Article

Estimation of Emissions from Sugarcane Field Burning in Thailand Using Bottom-Up Country-Specific Activity Data

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Abstract: Open burning in sugarcane fields is recognized as a major source of air pollution. However, the assessment of its emission intensity in many regions of the world still lacks information, especially regarding country-specific activity data including biomass fuel load and combustion factor. A site survey was conducted covering 13 sugarcane plantations subject to different farm management practices and climatic conditions. The results showed that pre-harvest and post-harvest burnings are the two main practices followed in Thailand. In 2012, the total production of sugarcane biomass fuel, *i.e.*, dead, dry and fresh leaves, amounted to 10.15 million tonnes, which is equivalent to a fuel density of 0.79 kg·m^{-2}. The average combustion factor for the pre-harvest and post-harvest burning systems was determined to be 0.64 and 0.83, respectively. Emissions from sugarcane field burning were estimated using the bottom-up country-specific values from the site survey of this study and the results compared with those obtained using default values from the 2006 IPCC Guidelines. The comparison showed that the use of default values lead to underestimating the overall emissions by up to 30% as emissions from post-harvest burning are not accounted for, but it is the second most common practice followed in Thailand.

1. Introduction

Thailand is the fourth largest sugarcane producer in the world, with a production of 98.40 million tonnes achieved in 2012 for a harvested area of 1.28 million ha [1]. The area of sugarcane cultivation has been significantly increasing over the past few years in response to larger domestic and international demand for sugar and ethanol. Thailand is the second world exporter of sugar with 4.50 million tonnes of export in 2012 [2]. About 70% of bioethanol is currently produced from molasses and another 7% from sugar juice. In addition, 70% of the ethanol plants in Thailand have sugar mills as their core business as a response to the governmental policy on renewable energy promotion [3]. Sugarcane cultivation in Thailand is mainly located in the Northeastern, Central, and Northern regions of the country as shown in Figure 1. The rainfed cultivation system accounts for the largest fraction of the production.

Regarding the emissions from biomass open burning in croplands in Thailand, they were first estimated in 2005 by Garivait *et al.* [4] for the national Pollution Control Department (PCD) in order to evaluate their potential impacts on local and regional air quality [4]. The main findings of this study indicated that open burning occurred mainly in paddies followed by sugarcane plantations. In the case of rice fields, the occurrence can be observed all year round in the central and lower northern regions of Thailand, since the farmers generally plant two to three times per year. In relation to sugarcane plantations, it was found that biomass open burning occurred mainly during November to April, which corresponds to the harvesting season. Concerning the emissions of air pollutants, for example PM_{10}, it was shown that the total emissions from rice and sugarcane field burnings are comparable [4]. In addition, the sugarcane fire intensity is much higher than that resulting from paddies combustion, because the amount of biomass fuel per planted area unit is much larger in the case of sugarcane [4]. Presently, there are efforts aiming at reducing sugarcane burning practices in Thailand, more particularly through the action plan to support the national master plan to prevent and control emissions from biomass open burning, under the Association of Southeast Asian Nation (ASEAN) Transboundary Haze Pollution Agreement, which Thailand ratified in 2003.

Open burning in sugarcane fields has been practiced for quite a long time as a result of increasing national demand for sugarcane production. The practice, referred to as pre-harvest burning, is generally performed to burn most of the residues associated with sugarcane, e.g., dead, dry, and fresh leaves in the field to facilitate manual harvesting operations. Also, the residues resulting from green-cane harvesting, which represents the harvesting technique without burning to remove tops and leaves, can be burnt after harvest whether to protect the next new ratoon crop from potential fire, or to facilitate soil preparation. In this case, the practice is referred to as post-harvest burning. Both burning activities contribute to emissions of air pollutants that may adversely impact human health and the environment [4–7]. Knowledge about the contribution of prescribed burning practices on air pollutant emissions is therefore needed. Parameters to perform such an assessment include among others two

variables which data are still scarce, especially at the country-specific level: (i) the amount of sugarcane that can potentially burn; and (ii) the fraction consumed by open burning defined as combustion factor.

