Estimation of Methane Emissions Released from a Municipal Solid Waste Landfill Site through a Modelling Approach: A Case Study of Akouédo Landfill, Abidjan (Côte d'Ivoire)

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Abstract: ***Municipal Solid Waste landfilling is the most common waste elimination in the developing countries in general and particularly in Côte d'Ivoire. However, gaseous emissions from waste landfilled constitute an environment and human health concern by contributing to greenhouse gas effects, odour problems, explosion and fire hazards as well as sources of air pollution. In this study, methane emissions rates from Akouédo (Abidjan) landfill have been estimated using three theoretical models such as Landfill Gas Emission Model (LandGEM, version 3.02), Intergovernmental Panel on Climate Change (IPCC) waste model and Solid Waste Emissions Estimation Tool (SWEET). Two types of parameters have been used to estimate methane emissions, default parameters and site-specific parameters. The results of simulations of the three models are compared as well as the results from their default and site-specific parameters. Results show that LandGEM simulations using both default and site-specific parameters are higher than IPCC waste model's simulations, whilst SWEET predicts the lowest methane emissions. SWEET seems to make better simulations than LandGEM and IPCC waste model, for it uses more parameters. Comparison of emissions results show that Akouédo landfill is one of the most emitting methane sites after Karaj and Kahrizak landfills in Tehran (Iran).***

Keywords: LandGEM, IPCC, SWEET, Akouédo landfill.

1. Introduction

Landfill disposal continues to be the most economically viable municipal solid waste (MSW) management practice in many countries [1], however, mismanagement of landfills sites is an environmental concern. Today, there is a worldwide attention to emission of greenhouse gases (GHGs) from MSW treatment and disposal processes as one of the main sources of anthropogenic gas emissions. Approximately 70% of methane emissions are anthropogenic (e.g., agriculture, natural gas activities, landfills, etc.) and 19% (70 Tg/year) of these are attributed to landfill gas generation [2]. Solid waste generated is deposited into open dumping sites with hardly any segregation and processing. Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are the major greenhouse gases that are released from the landfill sites due to the biodegradation of organic matter [3]. Landfill gas contains roughly 50-55% of CH_4 and 45-50% of CO_2, with less than 1% of non-methane organic compounds (NMOCs) and trace amounts of inorganic compounds. Methane is a potent GHG, with a Global Warming Potential (GWP) 28 to 36 times higher than that of carbon dioxide over a 100 year period [4]. For, landfills are major sources of global methane emissions, it is important to have tools to estimate these emissions. Quantifying methane emission from landfills is important to evaluating measures for reduction of GHG emissions [5]. It's difficult to estimate the total potential biogas production and therefore past and future emissions due to the lack of site-specific data and knowledge about past landfill management. Due to the difficulties in precisely monitoring methane emissions of whole landfill sites, modelling approaches were applied [6]. These approaches included, various theoretical models such as Intergovernmental Panel on Climate Change (IPCC) models [7], the Landfill Gas Emissions Model (LandGEM) [8] and the Modified Triangular Method (MTM) [9]-[3]-[10] were commonly used to predict the annual methane emissions. However, landfill gas models continue to receive criticism due to their poor accuracy and insufficient validation [11]. Previous studies, [12]-[3] used several models (IPCC, LandGEM and MTM) to estimate methane emissions from landfills with sites specific parameters. For example, [13]

Table 1: Akouédo landfill characteristics

Characteristics	Data
Type of landfill	Open dump [14]
Area (ha)	153
Waste in place	2.0 10^7 ton from 1965 to 2004 [15]
Designed landfill capacity	Not designed
Average waste depth	4-8 m [15]
Year of start	1965
Year of closure	2018
Quantity of waste accepted	More than 1 million ton per

