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CONTENT

Development of a Taper Equation for Teak (*Tectona grandis* L.f.) Growing in Western Thailand

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ABSTRACT

Teak is an important and valuable tropical hardwood species. In this study, we developed and evaluated suitable taper equations for teak growing in Western Thailand using a formulation of Goodwin cubic polynomial model combined with a bark thickness model. The best taper model calibration was selected based on goodness-of-fit and leave-one-out cross validation statistical testing. In total, 12 different model calibrations were tested, with Thong Pha Phum (TPP) 2 being the most suitable for teak in Western Thailand. The mean prediction error of three validation statistics: (prediction of diameter under bark given height; prediction of height given diameter under bark; and prediction of under bark volume given log length) were within 10% and the overall validation index was 5.454, which was the lowest when compared to other calibrations. A comparison of TPP 2 with a teak taper equation developed for Northern Thailand, using a graphical analysis of the stem shape and bark thickness, indicated that the teak trees growing in the two regions have similar stem shapes, but the trees in Western Thailand tend to have a thicker bark. These results will also help in further work as they indicate that bark thickness equations are particularly important.

1. INTRODUCTION

Taper equations are used to predict the diameter under bark at all stem heights and can also estimate the volume and value of standing trees. In combination with log-bucking algorithms, they are also used to maximize the log value or optimize market constraints. The taper of a tree is a combination of natural growing processes and associated silvicultural practices. Therefore, the development of taper equations that are specific to different species, sites, and silvicultural practices can be used to accurately estimate the volume and value of a standing tree (Tasissa and Burkhart, 1998; Klos et al., 2007; Fonweban et al., 2011; Sabatia and Burkhart, 2014).

Teak is one of the most valuable tropical hardwood species in the world (Kollert and Kleine, 2017). In Thailand, the Forest Industry Organization (FIO) has around 80,000 ha under teak plantations, occurring naturally in Northern Thailand, in addition to some parts in Western Thailand (Hansen et al., 2014; FIO, 2018). The climate in the two regions is different, with Northern Thailand experiencing a tropical savanna climate, with an annual rainfall between 1,000-1,400 mm/year, while western Thailand is influenced by a tropical monsoon climate, with an annual rainfall ranging between 1,600-2,000 mm/year (Beck et al., 2018; Thai Meteorological Department, 2020). This may cause differences in the stem shape of trees growing in the two regions.

FIO generally carries out a pre-harvest inventory to estimate the volume and value of standing trees based on volume tables. However, a general volume table cannot be used to estimate the optimal value of standing trees, especially with teak log grade specifications, which are based on mid-log diameter and length classification. Warner et al. (2016) proposed that the FIO can use taper equations with log-bucking algorithms to optimize the stem crosscutting for maximum value and consequently reported the first taper model for teak plantations in Thailand. However, their equation was developed using trees sampled from teak plantations in Northern

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Thailand and was not tested on trees in plantations of Western Thailand. Consequently, this study aimed to evaluate the taper model calibration for teak growing in Western Thailand and to compare the tree shape in western and northern regions of the country.

2. METHODOLOGY

2.1 Study site

The study site is located in the Thong Pha Phum plantation in Kanchanaburi Province, Thailand (Figure 1). The teak plantation covers an area of 2,422 ha or 72% of the total area. The mean elevation of the plantation is 400 m.a.s.l. and the area was originally a mixed deciduous forest. This plantation practices selective thinning by removing all small, dead, and deformed trees. Additionally, no serious tree diseases have been reported in this area (FIO, 2016). All trees were planted at 4 m × 4 m spacing to increase profitability and management efficiency for medium and poorer quality sites (Noda and Himmapan, 2014).