Figure 1. Sugarcane plantation area in Thailand in year 2010.
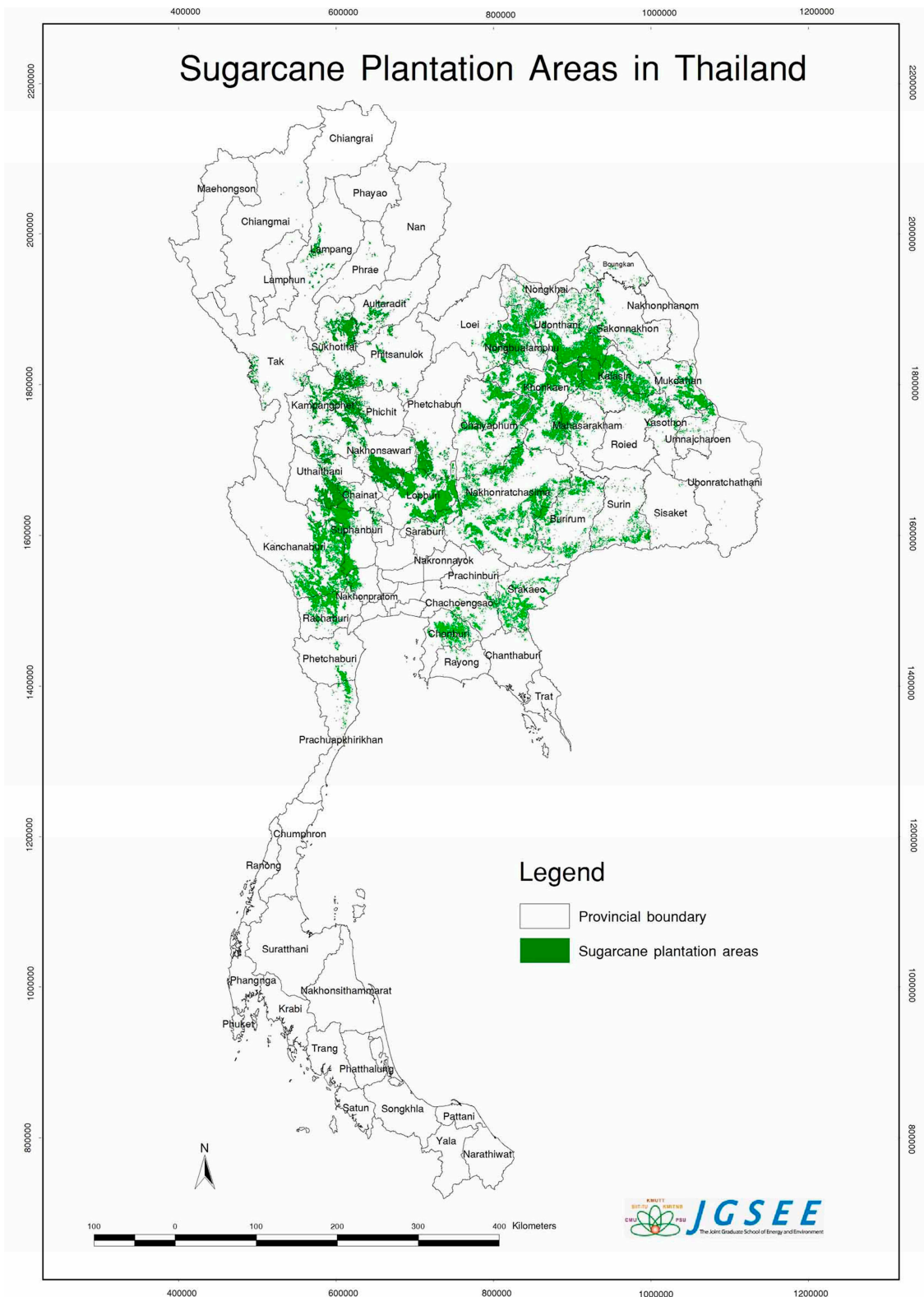
In this study, a methodology was developed based on a site survey sampling method to quantify bottom-up country-specific activity data including sugarcane biomass fuel load and fraction burned.

Representative sites in Thailand were selected based on a statistical sampling methodology. The values obtained were directly compared with those published in peer-reviewed literature. The emissions estimated using activity data from the field survey were evaluated against those determined using default values from the 2006 IPCC Guidelines [8] to assess their contribution to the improvement of the quality of the emission inventory associated with sugarcane field burning.

2. Materials and Methods

2.1. Determination of Numbers of Survey Sites

The study sites for the field survey were selected using a simple random sampling method. The sampling size was estimated based on a probability technique using population size and distribution of attributes as shown in Equation (1) [9]. Sugarcane biomass in Thailand is used as population size and equal to 2,493,667 tonnes [4], and biomass fuel load is a variable for determining variance. The variance of variable (S^2) was obtained using Equation (2) [9]. Sugarcane biomass fuel load in Thailand is derived from the report of Pollution Control Department [4]. In addition, the confidence level used in this research is set at 85% with 5% precision.

$$n = \frac{N\,Z^2\,S^2}{NE^2 + Z^2\,S^2} \tag{1}$$

$$S^2 = \frac{1}{36}\left(M_{max} - M_{min}\right) \tag{2}$$

where, n = sample size, N = population size (2,493,667 tonnes), Z = z-score at 85% confidence level, E = margin of error (0.05), S^2 = variance of variable (0.29), M_{max} = the maximum value of sugarcane biomass fuel load in dry mass (4.26 kg·m^{-2}), and M_{min} = the minimum value of sugarcane biomass fuel load in dry mass (1.03 kg·m^{-2}).

From Equation (1), the sampling size for this study is determined to be 12 sites. With a reserve of 5% of the sample size for data collection, the total sample size amounts to 13 sites of sugarcane plantation in Thailand.

2.2. Description of Field Survey Sites

Regarding the sugarcane plantation system in Thailand, the sugarcane crop is typically grown by replanting part of a mature cane stalk. It has to be replanted approximately after two to four harvests. The plant-cane cycle, named as the plant crop, starts with planting and ends after the first harvest. The ratoon-cane cycle, named for the ratoon crop which grows from the regenerative cane, starts after the harvest of the plant cane and continues with successive ratoon crops until field renewal.

In terms of water supply to sugarcane plantations, three systems exist in Thailand, *i.e.*, no water supply, full irrigation, and supplementary systems. The no water supply system is deployed in rainfed areas, where only rainfall serves as water supply for growing sugarcane. In irrigated areas, the water supply is generally ensured via a full irrigation system. The third system, called supplementary system, assures supply in water during the initial stage of planting using water from ponds or other water resources nearby; the rest of the time until the end of the crop-cycle, sugarcane plants are supplied in water from rainfall only.