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annually at landfill	year [15]
Waste management facility	No segregation of waste, very basic compaction
Landfill gas collection system	Currently not operational
Annual average precipitation (mm/year)	1750 (SODEXAM) in [16]

found that methane estimation with IPCC models were higher than those of LandGEM in Indore City (India). Moreover, [11] used Indian waste characteristics and site specific conditions to calculate parameters for estimating methane emissions using LandGEM model. Recently, [17] estimated Landfill Gas (LFG) generation and the energy potential from Akouédo landfill using the version 2.0 of Mexico Landfill Gas Model (MLGM). The LFG was estimated with the parameters k, CH_4 generation rate and Lo, CH_4 generation potential was determined according to the in situ characteristics. [6] predicted methane emissions of the new sanitary landfill of Kossihouen in the District of Abidjan using LandGEM defaults and site specific parameters from [17]. Thus, this study is the first which compares CH_4 emissions of Akouédo landfill with the most used theoretical models (LandGEM and IPCC waste model) and the Solid Waste Emissions Estimation Tool (SWEET). The aim of this study is to estimate methane emission from Akouédo landfill using LandGEM, IPCC and SWEET models and make comparison of the results to others studies.

2. Materials and methods

2.1 Site description

Akouédo landfill (5°21'07"N, 3°56'30"W) is located in the municipality of Cocody on the Abidjan-Bingerville axis (see figure 1). Built in 1965, it is covering about 153 ha. This landfill was intended for the burial of waste from the autonomous district of Abidjan composed of 10 municipalities in the city (Abobo, Adjamé, Attécoubé, Cocody, Koumassi, Marcory, Plateau, Port-Bouët, Treichville and Yopougon) and 3 neighbouring municipalities (Anyama, Bingerville and Songon). It receives more than one million tonnes of waste per year [15]. Its capacity was far exceeded. No proper compaction of solid waste was carried out at the site and the underground drainage system; liner cover system and leachate collection system were absent. Leachate is drained in an anarchistic way under the heaps of garbage [18]. In general, the average annual precipitation of Abidjan District is about 2000 mm with a transitional equatorial climate that is divided into four (4) seasons in the annual cycle, the great dry season from December to April, the great rainy season from May to July, the small dry season from July to September, and the small rainy season from October to November [19]. The climate of Abidjan is a great factor which permits rapid degradation of the waste. According to the results of the general population census in 2014, the District of Abidjan has an estimated population of more than 4.7 million inhabitants [20]. The characteristics of Akouédo landfill are summarised in table 1.

Table 1: Characteristics of Akouédo landfill

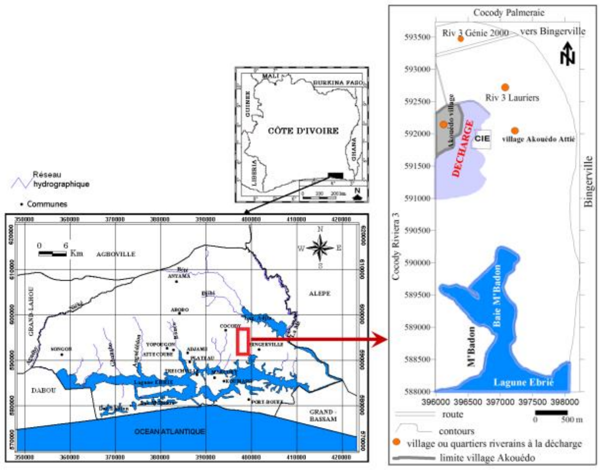

Figure 1: Location of Akouédo landfill [21]

2.2 Description of landfill gas models

In order to predict the potential annual methane emission from landfill, several models such as Intergovernmental Panel on Climate Change waste models, Shell Canyon model and Landfill Gas Emissions Model are wildly used. Landfill methane models are tools used to project methane generation over time from a mass of landfilled waste. These models are used for sizing landfill gas (LFG) collection systems, evaluations and projections of LFG energy uses, and regulatory purposes [22]. In this study, we used LandGEM US EPA's model, IPCC waste model, and Solid Waste Emissions Estimation Tool (SWEET) to estimate annual methane emissions of Akouédo landfill, these models are described below.

