application [6].

$$E_{GHG_{Digestate \text{ spreading}}} = Q_{digestate} \times C_{Spreading} \times E_{Fuel} \quad (12)$$

$$E_{GHG_{Fertilizer \text{ spreading}}} = \frac{Q_{digestate} \times C_{Spreading} \times E_{Fuel}}{2} \quad (13)$$

The data identified in section IV. B.2. allow for an assessment of the quantities of electricity, heat and digestate produced by the mowing of a one-kilometre stretch of roadside (TABLE IX).

Based on these equations and the identified data, GHG estimates for each scenario were obtained. In scenario 2, methane emissions during cogeneration account for 92% of the emissions (108 kilograms of CO_{2e} per km) while the spreading of digestate accounts for only 8% (10 kilograms of CO_{2e} per km). In total, the valorization of roadside grass through a methanisation process emits 118 kilograms of CO_{2e} per kilometre.

In scenario 1, non-renewable generated heat production emits the most (44% or 120 kilograms of CO_{2e} per km). The manufacture and supply of fertilizer accounts for 32% of

TABLE IX. ASSESSMENT OF THE QUANTITIES OF ELECTRICITY, HEAT AND DIGESTATE PRODUCED BY THE MOWING OF A ONE-KILOMETRE OF ROADSIDE

Initial conditions	A length of road section equivalent to 1 km 3 mowing passes per year
<i>Biomass removal yield</i>	0.8 tons/km
<i>Quantity of biomass recovered</i>	4.8 tons
<i>Quantity of electricity produced from the collected biomass</i>	768 kwh
<i>Quantity of heat produced from the collected biomass</i>	494 kwh
<i>Quantity of digestate produced for land applications</i>	4.32 tons

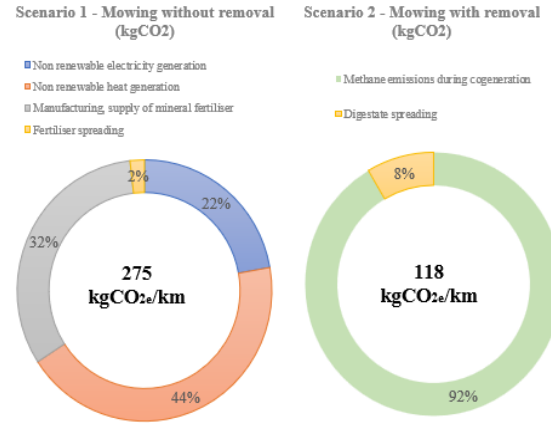


Fig. 4. Distribution of CO_{2e} emissions from each recovery activities under each scenario

emissions, *i.e.* 90 kilograms of CO_{2e} per kilometre. Non-renewable electricity generation emerges as 22% of emissions (61 kilograms of CO_{2e} per km) while fertilizer application accounts for 2% of emissions (5 kilograms of CO_{2e} per km). In total, the generation of electricity and heat and the production and use of fertilizers account for 275 kilograms of CO_{2e} per km, an increase of 133% compared to scenario 2.

The distribution of CO_{2e} per km emissions for each scenario is presented in Fig. 4.

D. Step 4. Interpretation of the study results

1) Activities at the roadside scale

This analysis shows that the maintenance of roadsides with the export of herbaceous biomass generates additional GHG emissions, which is logically explained by the presence of additional activities and the lengthening of worksite times. Mowing with removal emits almost 2.5 times more emissions than mowing without removal, which is due to the lower driving speed and higher consumption (additional equipment such as a suction unit or a trailer adds to the weight). The lower driving speed also implies an additional cost in terms of security, which is, however, limited by the increased routine maintenance cycles in scenario 2. Therefore, the emissions related to routine maintenance are lower in scenario 2 because, according to our previous assumptions, it is carried out less often. Finally, the scenario includes emissions related to the transport of herbaceous biomass that do not exist in scenario 1. The excess emissions from mowing with removal (+79 kilograms of CO_{2e} per km) coupled with the transport of biomass (+56.9 kilograms of CO_{2e} per km) lead to an increase of almost 4 times the mowing activity of scenario 1. The difference between the two scenarios lies in the approach to mowing. The comparison of CO_{2e} per kilometre emissions by activity for each scenario is presented in Fig. 5.

