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Climate change vulnerability risk assessment methodology for waste management infrastructure from public and private perspectives

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ABSTRACT: The increasing volume of waste and the impact of climate change pose significant challenges for landfill waste management. To address these issues, the LIFE GREEN ADAPT project aims to increase the resilience of European landfill infrastructures through the implementation of blue-green infrastructures and nature-based approaches. By managing flood risks, preventing fires and explosions, and improving soil and water quality, the project aims to enhance landfill resilience to climate-related impacts. Through the application of bio-technosoils and treatment wetlands, the project seeks to stabilize soil, treat polluted leachate, and reduce greenhouse gas emissions. This paper provides an overview of the vulnerability risk assessment conducted for Xiloga's landfill, highlighting the need for adaptive measures in landfill design and the potential for replicating the project's solutions throughout Europe.

Keywords: Climate change adaptation, fire, flood, risk

1. INTRODUCTION

Waste management constitutes today a major environmental, economic and social worldwide problem, mainly because the waste volume is growing faster than the world's population. Therefore, there is a need to consider potential challenges in landfill waste management over significant timescales to respond appropriately.

In line with the EU Strategy on Adaptation to Climate Change that aims at making Europe more climate-resilient, European landfill infrastructures need to anticipate and assess the vulnerability and risks to adapt to current and future climate variations and be resilient to any possible hazards or disruptions. The project LIFE GREEN ADAPT aims to increase the resilience of EU waste infrastructures against climate change. This will be achieved by demonstrating the potential of blue-green infrastructures (BGI) and nature-based approaches to manage flush flooding and run-off caused by heavy rainfall and prevent

fires and explosions caused by droughts and unusual heatwaves. LIFE GREEN ADAPT project will implement and demonstrate actionable solutions to trigger significant improvements in landfill resilience to climate change through bio-technosoils and treatment wetlands (TW) systems application, enhancing their adaptation against climate-related impacts (e.g., water scarcity, wildfires, landslides, leachate infiltration) caused by primary climate drivers (i.e. extreme temperatures or extreme precipitation). The risk of landfills being affected by climate change increases due to the longevity of the infrastructure, being operated and remaining active for decades (a closed landfill is issuing leachates and greenhouse gases for up to 25 years). A number of climate impacts threatens the waste sector, and particularly landfills:

- Increased risk of flooding from extreme precipitation events affecting soil stabilization and leachate infiltration,
- Reduced water availability for wet processes and site management (particularly during summer) from rises in temperature,
- Increased risk of wildfires and explosions caused by drought periods and unusual heatwaves.

The project expects to have a range of results and impacts from the application of bio-technosoils made of wastes from the landfill that will be used to stabilise and recover soil by improving its structure and increase soil quality by regulating nutrient supply. New wastewater treatment wetlands (TW) will be engineered to address polluted landfill leachate and run-off, achieving above 90% reduction in heavy metals, ammonium and DBO5 and providing treated water prepared for reuse. Finally, an industrial demonstration site will be used to validate the potential of the BGI and nature-based approaches and verify their performance. The present paper describes the vulnerability risk assessment developed for Xiloga's landfill infrastructures based on the Fifth Assessment Report, AR5, of the Intergovernmental Panel on Climate Change, IPCC (2014).

2. LIFE GREENADAPT - Nature based solutions for climate change resilient waste infrastructures

2.1.Landfill challenges

Waste disposal infrastructures are growing alongside population growth worldwide. According to the World Bank, waste disposal was about 2 billion annual tons in 2016, and is estimated to rocket to 3.4 billion by 2050. Municipal solid waste management in classic landfills or dumpsites continues to be the common practice worldwide (above incineration or compost). Recent estimates suggest that there are at least 500,000 operational and closed landfills in the EU-28 and most of them (~90% with an estimated total volume of 30–50 Gm3 of waste) are under 'non-sanitary' conditions, i.e., having none or little environmental protection technologies (EU Interreg, 2020). The evaluation of their impact is receiving increased attention, as: they will account for about 10% of GHG emissions by 2025; these emissions are oftentimes the cause of fires or explosions (often occurring inside the landfill); they can contaminate soil and groundwater when waterproof membranes break; they have been observed to alter migratory activity of birds and reduce the value of the surrounding areas; moreover, they can collapse and cause landslides (Vaverková, 2019).