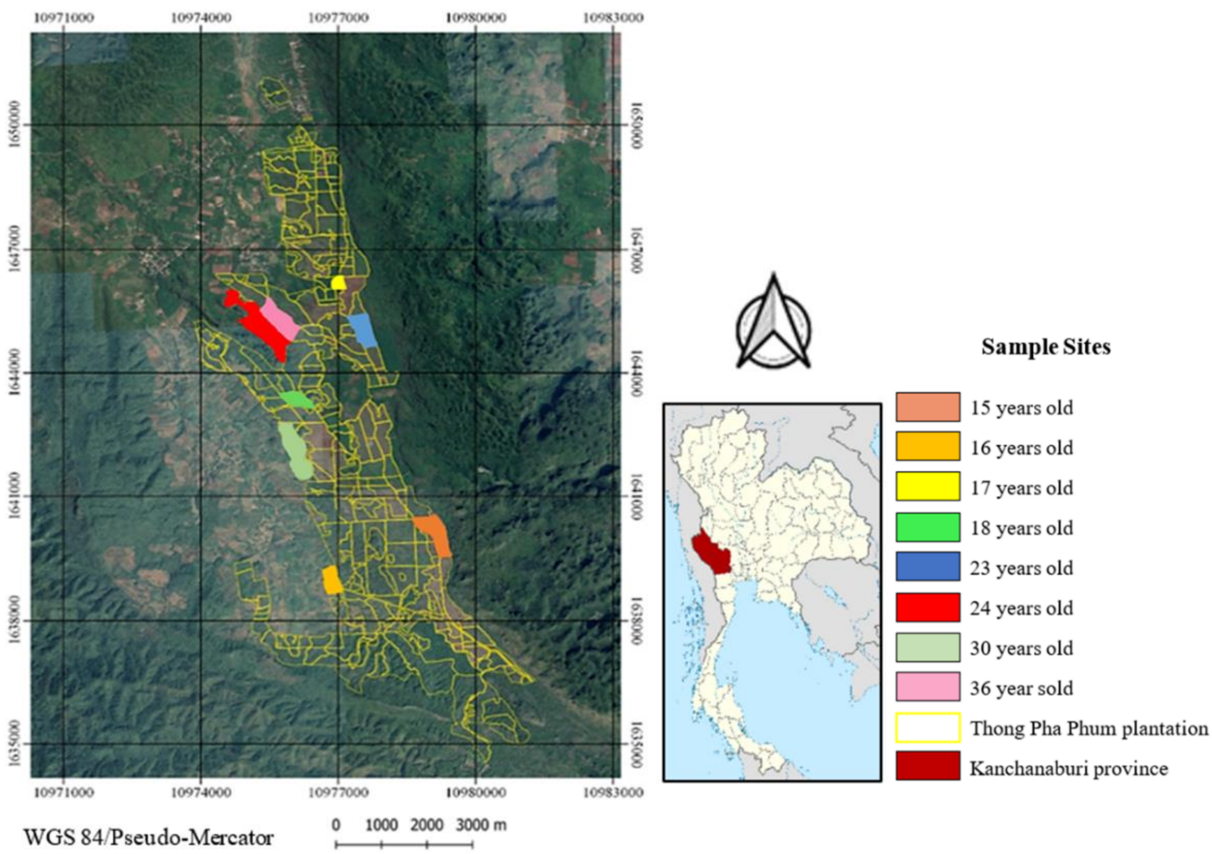

Figure 1. Planted area under teak at the Thong Pha Phum Plantation, Kanchanaburi Province

2.2 Tree sampling and measurement

We sampled 60 trees from thinned stands, which included eight age classes (15, 16, 17, 18, 23, 24, 30, and 36 years). Only those trees which had a diameter at breast height (DBH) over bark of up to 15 cm and a total height of up to 10 m were sampled, as such trees were large enough to produce a commercial teak sawlog (Warner et al., 2016). Apically dominant trees were selected, as the equation was primarily used to estimate the sawlog volumes, and irregularly formed trees generally removed from thinned stands. Diseased, deformed, or dead trees were not sampled as such trees are not representative of the general population (Brooks et al., 2007; Nigh and Smith, 2012). The sample size distribution was determined based on size of the area in each age class and the sampled trees were randomly selected, with a minimum of two trees required in class (Vanclay, 1982).