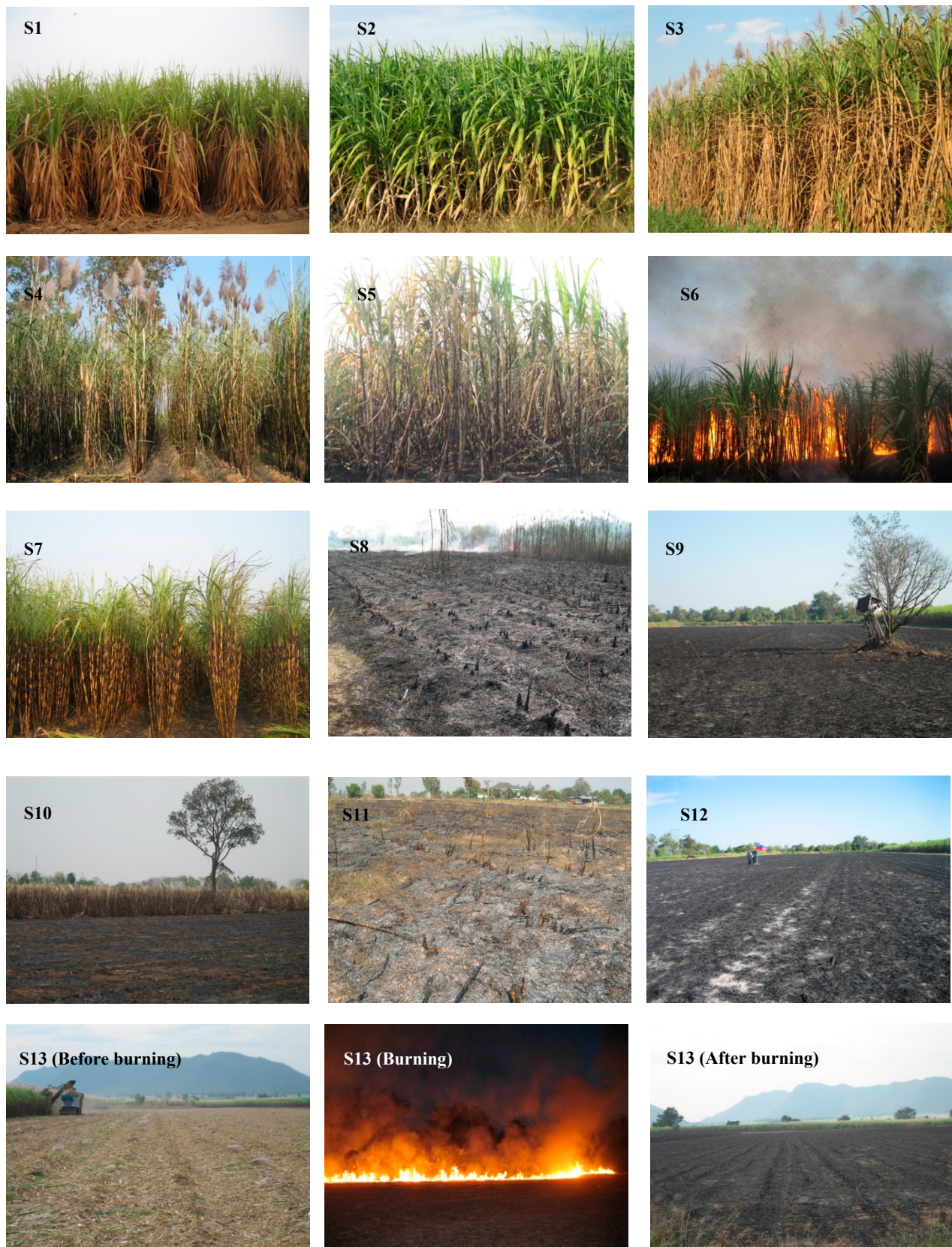**Figure 2.** Experimental sites of this study.

Table 1. Surveyed site characteristics.

Sites	Residue Management	Provinces	Regions	Water Supply to Plantation	Crop Class	Sugarcane Cultivar	Cultivation Period
S1	NB	Khon Kaen	Northeast	no	Plant crop	K 88-92	October 2011–January 2012
S2	NB	Nakhon Sawan	Northern	Supplementary	4th ratoon crop	LK 92-11	January 2011–January 2012
S3	NB	Nakhon Phathom	Central	Full irrigation	2nd ratoon crop	Uthong 8	November 2011–January 2012
S4	B1	Khon Kaen	Northeast	no	1st ratoon crop	Uthong 1	December 2011–January 2012
S5	B1	Nakhon Sawan	Northern	Supplementary	2nd ratoon crop	Suphanburi 80	February 2011–January 2012
S6	B1	Nakhon Sawan	Northern	Supplementary	2nd ratoon crop	LK 92-11	November 2011–January 2012
S7	B1	Nakhon Phathom	Central	Full irrigation	Plant crop	LK 92-11	January 2011–January 2012
S8	B2	Khon Kaen	Notheast	no	Plant crop	K 88-92	October 2011–January 2012
S9	B2	Nakhon Sawan	Northern	Supplementary	1st ratoon crop	LK 92-11	March 2011–February 2012
S10	B2	Nakhon Sawan	Northern	Supplementary	2nd ratoon crop	K 92-9	February 2011–March 2012
S11	B3	Khon Kaen	Northeast	no	2nd ratoon crop	K 88-9	February 2011–January 2012
S12	B3	Nakhon Sawan	Northern	Supplementary	2nd ratoon crop	Suphanburi 80	December 2011–February 2012
S13	B3	Nakhon Sawan	Northern	Supplementary	3rd ratoon crop	LK 92-11	February 2011–February 2012

Two different methods for harvesting were identified in Thailand, *i.e.*, manual and mechanical harvesting. Field surveys showed that the practice of sugarcane residues management differs depending on the harvesting method and farming practice followed. In the case of manual harvesting, sugarcane residues are usually burned before harvesting to facilitate the work of the laborers. In the case of mechanical harvesting, sugarcane residues are burned after harvest to facilitate soil preparation for a new planting or to protect the next ratoon crop from fires that may propagate from neighboring fields. Because in some of the surveyed sites there were no-burning before- or after-harvesting, a no-burning residue management was also taken into account. In summary, sugarcane residues management practice in Thailand can be classified into four main categories as follows.