US EPA's LandGEM

The Landfill Gas Emissions Model (LandGEM) provides an automated estimation tool for quantifying air emissions from municipal solid waste (MSW) landfills [8]. LandGEM was developed by the United States Environmental Protection Agency (US EPA) in order to determine and predict methane, carbon dioxide and non-methane organic compounds (NMOCs) and others pollutants emissions from municipal solid waste landfills. LandGEM uses the first-order decay equation below to estimate methane generation.

$$Q_{CH4} = \sum_{i=1}^{n}\sum_{j=0.1}^{1} kLo\left(\frac{Mi}{10}\right)\left(e^{-ktij}\right) \quad (1)$$

Where Q_{CH4} is the annual methane production in a given year of calculation (m^3/year) ; $i = 1$ and $j = 0.1$ are the year time increment; n is the difference between the year of the calculation and the initial year of waste acceptance; k is methane generation rate ($year^{-1}$) ; L_0 is potential methane generation capacity (m^3/Mg or cubic feet per ton) ; M_i is the mass of solid waste disposed in the i^{th} year (Mg or ton); t_{ij} the age of the j^{th} section of waste mass disposed in the i^{th} year (decimal years).

IPCC Waste Model

The IPCC waste model 2006 is a first order multi-phase model based on waste composition data. The amounts of degradable waste material (food, garden and park waste,

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paper and cardboard, wood, textiles) contained in the waste are entered separately [23]. It is used for the estimation of CH_4 generation from all the countries in the world. The IPCC model, similarly to the US EPA's LandGEM, uses a first order decay equation [3].

$$Q_{CH4}\ Emission = \sum [MSWt * MSWf * MCF * DOC * DOCf * F * (\frac{16}{12} - R] * (1 - OXt) \quad (2)$$

Where Q_{CH4} $Emission$ is the amount of methane emissions (Gg/year), $MSWt$ and $MSWf$ are respectively the waste mass (Gg_{MSW}) and the fraction of municipal solid waste landfilled for the considered year; DOC; $DOCf$ are respectively the Degradable Organic Carbon (Gg/Gg_{MSW}) and the fraction of DOC dissimilated; F is the fraction of CH_4 in the landfill gas (set equal to 0.5); MCF is methane correction factor based on landfill management strategy (set equal to 1); R is the CH_4 recovered (Gg/year); OX is the methane oxidation factor (fraction), $OX = 0$ (default value); $16/_{12}$ is a stoichiometric factor, the quotient of the molecular weight of methane and carbon.

Solid Waste Emissions Estimation Tool (SWEET)

SWEET was developed by Abt Associates and SCS Engineers on behalf of the U.S Environmental Protection Agency (EPA) and the Climate and Clean Air Coalition (CCAC) Municipal Solid Waste Initiative. The tool assists users in determining first-order city-level estimates of annual emissions of methane, black carbon, and other pollutants (e.g., carbon dioxide) from various sources in the waste sector. The tool was designed with a particular focus on methane and black carbon, which are short-lived climate pollutants (SLCPs) [24]. Methane generation is calculated in SWEET using the following equation derived from the EPA's Landfill Gas Emissions Model (LandGEM) version 3.02.

$$Q_{CH4} = \sum_{t=1}^{n} kL_0 Mi(e^{-kti})(MCF) \quad (3)$$

Where: Q_{CH4} is the maximum expected methane generation flow rate (m^3/year); $i = 1$ is the year time increment; n is the difference between year of the calculation and the initial year of waste acceptance; k is the methane generation rate ($year^{-1}$); L_0 is the potential methane generation capacity (m^3/Mg); M_i is the mass of solid waste disposed in the i^{th} year (Mg); t_i is age of the waste mass Mi disposed in the i^{th} year; MCF is the methane correction factor.

2.3 Models parameters

IPCC waste model can be used either with default values or site-specific data such as waste generation rate, population, composition of waste, degradable organic carbon (DOC), fraction of degradable organic carbon dissimilated (DOC_f), waste decay rate (k), CH_4 correction factor (MCF), LFG collection efficiency and oxidation factors [3]. In this paper, two types of parameters are used for IPCC waste model. Defaults parameters from [7] and site-specific calculated parameters from [17]. Table 2 summarises parameters used to run the IPCC waste model in this paper. For estimating methane emission rates, LandGEM uses either site-specific data or default parameters from Clean Air Act (CAA) or Inventory defaults. In this paper, we used CAA defaults and site specific parameters from [17]. These parameters are listed in the table 3. According to SWEET, details information about landfill management and climate of the considered site are required. These data are summarised in the table 4. SWEET model does not provide alternative default data.