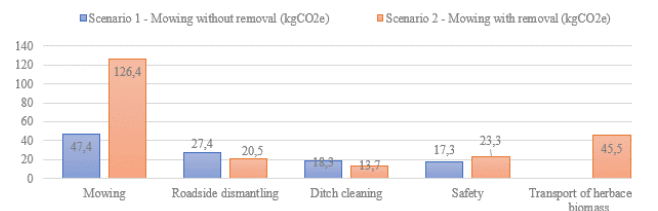


Fig. 5. Comparison of CO_{2e} emissions by activity according to the scenarios

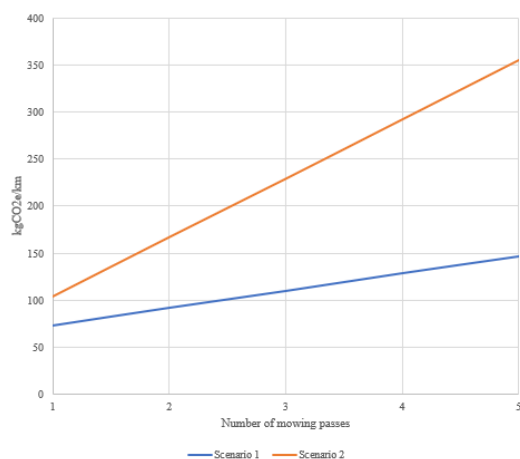


Fig. 6. Evolution of GHGs of the different scenarios following a change in the number of mowing passes

The excess emission linked to the biomass removal is not fixed, it evolves according to the initial conditions chosen for mowing, *i.e.* the number of passes made per year, while the emissions linked to routine maintenance remain linked to the length of the road section studied (Fig. 6). This change is partly explained by the inclusion of a grass biomass transport activity in scenario 2. Indeed, the GHG emissions of the majority of the activities increase relatively proportionally between the two scenarios, but the increase in the number of mowing operations increases the amount of grass collected, which leads to a higher frequency of transport of herbaceous biomass.

2) Activities at the supply chain scale

As seen before, at the roadside scale, the previous analysis tends to show that scenario 1, without biomass removal, emits less greenhouse gases than scenario 2. Thus, an analysis of roadside maintenance only seems to show that scenario 1 is the most favourable. However, at the supply chain scale, the above analysis tends to show that scenario 2, with biomass removal, emits less greenhouse gases than scenario 1. The integration of the two scales tends to show that from a greenhouse gas point of view, scenario 2, which consists of recovering roadside biomass through a methanisation process, would have a more favourable impact in terms of GHG emissions than scenario 1 (approximately 40 kilograms of CO_{2e} per km) (Fig. 7).

V. CONCLUSION

A. Limitation and future work

This article highlights the complexity of such an approach to roadside management, as this analysis required a number of assumptions and approximations in maintenance activities. Choices and assumptions were made at different steps of the method used. Concerning the step 1 dedicated to the definition of the objectives and the scope of the study, a decision was made to focus on the maintenance and recovery of one kilometre of roadside. Emissions generated by equipment between the workshop and the work site were not considered because (i) it was difficult to establish a fixed distance between these two locations and (ii) this information depends on the specificities of the territory (mountainous area, urban area...). However, our study showed that, as for mowing, the emissions linked to mowing equipment on these workshops/worksite routes would vary according to the scenario (higher consumption linked to the weight of the