(1) No-burning (NB): green-cane harvesting system without burning after harvesting;
(2) Pre-harvest burning (B1): burnt-cane system, where fire is used before cutting sugarcane to facilitate manual harvest;
(3) Post-harvest burning for ratoon protection (B2): green-cane harvesting system, where fire is used to burn sugarcane residues after harvesting to protect the next ratoon crop from fire;
(4) Post-harvest burning for soil preparation (B3): green-cane harvesting system, where fire is used to burn sugarcane residues after harvesting to clear the land before soil preparation for a new planting crop.

From the literature review, it was found that the sugarcane area with no-burning accounted for 23% of the total plantation area in 2012. About 77% of the total area of harvested sugarcane plantation is subject to open burning, for which the pre-harvest burning system represents the largest share with 82%, post-harvest burning contributing the remaining 18% [10].

In this study, the experimental sites were selected based on the set of sugarcane farming practices applied in Thailand over the three main regions where the plantations are located. The criteria considered for selecting the sites to survey include, the residue management practice, water supply system, sugarcane crop class and sugarcane cultivars. The characteristics of the 13 sites investigated in this study are summarized in Table 1 and illustrated in Figure 2.

2.3. Determination of Sugarcane Biomass Fuel Load

Sugarcane biomass fuel is defined as sugarcane biomass which can fuel the combustion process. From field observations, this includes fresh leaves, dry leaves, and dead leaves. In this study, the quantity of sugarcane biomass fuel available in Thailand in 2012 was estimated based on the combination of residue-to-product ratio (RPR) and sugarcane crop yield on dry mass basis, as formulated in Equation (3). In addition, sugarcane biomass fuel load was estimated based on the amount of sugarcane biomass fuel per unit of land area as shown in Equation (4). The RPR_s was obtained from the field experiments conducted in this study. The sugarcane crop yield (P_s) and sugarcane harvested area (A) were also taken from the report of the Office of Agricultural Economics (OAE) of Thailand [1].

$$Q_s = (P_s).(RPR_s) \qquad (3)$$

$$BL = \left(\frac{Q_s}{A}\right).(10^{-1}) \tag{4}$$

where, Q_S = Quantity of a dry sugarcane residue (tonnes·y^{-1}); P_S = Sugarcane production on a dry weight basis (tonnes·y^{-1}); RPR_s = Sugarcane residue-to-cane production ratio; BL = sugarcane biomass fuel load (kg·m^{-2}), and A = sugarcane harvested area (ha).

The field surveys to estimate RPR_s values were carried out during the harvesting period of sugarcane between December 2011 and March 2012. To ensure representative sampling, field measurements of sugarcane biomass in the area of no-burning (NB) and pre-harvest burning systems (B), seven sites in total, were made using crop experimental plots of four rows with a size ranging from 4.00 to 6.64 m in width and 10 m in length. At each site, the sugarcane area was divided into five replicated plots. The total sample size for NB and B1 was 35 plots (n = 35). The total above-ground biomass in each experimental plot was determined by collecting cane stalk, fresh leaves, dry leaves, and ground trash or dead leaves one day before harvesting. Sub-samples of each component were weighed, brought back to the laboratory, and then oven-dried at 70 °C during at least 24 h until obtaining a constant weight to determine the moisture content. The dry mass of each component was calculated based on their respective fresh mass and moisture content.

The dry mass of each component was then summed up to obtain the total dry mass of the sugarcane above-ground biomass. Finally, a sugarcane residue to product ratio (RPR) was determined for each surveyed site.

For post-harvest burning plots (B2 and B3), sugarcane residues generated by the green-cane harvesting system are homogenous all over the plantation area. Biomass samples were collected 3–5 days after harvesting with five replications from six surveyed sites in total. The total sample size for B2 and B3 was 30 plots (n = 30). The sampling area varied from 0.59 to 1.15 m^2 depending on the spacing between rows and between plant clumps. The bigger row spacing leads to larger sampling area. Sugarcane fresh residues were weighed, brought back to the laboratory, and then oven-dried at 70 °C at least during 24 h until obtaining a constant weight to determine the dry mass and moisture content. For cane production (P_s), the total cane yield for all sample sites was provided by the farmers participating to the survey. The ratio of sugarcane residue to cane production (RPR_s) was then estimated for each site. To determine the RPR values of sugarcane in Thailand, the results from the 13 surveyed sites were analyzed using the descriptive statistical method, *i.e.*, mean, standard error of means, maximum, and minimum were calculated.

2.4. Determination of Combustion Factor from Sugarcane Field Burning

To measure the combustion factor of sugarcane biomass fuel open burning, 10 sites were selected, out of which four were used for the pre-harvest burning system, and six for the post-harvest burning system. Sugarcane biomass samples were collected a day before the field open burning to determine their dry matter. At each site, five replicate plots were set for collection of biomass samples. The dimension of each plot ranged between 0.59 and 1.15 m^2 depending on the spacing between rows and between sugarcane plant clumps. Within a day after burning of the sampling plot, the residues of sugarcane biomass subject to fire were sampled to determine their dry matter content.

The combustion factor, which is defined as the ratio of the amount of sugarcane biomass consumed by fire to the total sugarcane biomass subject to burning, was estimated using the dry mass of the sugarcane biomass sampled before and after burning as described in Equation (5). The biomasses sampled were composed of fresh leaves, dry leaves and dead leaves.

$$C_f = \frac{(M_B - M_A)}{M_B} \qquad (5)$$

Equation (5) where, C_f = combustion factor (dimensionless), M_B = dry mass of biomass before burning (kg·m^{-2}), and M_A = dry mass of biomass after burning (kg·m^{-2}).