We followed the tree measurement procedures used for sampling teak trees in Northern Thailand (Warner et al., 2016). Briefly, a diameter tape was used as a representative (no obvious defect or exceptional bumps in the diameter) measurement of the diameter above ground level at 0.3 m, 0.5 m, and 0.8 m, where pronounced buttressing is often presented and finally at the breast height (1.3 m above ground on the uphill side of a tree). As noted in other studies, pronounced buttressing may increase the model variability, resulting in a poor prediction of the lower bole (Fonweban et al., 2011; Sumida et al., 2013; Westfall and Scott, 2010). Therefore, the trees were felled and cut at 0.3 m, 0.5 m, and 0.8 m and a digital photograph of the cross section was taken alongside a steel ruler as a standard for metric scale measure, to provide for any corrections to the sectional area of any pronounced buttressing. Any diameter data affected by pronounced buttress were adjusted using a cross sectional area analysis using the digital images as proposed by Warner et al. (2017). Further, the measurement of diameter over bark and bark thickness was done usually at an interval of 2 m above the breast height at a representative point until the main stem was no longer apparent. The ground diameter under bark was estimated assuming a convex equation and the sectional under bark volumes for each tree were calculated using Smalians formula. Summary statistics are provided in Table 1.

Table 1. Summary statistics of 60 sampled trees

Tree or stand variable	Minimum	Mean (± SD)	Maximum
DBH over bark (cm)	15.3	29.5±9.0	52.7
DBH under bark (cm)	13.4	26.7±8.7	48.6
Total height (m)	12.6	22.4±4.4	32.0
Double bark thickness (mm)	12.0	28±8.0	52.0
Age (year)	15.0	24±4.3	36.0
Numbers of sample points per tree	8.0	11±1.8	15.0

2.3 Taper modeling

The Goodwin (2009) taper model was selected for calibration as it has been successfully used for teak growing in Northern Thailand (Warner et al., 2016). The model is described by a cubic function comprising of hyperbolic and parabolic terms (Goodwin, 2009) (Equation 1); it is algebraically invertible and integrable and can accommodate one or two diameter constraints, neither of which needs to be at the breast height. Only one diameter constraint was used in this work. The primary has three parameters (β_1, β_2 and β_3), which are modelled as secondary functions of tree, stand, and regional variables. Second stage models in Goodwin (2009) did not include DBH under bark and therefore the diameter constraints in that model could be at any height. However, DBH was an important term in the second stage models for the present work, and so it was sensible to constrain the primary model with DBH under bark.

$$d_{ub} = (H\text{-}h)\left(\frac{\beta_1\beta_2^2(BH\text{-}h)}{(1+\beta_2 h)(1+\beta_2 BH)(1+\beta_2 H)}+\beta_3(h\text{-}BH)+\frac{D_{ub}}{H\text{-}BH}\right) \quad (1)$$

$$\beta_1 = c_0+c_1H+c_2H^2+c_3\left(\frac{D_{ub}}{10}\right)^2$$

$$\beta_2 = d_0+d_1H+\frac{d_2}{H}$$

$$\beta_3 = f_0+f_1H+\frac{f_2}{H}+f_3\left(\frac{D_{ub}}{10}\right)+f_4\left(\frac{D_{ub}}{10}\right)^2$$

Where; d_{ub} is the diameter under bark (cm) at height h (m), D_{ub} is diameter under bark (cm) at breast height (BH) (m), H is the total height of the tree (m), and c_i, d_i, and f_i are second stage candidate coefficients for the terms which have been reported to be significant for other species and regions (Warner et al., 2016; Goodwin, 2009; Wang and Baker, 2007).

The Goodwin model uses D_{ub}, H, and h to predict d_{ub} and this approach is suitable when applied at two heights to estimate the under bark volume of the section between the two heights. As such, a separate bark thickness model is required to utilize D_{ob} as an input parameter, which is measured at the time of inventory. Therefore, the sample tree data were used to develop a bark thickness model using a power law in equation 2 and combined with equation 3 to convert the measured D_{ob} to D_{ub} to be used in the taper model as:

$$BT2 = a\,(d_{ob})^b, \quad (2)$$

$$d_{ub} = d_{ob} - \frac{BT2}{10}, \quad (3)$$

Where; BT2 is the double bark thickness (mm), a and b are model coefficients, and d_{ob} is the diameter over bark (cm).