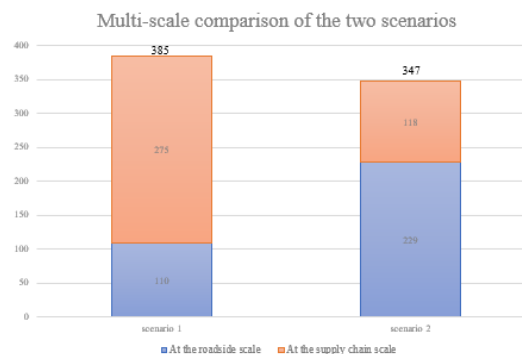


Fig. 7. Balance of GHG emissions of each scenario based on the assumptions considered in our study

mowing equipment for example). In addition, this analysis does not consider emissions related to the manufacture of biomass recovery equipment and infrastructure. We considered that the recovery of roadside biomass was carried out in existing infrastructure. Concerning the step 2 dedicated to the life cycle inventory, several assumptions were made. In the two scenarios studied, the data used are averages (consumption, forward speed), which will depend on several parameters such as vegetation density, weather conditions, presence of obstacles, driver experience. The strategy of mowing with biomass removal is still at the experimental stage in France and only a few departments have implemented this new strategy on a few road sections. This implies a limited data set (speed of progress in particular) and a lack of hindsight on long-term impacts (routine maintenance cycle for example). In addition, the yield of biomass recovery can vary depending on the type of biomass, the geographical location, and the climatic conditions. The scenario 2 focuses only on the recovery of grass alone in a cogeneration methanisation process. Once again, the data may change depending on the process or the type of input. It should also be noted that it would be interesting to carry out this analysis on other recovery methods (composting, methanisation by injection, recovery in the form of insulation, etc.). Finally, approximations were made on the nutrient composition of the digestate to compare its contribution to that of mineral fertilizers.

Consequently, the GHG emission estimates presented here should be treated with caution. Experiments will therefore have to be carried out to validate our approximations. However, this analysis, which focuses on greenhouse gas emissions, highlights the importance of multi-scale approaches in analysing the impacts of human practices. Indeed, the study highlights the importance of life cycle analysis in analysing the impacts of decisions and thus guiding decision-makers in their management choices, particularly for sustainability purposes.

Finally, the paper presents an analytical framework that can be used to explore the potential impacts of two mowing strategies. The use of a single indicator allows us to test the methodology and discuss the scale of our study. However, evaluating roadside management with biomass use using LCA methodology remains rough and exploratory but has the merit of indicating the magnitude of change needed. The ability to demonstrate the sustainability of the carbon footprint beyond the quantitative indicators by extrapolating to the meso-level analysis (environment: geographic and climatic characteristics of the location, distance travelled) presents a

limit to the generalization of the methodology. Consequently, one of the avenues for future work would be to go further in the environmental analysis of these scenarios by proposing an integrated set of indicators for the management of these spaces, considering GHG reduction. In addition, this analysis could be completed by a study of the impacts of these scenarios on the ecosystem services provided by roadsides in order to establish their relevance.

B. Match and contribution

In a context shaped by the acceleration of climate change, the scarcity of resources and geopolitical tensions, the energy transition is at the heart of many countries' concerns. The bio economy contributes to this transition by encouraging the shift from fossil-based production to that based on renewable biomass [29]. It refers to multiple realities in terms of processes, actors and conceptions of the ecological transition, in particular through the recycling of waste [30]. A sustainable bio economy requires sustainable production, conversion and distribution of biomass [31], it is about minimizing the impact of human activities on the natural environment and natural resources [32]. This study questions these notions of the bio economy and the impact of human activities through the prism of greenhouse gas emissions. The aim is to ascertain the interest of new roadside management practices that could lead to the exploitation of new biomass sinks while guaranteeing sustainable exploitation. This multi-scale approach therefore underlines the importance of having wider studies when evaluating new approaches to identify whether they will actually minimize impacts. Furthermore, it highlights that separate views (economic, environmental) are not representative and that multi-perspective approaches are needed to find the best trade-offs. Finally, it is also important to seek to capture specific data to refine assessments and studies and ensure the quality of analyses.

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