Landfills are vulnerable to the expected effects derived from climate change due to the increased temperatures, rising sea-levels and frequency and extreme weather events, with potential for droughts, floods, heatwaves, and greater pressure on water availability. They can remain operational (including the aftercare and restoration period) for 100 years or more. These facilities will potentially need to continue to operate under the changing climate conditions that will be experienced over the course of the 21st century, and beyond. To this regard, climate change impacts should be considered not only when designing new infrastructure, but also there is a legacy of landfill sites that may need enhanced resilience to deal with the future climate conditions. One of the adverse effects introduced by climate severe changes is the potential rise on the amount of leachate infiltrated into the soil and groundwater due to

increased rainfall and run-off. On the other hand, fires have a greater chance to happen due to the global warming influence, which in turn increase the chance of erosion and consequent landslides. To this end, an strategy to enhance the resilience of landfill sites to upcoming climatic challenges should be built up through the employment of management practices that provide environmental, economic and social benefits.

2.2.LIFE GREEN ADAPT project

The European project LIFE GREEN ADAPT aims at increasing the resilience of the EU waste infrastructures (focused on landfills) against climate change by demonstrating the potential of blue-green infrastructures and ecosystem-based approaches to manage flush flooding and run-off caused by heavy rainfall and prevent fires and explosions caused by droughts and unusual heatwaves. Specifically, LIFE GREEN ADAPT will employ an innovative and widely replicable approach through the application of bio-technosoils and a combination of large-scale constructed wetlands to treat run-off and leachate from a landfill in NW Spain.

The application of these innovations will reduce the risk of landslides associated with floods and heavy rainfall events, by stabilising and amending the soil through the use of bio-technosoils and the application of circular economy principles. In addition, it will allow the effective management of new green areas, such as landfill covers, by reducing water consumption and stormwater run-off, thanks to the greater retention and infiltration capacity (and encourage the non-use of peat, leonardite or topsoil). Moreover, the project will include an innovative combination of improved treatment wetlands to enhance the water storage and removal performance of biodegradable organic compound and heavy metals from landfill leachate. These include a first pretreatment of leachate within a floating treatment wetland (FTW) containing floating macrophytes. Water is then conveyed to an innovative combination of aerated vertical flow wetland with geopolymers used as filter media (GPs-ATW) and a wetland containing microbial electrochemical technology (electroactive biofilm-based treatment wetland, EAB TW). The main expected results at the end of the project are an increased landfill life span of 50%, more than 4 ha recovered with biotechnosoil, more than 6,000 m3/year of treated wastewater, freshwater consumption saving around 600 m3/year and above 93,000 tCO_2eq/year avoided.

The technologies developed within the project will be validated on a real scale at Xiloga's landfill, in As Somozas (Galicia), during the next four years. GREEN ADAPT solutions are expected to be replicated in waste management facilities throughout Europe. To this end, the knowledge base for the development, assessment and monitoring of adaptation actions at the landfill level will be improved and will aid in boosting the adoption of climate change adaptation measures according to the EU policies.

3. VULNERABILITY RISK ASSESSMENT

The vulnerability risk assessment for Xiloga's landfill considers the current (baseline) and future (improved) infrastructure situation, and will analyse the landfill's current adaptive situation and the increase in resilience achieved through LIFE GREEN ADAPT (e.g., fire risk reduction, less polluted leachates). For a more comprehensive analysis, the risk assessment will be done from both public and private perspectives.