Table 2: IPCC waste model parameters

	Sources	
	Defaults parameters from [26]	site parameters from [17]
DOC (Degradable organic Carbon) (weight fraction, wet basis)		
Food waste	0.15	0.15
Green waste	0.2	0.17
Paper-cardboard	0.4	0.4
Wood	0.43	0.3
Textiles	0.24	0.4
DOC_f (fraction of DOC dissimilated)	0.5	0.5
CH_4 generation rate k ($year^{-1}$)		
Food waste	0.4	0.3
Green waste	0.17	0.13
Paper-cardboard	0.07	0.05
Wood	0.035	0.025
Textiles	0.07	0.05

Table 3: LandGEM parameters

Parameters	CAA defaults	Site parameters from [17]
CH_4 generation rate k ($year^{-1}$)	0.05	0.149
CH_4 generation potential L_O (m^3/Mg)	170	108
Fraction of CH_4 in the biogas (%)	50	60

Table 4: SWEET parameters

	Data required	Values or references
General information	-Waste generation rate -Waste collection rate -Population whose waste are collected -Waste composition	-290 (kg/capita/year) -69 (%) -Data from [20] -Data from [17]
Landfill or open dump	-Waste quantity -Waste garbage depth -Landfill open and closure year -Gas collection system	-Calculated -4-8 m [15] -(1965-2018) -no
Climate	-Average annual precipitation -Mean annual temperature	-1750 (mm/year) (SODEXAM) in [16] -27 (°C) [25]

2.4 Models data

In order to determine CH_4 emissions, we used two main data: populations' data and waste quantities. The total percentage of inert waste was subtracted from the total waste and entered into LandGEM [23]. Hence, according to waste composition (table 5), 71.59% of waste was considered to be degradable [17]. Population data from national statistics were also used. For years without data, equation (4) was used to generate the corresponding population estimation:

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$$P(n) = P_0(1+r)^n \quad (4)$$

Where $P(n)$ is the expected population according to the population growth rate r; P_0 is the population of the reference year; n is the difference between the targeted and the reference year. Waste quantities were calculated using tier 1 method; as shown in the following equation (5):

$$Q = 0.69 * P(n) * W * 365 \quad (5)$$

Q (kg) is the total mass of the waste, W is the waste generation rate, which is of 0.79 kg/capita/day [26], 0.69 is the waste collection rate [26], default value.

2.5 Characteristics of waste

In this study, MSW composition data from [17] are used. The table 5 shows the characteristics and average composition of Municipal Solid Waste disposed in Akouédo landfill. The organic and the inorganic fraction of the waste disposed at Akouédo landfill are 70.17% and 29.83% respectively. The moisture contain of these waste on the site was estimated at 43% [17].

Table 5: waste characteristic and composition disposed in Akouédo landfill [17]

Composition	Fraction (%)
Putrescible	45.42
Leaf	2
Wood	4
Bones and straw	3.42
Paper-cardboard	14
Textiles	2.75
Plastics	8.5
metals	1.75
Glass	2.5
Batteries	1.41
Sand, dust	13.25
stone	1

3. Results and Discussion

3.1 Population and waste quantity estimated

Equations (4) and (5) were used to estimate waste quantities collected and the corresponding populations producing that waste from 1965 to 2018. Figure 2 shows the population growth of Abidjan and the waste collected and disposed at Akouédo landfill from 1965 to 2018. Populations data are from [27], [20], [28], [29] and [30]. These results show that the increasing population growth is associated with increase in waste production. This increase of waste production and the poor waste collection rate which is less than 90% (the recommended rate) had impacted the environment: odours and air pollution, leachate proliferation and greenhouse gas emissions.