A weather station (Lacrosse Technology, model WS1600) was installed near the experimental sites at 4 m height for measuring the relative humidity (RH) of the ambient air. It was recorded manually every minute one hour before the burning and during the burning period. This study considered only the ambient air relative humidity as indicator of weather condition since it may have direct impact on the biomass fuel moisture content.

2.5. Estimation of Emissions from Sugarcane Field Burning

The air pollutant emissions or emission fluxes resulting from sugarcane field burning can be estimated as the product of the amount of sugarcane biomass consumed by fire and the pollutants specific emission factors. Equation (6) from the 2006 IPCC Guidelines methodology [8] is used to estimate emissions from sugarcane field burning. The amount of sugarcane biomass consumed by combustion (B_b), was estimated based on Equation (7).

$$E_a = B_b \times EF_a \qquad (6)$$

$$B_b = BL \times C_f \qquad (7)$$

where E_a = emission of the air pollutant "a" (g·m^{-2}), B_b = sugarcane biomass consumption (kg·m^{-2}), EF_a = emission factor of the air pollutant "a" (kg·m^{-2}), BL = sugarcane biomass fuel load in dry mass basis (kg·m^{-2}), and C_f = combustion factor (dimensionless).

According to Equations (6) and (7), there are three factors, including biomass fuel load (BL), combustion factor (C_f), and emission factor (EF_a), involved in the calculations of emissions from sugarcane field burning. The first two factors, BL and C_f, were obtained from the experimental sites surveyed in this study. The emission factors were derived from the 2006 IPCC Guidelines [8].

3. Results and Discussion

3.1. Sugarcane Biomass Fuel Load in Thailand

The moisture content of different components of the above-ground biomass of sugarcane, including, cane stalk, fresh leaves, dry leaves, and dead leaves of the top five sugarcane cultivars cultivated in Thailand, as collected from the no-burning and pre-harvest burning surveyed sites, is reported in Table 2. The average value of cane stalk moisture content was found to be 72.13% on a wet weight basis. This is consistent with the work conducted in Puerto Rico by Alexander [11], who reported stalk moisture content in the range of 70%–75% on net wet weight basis. From Table 2, it is observed that

fresh leaves represent the component of the plant that possesses the highest moisture content, with a mean value of 75.74%. On the other hand, the moisture content of dry and dead leaves are quite similar, although the dead leaves are slightly drier, with average fuel moisture content values of 12.30% and 9.83%, respectively. The low moisture content of these two components makes them a perfect fuel for burning, whether it is a pre-harvest or post-harvest one. Also, it is observed that the variation in moisture content of sugarcane biomass is directly influenced by the sugarcane cultivar and farming system, e.g., with or without irrigation, or plant or ratoon crop.

Table 2. Moisture content of surveyed sugarcane biomass.

Sites	Sugarcane Cultivars	Crop Class	Water Supply	Moisture Content (% wb)			
				Cane Stalks	Fresh Leaves	Dry Leaves	Ground Leaves
S1	K 88-92	Plant crop	no	73.83	79.42	17.62	14.40
S2	LK 92-11	4th ratoon crop	Supplementary	71.00	72.34	12.35	12.50
S3	Uthong 8	2nd ratoon crop	Full irrigation	72.31	76.52	12.06	7.32
S4	Uthong 1	1st ratoon crop	no	74.34	72.34	9.94	5.72
S5	Suphanburi 80	2nd ratoon crop	Supplementary	72.50	76.40	10.00	7.00
S6	LK 92-11	2nd ratoon crop	Supplementary	68.00	78.40	12.00	10.00
S7	LK 92-11	Plant crop	Full irrigation	72.95	74.80	12.16	11.86
Mean				72.13	75.74	12.30	9.83
Standard error (SE)				2.12	2.76	2.56	3.25

The RPR values collected from the 13 surveyed sites are summarized in Table 3. They are in the range of 0.24–0.47 with a mean value of 0.37. This is close to the RPR value of 0.35 reported by Warcharapirak and Pattanakiat [12] for sugarcane in Thailand. It should be noted that in the literature, this ratio varies largely within the range of 0.1–0.5. The main reasons for this variation are the variety of farming conditions and measurement techniques used [4,13–18]. Based on observation from our experimental site survey, the variation in RPRs in this study is on large part due to the variety of crop cultivars (Table 2), and to some extent to climatic conditions, number of ratoon crops and farming systems. The LK 92-11 cultivar possesses the highest RPRs and Suphanburi 80 the lowest (Table 3). Also, the higher the number of ratoon crops is, the higher the RPR is, as demonstrated from the values determined for LK 92-11 cultivar.

Based on a sugarcane production of 98.40 Tg, on a fresh mass basis; this equivalent to 27.42 Tg on a dry mass basis as reported by the Office of Agricultural Economic (OAE) for 2012 [1]; and a mean RPR value of 0.37, the quantity of sugarcane residues (*i.e.*, sugarcane biomass fuel) produced in 2012 was estimated. It was determined to amount to 10.15 Tg, on a dry mass basis, which corresponds to a sugarcane biomass fuel load of about 0.79 $kg \cdot m^{-2}$, on a dry mass basis. This result is within the range of values reported by other research studies in Thailand, *i.e.*, 0.47–1.72 $kg \cdot m^{-2}$ [12,18,19]. It should be noted that the biomass fuel load found in this study is approximately 20% higher than the default value provided in the 2006 IPCC guidelines, *i.e.*, 0.65 $kg \cdot m^{-2}$ [8]. Table 4 summarizes the amount of sugarcane biomass fuel estimated for the three regions and the whole country in 2012. The Northeast is the region where the harvesting area is the largest, and so the highest quantity of sugarcane residues is produced.