3.1. Methodologal analysis

3.1.1. Vulnerability assessment from a Public Authorities perspective

From the point of view of the public authorities, a climate risk analysis will be carried out applying a vulnerability and risk assessment methodology in alignment with the following IPCC AR5 concepts and definitions (IPCC, 2014) that identify climate risk as a result of the interaction among different factors (Figure 1):

- **Hazards**: "The potential occurrence of a (…) physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources (…)". Hazards can be divided into current and future hazards; the latter being determined based on climate projections.
- **Exposure**: "The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected."
- **Vulnerability**: "The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt (…)."
    - **Sensitivity**: "The degree to which a system or species is affected, either adversely or beneficially, by climate variability or change."
    - **Adaptive capacity**: "The ability of a system to adjust to climate change, to moderate potential damages, to take advantage of opportunities, or to cope with the consequences."

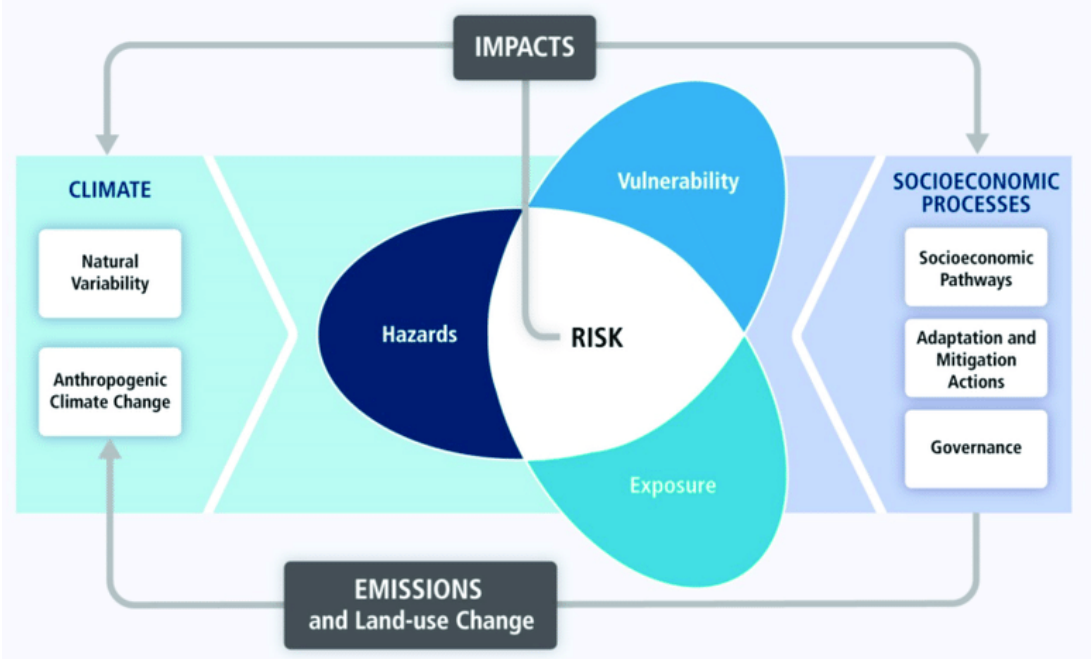


Figure 1. Risk determinants. (Source: (IPCC, 2014))