Nonlinear fixed effects analysis was used in the taper modeling. Model calibrations were started with 12 second stage candidate coefficients and insignificant terms (p-value>0.05) were neglected, resulting in different candidate calibrations having different terms or number of second stage candidate coefficients. Each calibration was named as TPP, which was the abbreviated form of Thong Pha Phum. The best calibrations were parsimonious models and were those with the best combined goodness-of-fit (GOF) statistics, namely a low residual standard error (RSE), a high adjusted coefficient of determination (adjusted R^2), and a low Bayesian information criterion (BIC) (Fonweban et al., 2011; Hastie et al., 2013; Warner et al., 2016). Calibrations were compared using a leave-one-out (LOO) cross validation to assess the prediction accuracy (Kozak and Kozak, 2003; Miguel et al., 2012; Kuželka and Marušák, 2014; Yang and Huang, 2014; Warner et al., 2016). As the residuals for the records of BH (1.3 m above ground) were already constrained to zero through the Goodwin model formulation, such records were omitted during the validation process.

Estimates were tested using the percentage error ($\bar{e}$ %) (Equation 4) as a measure of the overall prediction accuracy, which also indicates any overestimation (negative values) or underestimation (positive values) and the relative prediction error (RE%) (Equation 5) to indicate the precision of the model estimates, which is always a positive value. Values close to zero indicate that the model is accurate and precise for the measured data (Kozak and Smith, 1993; Fonweban et al., 2011; Huang et al., 2003). The mathematical formulations of the two indicators are as follows:

$$\bar{e}\% = 100 \times \left(\frac{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)}{n}}{\bar{y}}\right), \quad (4)$$

$$RE\% = 100 \times \left(\frac{\sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n}}}{\bar{y}}\right), \quad (5)$$

Where; y_i is the observed value, $\hat{y}_i$ is the respective predicted value, n are the number of observations, and $\bar{y}$ is the mean of the observed values.

It was noted that both the equations are more likely to be biased towards the larger trees compared to the smaller ones. However, the majority of trees sampled were either older or larger trees, with a majority of commercial harvesting often occurring in this tree size class. Therefore, both the equations were appropriate for use in this study.

LOO cross validation was used to investigate 3 different aspects of the taper models combined with the bark thickness as follows: 1) prediction of d_{ub} given h; 2) prediction of h given d_{ub}; and 3) prediction of the under bark volume given log lengths. The sample tree measurements were binned into classes with approximately equal size and the validation was appraised for different diameter and relative height ranges in the sampled trees. The absolute values for each calibration in each class and each statistic were summarized using a single model index evaluated by taking the mean of the scaled statistics, based on a simple, unweighted scaling of each statistic. Using this approach results in each statistic having an equal contribution to the index, with a perfect calibration having an index value close to zero (Kozak and Kozak, 2003; Goodwin, 2009; Fonweban et al., 2011; Miguel et al., 2012; Warner et al., 2016).

3. RESULTS AND DISCUSSION

3.1 Best candidate calibrations

Twelve calibrations were fitted using an unweighted nonlinear regression and evaluated based on their GOF statistics. The GOF results for the selected candidate calibrations are summarized in Table 2. High adjusted R^2 values (0.98279-0.98428) indicate that these calibrations are a good fit for the present data. Generally, the calibration variants can be reduced to include only 4-6 terms without any noticeable reduction in the value of GOF statistics and these calibrations form a parsimonious model which is selected for validation (the coefficients for these calibrations are shown in Table 1). As shown for an example calibration in Figure 2, a plot of the standardized residuals did not indicate any heteroscedasticity trend. The standardized residuals are normally distributed (p-value>0.05; tested by Shapiro-Wilk test).