Table 3. Sugarcane residue-to-product ratio (RPR) in Thailand in 2012.

Sites	Sugarcane Cultivars	Crop Class	Water Supply	Cane Yield	Sugarcane Residue	RPR
				$(kg \cdot m^{-2})$	$(kg \cdot m^{-2})$	
S1	K 88-92	Plant crop	no	3.77	1.14	0.30
S2	LK 92-11	4th ratoon crop	Supplementary	2.92	1.39	0.47
S3	Uthong 8	2nd ratoon crop	Full irrigation	3.08	1.12	0.36
S4	Uthong 1	1st ratoon crop	no	2.93	0.97	0.33
S5	Suphanburi 80	2nd ratoon crop	Supplementary	2.21	0.53	0.24
S6	LK 92-11	2nd ratoon crop	Supplementary	2.72	1.13	0.42
S7	LK 92-11	Plant crop	Full irrigation	3.05	1.14	0.38
S8	K 88-92	Plant crop	no	1.83	0.68	0.37
S9	LK 92-11	1st ratoon crop	Supplementary	2.20	0.94	0.44
S10	K 92-77	2nd ratoon crop	Supplementary	2.57	1.05	0.47
S11	K 88-92	2nd ratoon crop	no	2.13	0.58	0.27
S12	Suphanburi 80	2nd ratoon crop	Supplementary	2.12	0.50	0.24
S13	LK 92-11	3rd ratoon crop	Supplementary	2.22	1.05	0.47
Mean				2.60	0.94	0.37
Standard error (SE)				0.54	0.28	0.09

Table 4. Sugarcane harvesting areas and associated sugarcane biomass residues (Mg on dry mass basis) in Thailand in 2012.

Regions	Harvesting Area * (ha)	Biomass Fuel (Mg)	Biomass Fuel Load $(kg \cdot m^{-2})$
Northern	348,770	2,981,437	0.85
Northeast	518,395	3,836,985	0.74
Central	414,939	3,328,716	0.80
Whole kingdom	1,282,104	10,147,139	0.79

Remark: * Data from [1].

3.2. Combustion Factor from Sugarcane Field Open Burning

The combustion factors determined for the pre-harvest and post-harvest burning systems using the data collected from the 10 sites surveyed are detailed in Table 5. It is observed that the mean value of the combustion factor of the pre-harvest burning system is lower than that of the post-harvest burning system, *i.e.*, 0.64 *vs.* 0.83. It is noted that for the post-harvest burning system, whether its purpose is to protect the ratoon for the regrowth or to assure soil preparation for new crop plantation, the average value of the combustion factor is the same, which confirms that the combustion factor depends mainly on the fuel characteristics and physical arrangement. For the case of the pre-harvest burning system, we also investigated the combustion factor of each component of the sugarcane biomass fuel, as detailed in Table 6. Dead leaves are the component characterized by the highest combustion factor (mean = 0.93), followed by dry leaves (mean = 0.88) and fresh leaves (mean = 0.21). The overall mean value of 0.64 determined in this study for the pre-harvest burning system is about 25% lower than the default value of 0.80 recommended by the 2006 IPCC Guidelines. This seems to indicate that pre-harvest burning in Thailand is performed when the proportion of fresh

leaves is still high comparatively to those reviewed by IPCC to establish the default value. It should be noted that the site-specific overall mean combustion factor of 0.83 of the post-harvest burning system cannot be compared to the IPCC default value because this latter is actually provided for the pre-harvest burning. From Table 6, it can be noted that another parameter that may influence the combustion factor is the cultivar, especially regarding fresh leaves. Based on the data reported in Table 6, it is observed that the water supply system for sugarcane cultivation does not affect the combustion factor.

Table 5. Combustion factor *vs.* sugarcane field burning practice in Thailand.

Burning Practice	Combustion Factors	
	Mean Value	SE
B1: Pre-harvest burning	0.64	0.05
B2: Post-harvest burning system for fire protection	0.83	0.03
B3: Post-harvest burning system for soil preparation	0.83	0.04