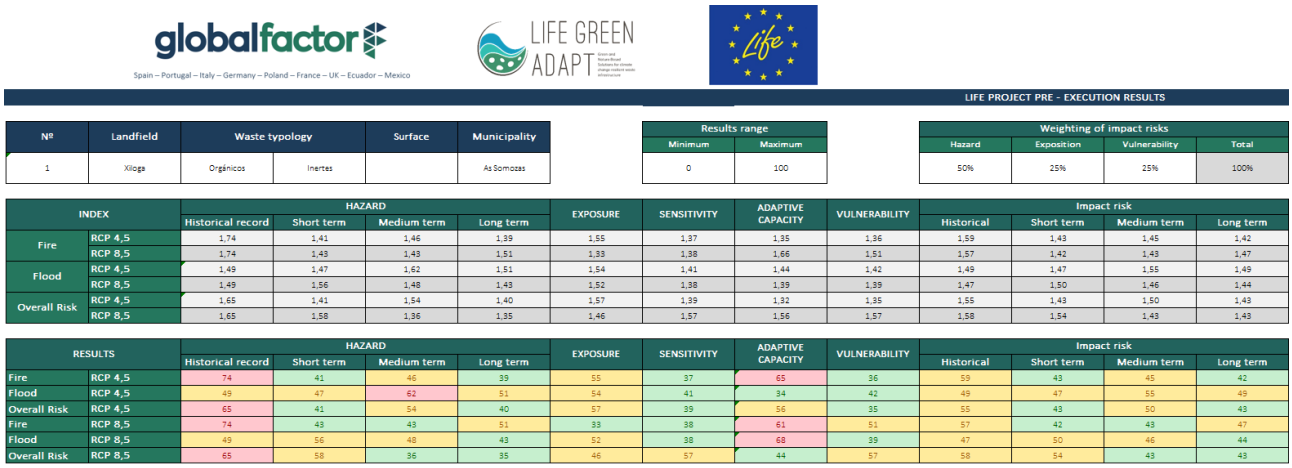
In the context of climate change impacts, risk results from the dynamic interactions between the different climate-related hazards (high temperatures, heavy rainfall, etc.) and the exposure and vulnerability of the affected human or ecological systems. Climate risk is thus a result of the interaction between hazards, exposure, and vulnerability.

The two main priority hazards to Xiloga's waste infrastructure include heat waves/extreme temperatures, and flooding from extreme precipitation. Increased temperatures can cause small fires and/or explosions, and flooding events can lead to uncontrolled polluted leachate spillovers in landfills.

In this context, the current and (baseline) future (improved, through the use of BTS) climate-related risk of Xiloga's landfill's infrastructure will be assessed through a tool specifically designed for the site

that reflects a five-step preocedure (Nardo et al., 2005; Saisana & Tarantola, 2002)[1] consisting of (i) selecting appropriate indicators, (ii) data quality check and normalization, (iii) assigning weights to the indicators, (iv) aggregation, and (v) results. This tool will allow calculating the risk associated with the two main climate-related threats that were identified for Xiloga's landfill (fires and floods), with and without the innovative solutions (BTS) of LIFE GREEN ADAPT.

The climate-related indicators associated with the two main climate-related threats that were identified for Xiloga's landfill (fires and floods), were downloaded from AdapteCCa, a platform for exchanging and consulting information on adaptation to climate change in Spain. The indicators associated with the exposure, sensitivity and adaptive capacity are still being identified and discussed with other project partners, namely AIMEN and Xiloga. The vulnerability assessment will be undertaken using different future scenarios (RCP4.5 and RCP 8.5) and time horizons (historical record, short-, medium- and long-term) (see Figure 2).



LIFE PROJECT PRE - EXECUTION RESULTS

Nº	Landfield	Waste typology		Surface	Municipality
1	Xiloga	Orgánicos	Inertes		As Somozas

Results range	
Minimum	Maximum
0	100

Weighting of impact risks			
Hazard	Exposition	Vulnerability	Total
50%	25%	25%	100%

INDEX		HAZARD				EXPOSURE	SENSITIVITY	ADAPTIVE CAPACITY	VULNERABILITY	Impact risk			
		Historical record	Short term	Medium term	Long term					Historical	Short term	Medium term	Long term
Fire	RCP 4,5	1,74	1,41	1,46	1,39	1,55	1,37	1,35	1,36	1,59	1,43	1,45	1,42
	RCP 8,5	1,74	1,43	1,43	1,51	1,33	1,38	1,66	1,51	1,57	1,42	1,43	1,47
Flood	RCP 4,5	1,49	1,47	1,62	1,51	1,54	1,41	1,44	1,42	1,49	1,47	1,55	1,49
	RCP 8,5	1,49	1,56	1,48	1,43	1,52	1,38	1,39	1,39	1,47	1,50	1,46	1,44
Overall Risk	RCP 4,5	1,65	1,41	1,54	1,40	1,57	1,39	1,32	1,35	1,55	1,43	1,50	1,43
	RCP 8,5	1,65	1,58	1,36	1,35	1,46	1,57	1,56	1,57	1,58	1,54	1,43	1,43