Table 2. Goodness-of-fit statistics for 12 calibrations (rows in **bold** indicate the best calibrations selected for validation)

Calibration	Adjusted R^2	RSE	BIC	Number of coefficients
TPP 1	**0.98425**	**1.071**	**1889**	**6**
TPP 2	**0.98423**	**1.071**	**1883**	**5**
TPP 3	**0.98389**	**1.083**	**1903**	**5**
TPP 4	0.98430	1.069	1977	7
TPP 5	0.98434	1.067	1978	8
TPP 6	0.98436	1.064	1987	9
TPP 7	0.98437	1.065	2047	12
TPP 8	0.97886	1.145	2213	3
TPP 9	0.97564	1.361	2352	3
TPP 10	**0.98279**	**1.095**	**1959**	**4**
TPP 11	**0.98387**	**1.084**	**1903**	**5**
TPP 12	**0.98428**	**1.070**	**1888**	**6**

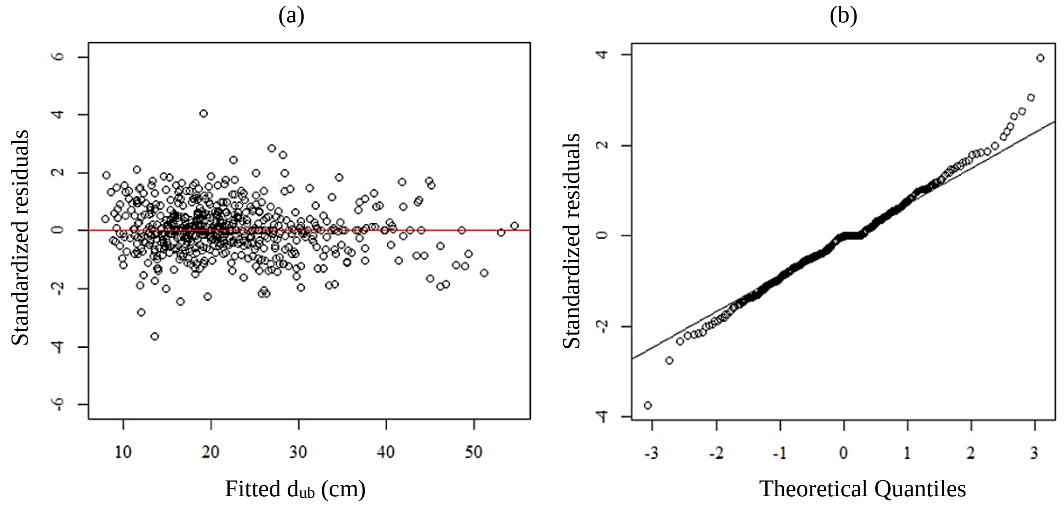

Figure 2. TPP 2 residual analysis: (a) fitted diameter under bark (d_{ub}); (b) normal probability plot of the standardized residuals

3.2 Bark thickness model

A bark thickness model was constructed using all the measured double bark thickness data, which excluded the buttressed records to avoid any issues resulting from the complexity of bark thickness in the heavily buttressed lower parts of a bole (the regression ANOVA table is shown in Table 2). The standardized residuals of the double bark thickness prediction were evenly distributed without any heteroscedasticity (Figure 3). This indicated that the model was suitable for use with the taper models selected for validation. The bark thickness model equation is shown in equation 6 (adjusted R^2=0.68943).