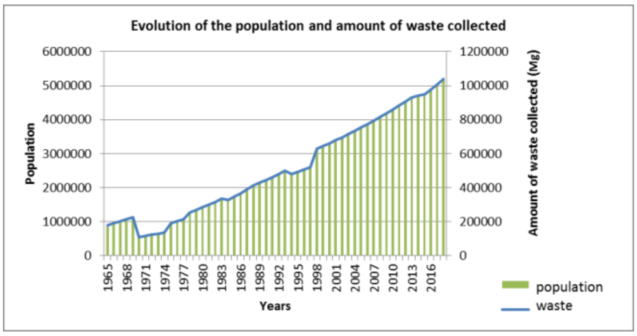

Figure 2: Annual evolution of population and amount of waste collected

3.2 Methane production

The amount of waste collected and disposed in Akouédo landfill and the related composition were used as input data for models in order to determine the annual methane emissions estimation. Figure 3 illustrates the annual methane emissions at Akouédo landfill from 1965 to 2105. All the models show an increase of methane emissions with increasing waste deposition over time. The results demonstrate that for a period of 141 years, the maximum amount of methane emissions is reached in 2019 one year after landfill closure for LandGEM and IPCC. However, this maximum will be reached in 2020 using the SWEET model. Methane generation rate will decrease exponentially after the landfill closure in parallel to the amount of decomposable matter in the landfill. Methane emissions predicted using LandGEM are considerably higher than both predicted by IPCC and SWEET models. This result is in line with the result of [23] in South Africa. They found that LandGEM simulations are higher than IPCC Waste Model simulation. This can be attributed to LandGEM applying a single methane generation rate (k) value for all waste degradation and that the waste volumes entered are not separated into different waste composition that is the key for estimating the GHG emission from MSW landfills [31].

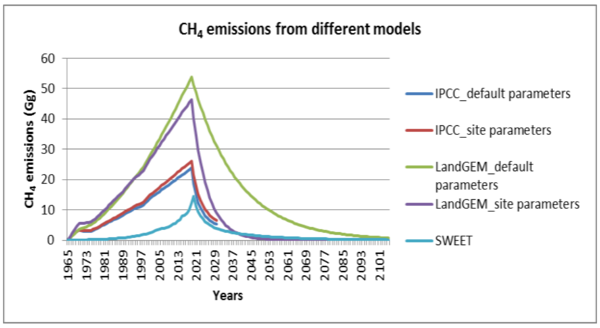

Figure 3: Predicted CH_4 emission by LandGEM (with CAA default and site-specific parameters), IPCC (default and site-specific parameters) and SWEET models.

The maximum methane emissions are estimated to 23.86, 26.13, 53.78, 46.44 and 12.26 Gg/year respectively for IPCC with default parameters, IPCC with site-specific parameters, LandGEM with default parameters; LandGEM with site-specific parameters and SWEET. The lowest methane emission predicted by SWEET may be explained by the fact that, SWEET uses additional parameters to make estimation. These parameters are the mean annual temperature, the

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average annual precipitation and the waste garbage depth (see table 4). These parameters are found in the literature and are specific for Akouédo landfill. In addition, the peaks of methane emissions simulated by IPCC waste model with default parameters and site-specific parameters are similar due to their similar input values (see table 2). Although CH_4 generation rate (0.149 $year^{-1}$) from [17] is higher than that of CAA default (0.05 $year^{-1}$), the peak of CH_4 emissions simulated by LandGEM with default parameters is higher than simulation made by LandGEM with site-specific parameters. This difference can be explained by the CH_4 generation potential (Lo) that is the amount of CH_4 (m^3) generated per amount of MSW decomposed Mg. Indeed, default value of L_O (170 m^3/Mg) is very higher than site-specific L_O (108 m^3/Mg) from [17]. L_O depends on the type and composition of wastes put in the landfill. A waste with higher cellulose content would have higher Lo, while the waste having higher lignin content would have lower Lo value [31].

3.3 Akouédo landfill methane emissions compared to world landfills methane emissions

The results from this study were compared to the predictions made in previous studies and were presented in the table 6. The table shows that few studies have been done on the comparison of methane emission simulations with at least two models. As it's showed in the table 6, the simulations were in most cases carried out by the LandGEM model. These results show that Akouédo landfill is one of the most emitting methane sites after Kahrizak landfill in Tehran (Iran). The high methane emission may be due to the fact that these landfills have no landfill gas collection system. In addition, the relatively higher methane emissions in Akouédo landfill than Nigerian landfills (Afofunra, Ajakanga, Awotan, Mpape) may be explained by its size and the annual waste acceptance rate. More than 1 million ton of Municipal Solid Waste is disposed in Akouédo landfill