RESULTS		HAZARD				EXPOSURE	SENSITIVITY	ADAPTIVE CAPACITY	VULNERABILITY	Impact risk			
		Historical record	Short term	Medium term	Long term					Historical	Short term	Medium term	Long term
Fire	RCP 4,5	74	41	46	39	55	37	65	36	59	43	45	42
Flood	RCP 4,5	49	47	62	51	54	41	34	42	49	47	55	49
Overall Risk	RCP 4,5	65	41	54	40	57	39	56	35	55	43	50	43
Fire	RCP 8,5	74	43	43	51	33	38	61	51	57	42	43	47
Flood	RCP 8,5	49	56	48	43	52	38	68	39	47	50	46	44
Overall Risk	RCP 8,5	65	58	36	35	46	57	44	57	58	54	43	43

Figure 2. Tool developed for Xiloga's landfill vulnerability assessment.

Finally, based on the results from the risk assessment, an economic analysis reflecting potential climate change-related costs on the landfill will also be developed.

3.1.2. New tools for waste management private sector

From the private point of view, the main climate-related risks and opportunities for private actors in the European waste management sector will be identified. A situational analysis of landfills in Europe will allow the identification of potential risks and related opportunities associated with the management of this type of infrastructure. For three (3) of these risks and opportunities, an estimation of the financial impacts will be developed. The assessment aims to provide valuable insights to private actors in the European waste management sector and assist them in understanding and addressing potential risks and opportunities. A thorough situational analysis will be carried out to identify the key climate-related risks and opportunities for private actors in the waste management sector. This analysis will involve examining the current state of landfills in Europe, taking into account factors such as location, design, operational practices, and environmental regulations. The identified risks will encompass various climate-related hazards, including but not limited to increased temperatures, extreme precipitation events, flooding, and wildfires. These hazards can have direct and indirect impacts on landfill operations, infrastructure integrity, waste containment, and environmental protection measures. Conversely, the assessment will also identify potential opportunities that arise from climate change, such as the adoption of innovative

[1] Nardo, M., Saisana, M., Saltelli, A., Tarantola, S., Hoffman, A., & Giovannini, E. (2005). *Handbook on constructing composite indicators.* Retrieved from https://pdfs.semanticscholar.org/33eb/3485d310454e9874c3a05dabd3d4b33623b5.pdf

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technologies, improved waste management practices, and the implementation of sustainable and resilient solutions. To evaluate the financial implications of the identified risks and opportunities, a detailed estimation of the potential financial impacts will be carried out. This assessment will provide private actors with valuable insights into the costs associated with climate change-related risks and the potential benefits that can be derived from addressing these risks effectively.

The financial impact assessment will consider multiple factors, including investment requirements for adaptation measures, operational costs, potential revenue streams from innovative solutions, and potential cost savings resulting from improved waste management practices. By quantifying the financial implications, private actors can make informed decisions and prioritize their actions based on the risk-reward trade-offs.

4. Conclusion

In conclusion, the vulnerability risk assessment methodology developed for Xiloga's landfill infrastructure considers both the public and private perspectives. The assessment aims to provide a comprehensive understanding of the climate-related risks and opportunities associated with waste management infrastructures. By analyzing and evaluating these risks, decision-makers can develop effective adaptation strategies and enhance the resilience of waste management systems. The assessment encompasses a range of factors, including hazards, exposure, vulnerability, and adaptive capacity. It considers climate-related threats such as fires and floods and employs a tailored tool for risk assessment. Additionally, an economic analysis will be conducted to estimate potential climate change-related costs on the landfill. From the private sector perspective, a situational analysis will identify risks and opportunities in the waste management sector. Financial impact assessment will quantify the potential financial implications and enable informed decision-making. By integrating the results from both perspectives, the vulnerability risk assessment methodology provides valuable insights for stakeholders in the waste management sector, aiding in the development of robust adaptation strategies and the promotion of climate-resilient waste infrastructures.

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