Table 6. Combustion factors of different fractions of sugarcane biomass residues burned in case of pre-harvest burning.
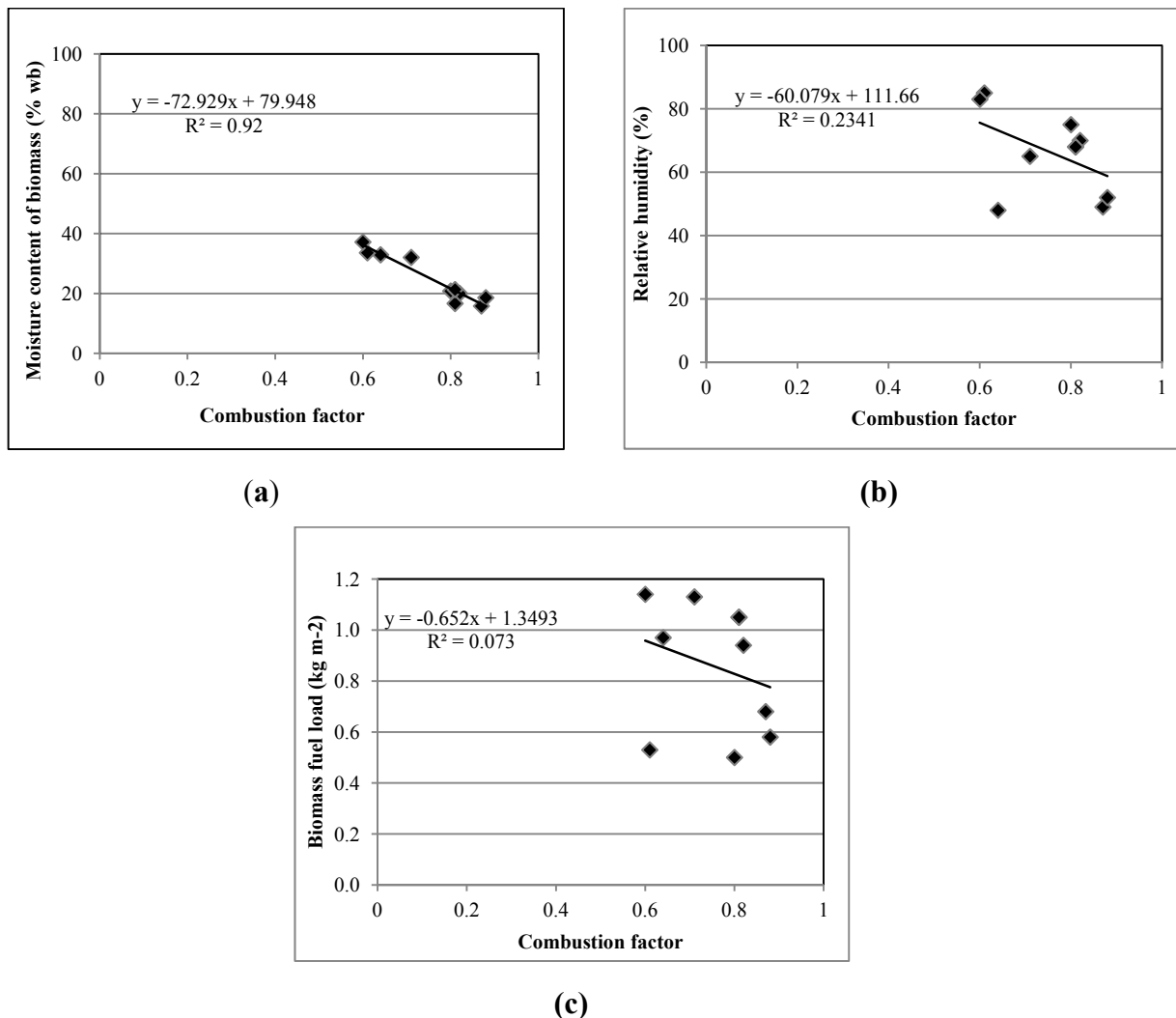
Sites	Combustion Factors			
	Fresh Leaves	Dry Leaves	Dead Leaves	Overall
S4	0.24	0.88	0.92	0.64
S5	0.21	0.83	0.89	0.61
S6	0.21	0.93	0.95	0.71
S7	0.17	0.88	0.95	0.60
Mean	0.21	0.88	0.93	0.64
Standard error (SE)	0.02	0.05	0.03	0.05

On the other hand, high variability of the combustion factor can be observed for all components and from one site to another. This underlines a certain relationship between combustion factor and biomass fuel moisture content. In order to investigate the variables that may influence the combustion factor, and consequently the combustion behavior and its associated emissions of pollutants, the combustion factor data were plotted *versus* sugarcane biomass fuel moisture content, biomass fuel load, and atmospheric relative humidity (Figure 3). It is observed that the combustion factor has a strong correlation with biomass fuel moisture content ($R^2 = 0.92$), confirming that fuel moisture content is the most significant variable influencing the combustion factor. Some correlation can be observed with relative humidity, but with much less significance ($R^2 = 0.234$). Finally, no significant relationship is found between the combustion factor and biomass fuel load.

In addition, it was observed from all the 13 site surveys that biomass fuel physical properties; such as fuel bed compactness, fuel bed arrangement, fuel bed bulk density, *etc.*; can significantly influence the combustion efficiency. It was found that fuel bed composed mainly of dry and dead leaves, *i.e.*, low bulk density and compactness was burned efficiently, contributing to a high combustion factor. Also, in case of post-harvest burning, the residues resulting from manual harvesting were found to be easily ignited and burned, leading to a higher combustion factor, comparatively to those from mechanical harvesting. This observation may be explained by the difference in fuel bed arrangement:

in case of manual harvesting, the residues possess a high surface-to-volume ratio, which is much lower than those from mechanical harvesting since these latter were shred into pieces before spreading onto the ground to form the fuel bed.

Figure 3. Correlation between combustion factor and (**a**) biomass fuel moisture content; (**b**) atmospheric relative humidity; and (**c**) biomass fuel load.

(**a**)

(**b**)

(**c**)

3.3. Estimation of Air Pollutant Emission Fluxes from Sugarcane Field Burning in Thailand

Using the data obtained in this study, for a sugarcane biomass fuel load of 0.79 $kg \cdot m^{-2}$ and combustion factor of 0.64 for the pre-harvest burning system and 0.83 for the post-harvest burning system, the amount of sugarcane biomass fuel consumed by fire in Thailand was determined to amount to 0.51 $kg \cdot m^{-2}$ and 0.66 $kg \cdot m^{-2}$ for each system, respectively. These results indicate that the consumption of sugarcane biomass fuel for the post-harvest burning system is 30% higher than the pre-harvest burning system. As a consequence, the intensity of air pollutant emissions from a post-harvest burning system is expected to be about 30% higher than from a pre-harvest burning system. As stated in the previous section, the default values provided by the 2006 IPCC Guidelines [8]; with sugarcane biomass fuel load of 0.65 $kg \cdot m^{-2}$ and combustion factor of 0.80, leading to sugarcane biomass fuel

consumption by fire of 0.52 kg·m^{-2}; are recommended for pre-harvest burning. The value of sugarcane biomass fuel consumption determined in this study for the pre-harvest burning system is in good agreement with the value recommended by IPCC, *i.e.*, 0.51 kg·m^{-2} *vs.* 0.52 kg·m^{-2} (Table 7).