Table 6: Comparison of methane peaks emissions (Gg/year) to others studies. Simulation of total LFG made by Mexico Landfill Gas Model (MLGM)*

Landfill (country)	Models						References
	LandGEM	IPCC	MTM	GasSIM	SWEET	MLGM	
Akouédo (Côte d'Ivoire)	**46.44**	**26.13**	-	-	**12.26**	-	**This study**
Akouédo (Côte d'Ivoire)	-	-	-	-	-	96.15*	[17]
Kossihouen (Côte d'Ivoire)	44.11	-	-	-	-	-	[6]
Afofunra (Nigeria)	0.50	-	-	-	-	-	[32]
Ajakanga (Nigeria)	2.11	-	-	-	-	-	
Awotan (Nigeria)	0.57	-	-	-	-	-	
Mpape (Nigeria)	0.85	-	-	-	-	-	
Italy	28.53	-	-	-	-	-	[34]
Kahrizak (Iran)	76.6	-	-	-	-	-	[2]
Karaj (Iran)	134	-	-	-	-	-	
Shiraz (Iran)	7.35	-	-	-	-	-	
Sanandaj (Iran)	6.18	-	-	-	-	-	[35]
Al Akeeder (Jordan)	-	-	-	8.56	-	-	[36]
Tanjung Langsat (Malysia)	4.52	-	-	-	-	-	[37]
Indore (India)	0.307	0.388	-	-	-	-	[13]
Ghazipur (India)	10.4-13.3	-	17.0	-	-	-	[12], [31]
Bhalswa (India)	8.1-10.5	-	13.7	-	-	-	
Okhla (India)	5.7-7.3	-	10.7	-	-	-	
Guwahati (India)	3.12 and 1.49	3.57	1.52	-	-	-	[3]

per year against 29911; 35920; 35962 and 53145 tons/year respectively in Afofunra, Mpape, Awotan and Ajakanga landfill in Nigeria [32]. The greater CH_4 emission rates observed in this study, as compared to that of other studies in India landfills, could be mainly due to the presence of more biodegradable content of Akouédo land filled wastes, climatic conditions and the waste management facility. In general, CH_4 production increases with higher organic and moisture content in landfill. Anaerobic condition created at solid waste disposal site also generates more methane [11]. In addition, the amount of waste moisture, pH and temperature, and nutrient availability for methanogenic bacteria, the fraction of the landfilled waste influence the main parameters: methane generation constant (k) and methane generation potential (Lo). However, it is be difficult to compare methane emissions between different studies due to differences in waste composition, management practices and environmental conditions [33]. Landfill Gas peak simulated by Mexico Landfill Gas Model (MLGM) in Akouédo landfill [17] is twice higher than the peak of methane simulated by LandGEM in this study. This difference may be explained by the ability of the models in simulating greenhouse gas emissions on one hand, and on the other hand, it is good to know that total landfill gas emissions are twice higher than methane emissions. In this study, the double of methane emission (46.44 Gg) is 92.88 Gg this is in the order of the result found by [17] at Akouédo landfill (96.15 Gg). It is can be noticed that the peak of methane emissions in this study is in the same order of result found by [6] on the new sanitary landfill of Kossihouen in the District of Abidjan. This can be explained by the fact that Kossihouen landfill is projected to receive almost the same quantity and characteristics of waste as Akouédo landfill.

4. Conclusion

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Methane emissions from Akouédo landfill have been estimated by using three theoretical models LandGEM, IPCC waste model and SWEET. This landfill started operation in 1965 and closed in 2018 with the purpose to receive the generated solid waste for Abidjan city and the surrounded areas, Anyama, Bingerville and Songon. The peak of methane emissions is estimated in 2019-2020, one to two years after landfill closure. Also, estimations made by LandGEM are higher than IPCC and SWEET and are in agreement with recent studies from [6] and [14] using LandGEM and MLGM. The results of this study are estimates made by theoretical models based on mathematical formulas. In addition to modelling, more accurate results require some knowledge of the actual situation of the waste decomposition process and meteorological parameters of the site through in situ measurements. This will provide information on the model that best estimates methane emissions. At this stage of our study, we can conclude that SWEET would be the model that best estimates methane emissions, because it uses temperature and precipitations data in addition to L_O and k.

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