$$BT2 = 4.9736 (d_{ob})^{0.5052} \quad (6)$$

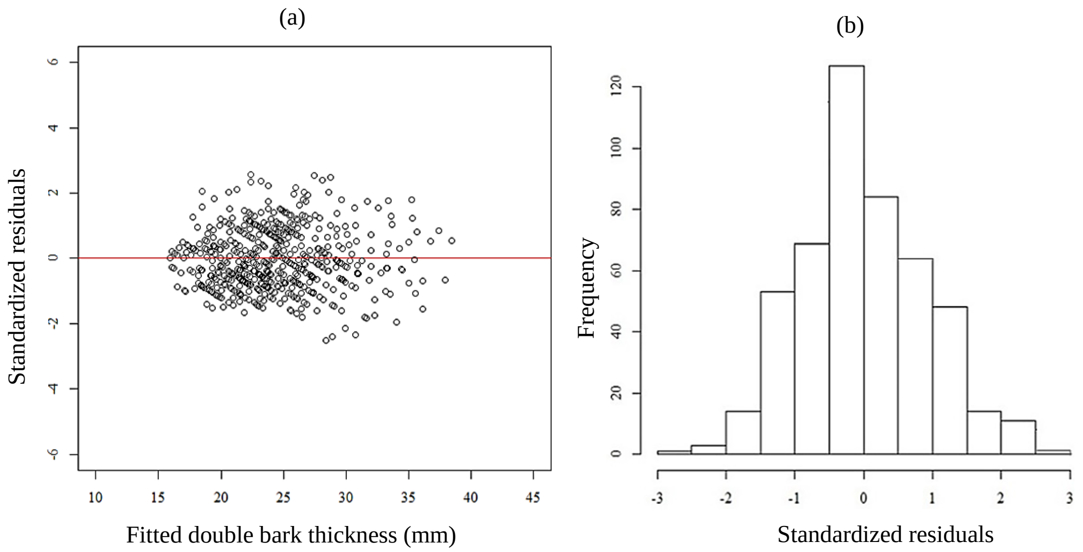

Figure 3. Bark thickness residual analysis: (a) fitted double bark thickness; (b) standardized residual histogram

3.3 Validation of calibrations

The three aspects of validation statistics that were evaluated are summarized in Table 3. Generally, the prediction of diameter given the height resulted in the most consistent predictions followed by the model used to determine the volume given diameter, and lastly, the model used to predict height given the diameter. Based on an even weighting of the three validation statistics, it was observed that no single statistic was suitable to determine the best calibration and no calibration performed the best on all the tests, supporting the deliberate inclusion of more than one test and instead using an overall best fit ranking (Kozak and Kozak, 2003).

The results showed that TPP 2 was the best taper model calibration for predicting the current dataset,

Table 3. Validation indices and overall statistic (numbers in **bold** indicate the best calibration for the respective statistic)

Calibration	d_{ub} at any given h	h at any given d_{ub}	Log volume at any given log length	Overall
TPP 1	3.417	**8.982**	3.986	5.462
TPP 2	3.271	9.346	**3.744**	**5.454**
TPP 3	3.460	9.137	4.123	5.573
TPP 10	3.538	9.865	4.269	5.891
TPP 11	3.484	10.231	4.147	5.954
TPP 12	**3.179**	9.942	3.781	5.634

as it resulted in the lowest overall validation index in addition to the residual histogram being normal distributed. The d_{ub} and log volume were slightly over-estimated while the model tended to slightly underestimate h (Figure 4). However, the mean prediction errors of all the three validation statistics were less than 10%, which indicated that the model prediction was sufficiently accurate, or as noted by Huang et al. (2003), was in a range that was realistic and reasonable.