Table 7. Comparison of emission fluxes from sugarcane open burning estimated from default values of 2006 IPCC guidelines and results obtained in this study.

Pollutants	EF * (g·kg^{-1})	Sugarcane Biomass Consumption (kg·m^{-2})			Emissions (g·m^{-2})		
		Using IPCC Default Values *	Using Results from This Study		Using IPCC Default Values *	Using Results from This Study	
			Pre-Harvest Burning	Post-Harvest Burning		Pre-Harvest Burning	Post-Harvest Burning
CO_2	1515	0.52	0.51	0.66	787.80	765.98	993.39
CO	92	0.52	0.51	0.66	47.84	46.52	60.32
CH_4	2.7	0.52	0.51	0.66	1.40	1.37	1.77
N_2O	0.07	0.52	0.51	0.66	0.04	0.04	0.05
NO_x	2.5	0.52	0.51	0.66	1.30	1.26	1.64

*: Default values from [8].

Due to the absence of country-specific emission factors associated to sugarcane field burning in Thailand, default values recommended in the 2006 IPCC Guidelines [8] were used. The obtained emission fluxes for key greenhouse gases are reported in Table 7. As expected, the fluxes using IPCC default values and those estimated from the pre-harvest burning system biomass fuel consumption are very close, *i.e.*, with only 3% difference, while the emission fluxes in the case of the post-harvest burning system are 26% higher. This finding underlines the importance of using country-specific information concerning sugarcane field burning practices. Although pre-harvest burning is more frequently practiced and concerns larger plantation areas than post-harvest burning, using the IPCC recommended default values would significantly underestimate the overall emissions, as only pre-harvest burning would be considered. However, it should be pointed out that sugarcane plantations affected by post-harvest burning can only be tracked via site surveys, and consequently are difficult to find in official statistics, while areas subject to pre-harvest burning can be monitored using the amount of burned canes delivered to sugar mills. Because of this difficulty in evaluating the plantation areas subject to post-harvest burning for all sugarcane producing countries, the global emissions from sugarcane field burning are expected to be underestimated.

4. Conclusions

Sugarcane field burnings in Thailand were investigated via site surveys to determine the biomass fuel load and combustion factor, two parameters defining the biomass fuel consumption or activity data in the estimation of air pollutant emissions from one of the major sources of biomass open burning in the country. The field survey performed in this study also enabled us to update the average value of RPR for sugarcane, which was found to be 0.37, leading to an amount of sugarcane residues which could have served as fuel for the open burning of 10.15 Tg in 2012. Using the obtained average RPR value, the overall mean sugarcane biomass fuel load was estimated to be 0.79 kg·m^{-2} on a dry

mass basis, which is about 20% higher than the default value recommended by IPCC in the 2006 IPCC Guidelines [8].

The combustion factors associated with pre-harvest and post-harvest burning were estimated to be 0.64 and 0.83, respectively. It was found that the sugarcane biomass moisture content significantly affects the combustion factor. Indeed, dry sugarcane biomass components were determined to have higher combustion factor values as compared to fresh ones, *i.e.*, average combustion factor of 0.88 for dry leaves and 0.93 for dead leaves *vs.* 0.21 for fresh leaves. Also, some correlations were observed between combustion factor and atmospheric relative humidity, but none between combustion factor and biomass fuel load. In addition, it was found from site survey observations that the physical properties of biomass fuel including fuel bed compactness and fuel bed arrangement significantly influence combustion efficiency, and so consequently the combustion factor. Finally, this study pointed out that the combustion factor can also be influenced by the planted cultivar, but not by the water supply to the plantation. The pre-harvest burning combustion factor obtained in this study was found to be 20% lower than the IPCC default value, *i.e.*, 0.64 *vs.* 0.80, and underlines that the harvesting in Thailand is practiced when a large part of the biomass residues is still fresh, and consequently is of high moisture content.

Although the biomass fuel load and combustion factor estimated for the pre-harvest burning in this study are different from those recommended in the 2006 IPCC Guidelines, their product, which is defined as the sugarcane biomass fuel consumption was found to be close to the one calculated using the IPCC defaults, *i.e.*, 0.51 *vs.* 0.52. In case of post-harvest burning, the sugarcane biomass fuel consumption was found to be 0.66, *i.e.*, about 30% higher than the pre-harvest burning value, leading to 26% higher air pollutant emission fluxes. This finding stresses the important issues that would affect the accuracy and reliability of the inventory of emissions from sugarcane field burnings, at the national as well as global scale. As the default values recommended by IPCC are for the case of pre-harvest burning, it is expected that the current global estimation of the emissions from sugarcane residues open burning is lower than the actual emissions.

The obtained results confirm the important role of country-specific and process-based information in the inventory of emissions from sugarcane field burnings. By collecting data on biomass fuel load, combustion factor, and the spatial distribution of pre-harvest and post-harvest burning, the accuracy of the emission inventory may be improved up to 30%. As the measurements of these parameters are easier to perform in comparison to the emission factors, it is highly recommended that sugarcane producing countries conduct field surveys to collect these country-specific data.

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Author Contributions

All the authors contributed to the research and experimental design of this study, and to the elaboration of this manuscript. Wilaiwan Sornpoon performed the data collection and analysis, and prepared the first draft of this paper. Savitri Garivait supervised the overall research work, provided guidelines for the write up of the manuscript, and contributed to its editing and finalization. Sebastien Bonnet supervised the overall write up and editing of the manuscript. Poonpipope Kasemsap and Praphan Prasertsak supported the implementation of the field experiments and provided scientific insight on sugarcane biomass.

Conflicts of Interest

The authors declare no conflict of interest.

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