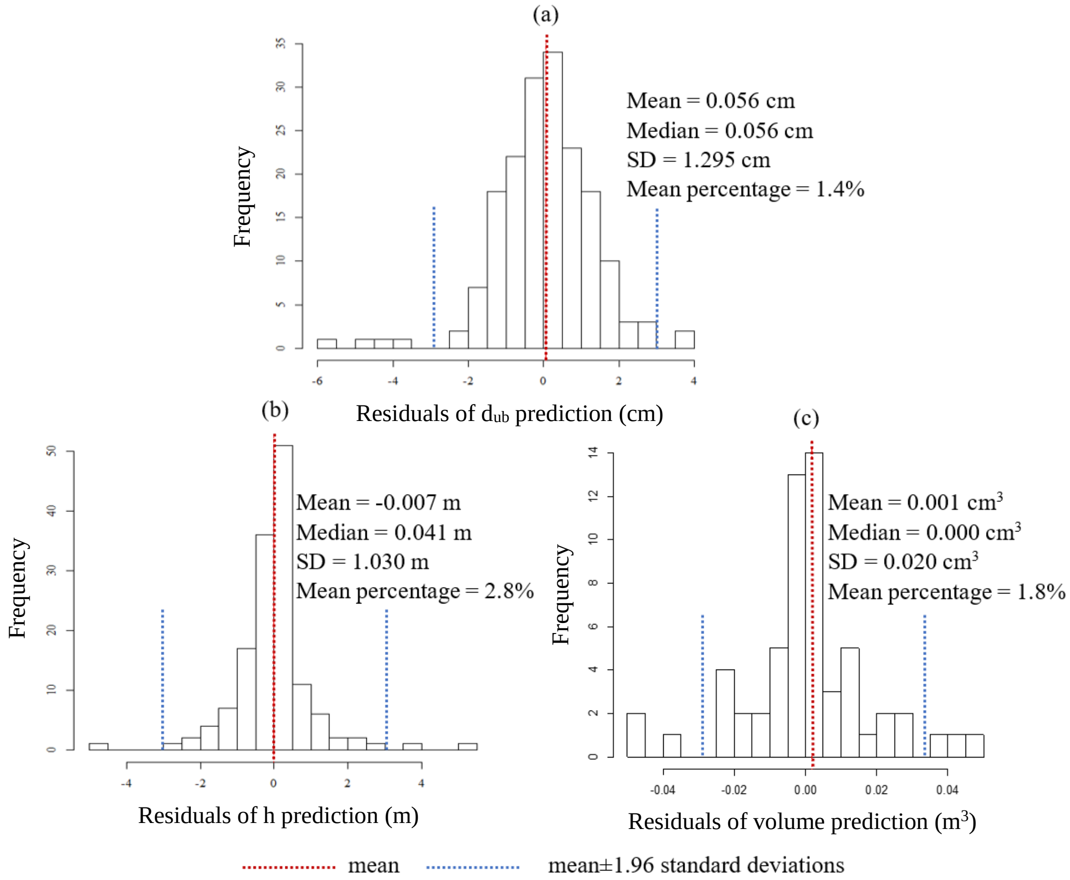

Figure 4. TPP 2 validation histograms: (a) diameter under bark (d_{ub}); (b) height (h) at d_{ub}; (c) log volume

An investigation of each class for each validation statistic of TPP 2 indicated that the mean prediction error of d_{ub} prediction at any given h, h prediction at any given d_{ub}, and log volume prediction at any given log length was within 0.8-2.3%, 1.5-4.8%, and 1.8-2.5%, respectively (Table 4). Importantly, the model predicted all 3 values within 1.8% in the lower bole, due to more sample points, resulting in a relatively higher accurate prediction in the lower bole, which is a more valued section of a tree (Fonweban et al., 2011; Warner et al., 2016; Zheng et al., 2017; López-Martínez et al., 2019). Overall, there was reduction in prediction accuracy for samples collected toward the top of the tree and of log volume prediction in taller trees. The log volume was generally overestimated except for a tendency to underestimation in the lower 6 m (the maximum teak log length sold to processors (FIO, 2013)).

Table 4. TPP 2 (with bark thickness model) validation statistics

Validation		Residual values				$\bar{e}$%	RE%
Prediction	Class	Mean	Mean %	Median	SD		
d_{ub} at any given height h	RH≤25%	0.089	0.8	0.092	1.123	-0.031	3.807
	RH>25%≤50%	0.127	1.1	0.203	1.205	-0.208	5.704
	RH>50%	-0.197	2.3	-0.186	1.535	0.056	9.822
h at any given d_{ub}	d_{ub}≤15 cm	0.033	4.8	0.086	1.020	-1.320	30.983
	d_{ub}>15 cm≤30 cm	-0.026	2.0	-0.082	1.098	0.983	15.732
	d_{ub}>30 cm	-0.005	1.5	0.110	0.886	0.242	6.814
Log volume at any given log length	Height≤6 m	-0.002	1.8	0.001	0.001	0.146	4.123
	Height>6 m≤12 m	0.006	2.1	-0.002	0.016	-0.689	7.783
	Height>12 m	0.008	2.5	0.002-	0.032	-0.073	9.650

Note: RH=Relative Height

3.4 Comparison between different teak taper models in Thailand

TPP 2 has the same formulation as the teak taper model developed for trees in Northern Thailand by Warner et al. (2016), known as the FIO-teak1 model. Its calibration is different from the present model formulation in terms of the coefficient values as well as the use of separate bark thickness models in combination with the respective teak taper models (Table 5).

Table 5. Model coefficient comparison (***): p<0.001

Model	Coefficient (±SE)		
	Coefficient	Teak taper model study	
		FIO-teak1 (Warner et al., 2016)	TPP 2 (This study)
Bark thickness model	a	3.035±0.445***	4.976±0.368***
	b	0.629±0.038***	0.505±0.023***
Taper model	c_1	0.593±0.012***	0.697±0.017***
	d_0	0.633±0.025***	0.511±0.021***
	f_2	0.777±0.031***	0.692±0.034***
	f_3	0.013±0.001***	0.015±0.001***
	f_4	-0.003±0.000***	-0.003±0.000***

The effects of different coefficient values used in the bark thickness models and taper model calibrations on the predicted values cannot be easily ascertained through visual inspection of the coefficients. Therefore, a scatter plot of double bark thickness at breast height versus diameter at breast height over bark was plotted to determine the differences between the different bark thicknesses models used to predict the bark thickness at breast height (Figure 5). For a comparison of taper models, D_{ub} was chosen as the model input to remove any confounding effects resulting from bark thickness and a plot of height above ground versus diameter under bark was drawn to assist with the comparison between different taper model calibrations based on the stem shape of a tree (Figure 6). A comparison of the bark thickness models indicated that the predicted bark thickness at breast height in TPP 2 was higher than for similar values using the FIO-teak1 bark thickness model, especially for small trees. A comparison of the taper model calibrations indicated that decreasing trends in the predicted diameter under bark along the stem from both taper models were similar for all representative tree sizes.

Figure 6 indicates that the stem shapes of teak trees grown in the Thong Pha Phum plantation and those in the teak plantations of Northern Thailand are similar. This could be because the seedlings planted in each FIO teak plantation are clones originating from the same genetic base as the ones in Northern Thailand. This observation is consistent with previous studies that reported that cloned trees had no distinct variations in stem shape even when they were grown under different conditions (Gomat et al., 2011; Morley

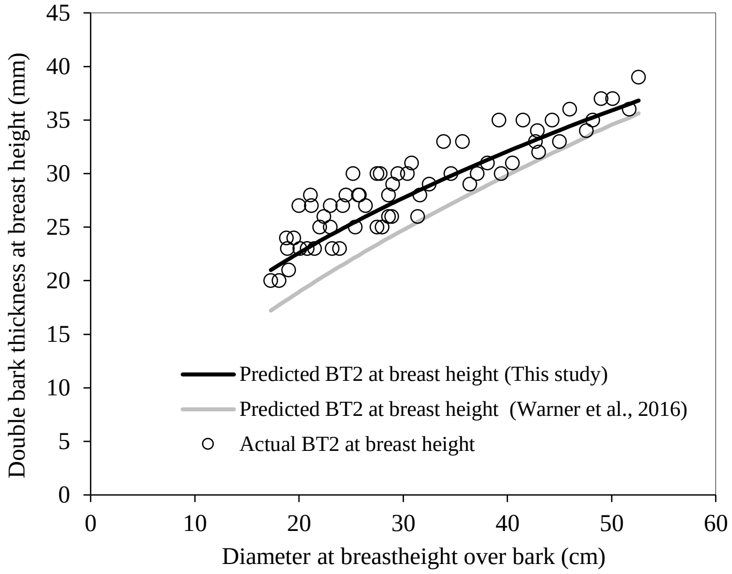

Figure 5. Model comparison of the predicted double bark thickness at breast height. (BT2=double bark thickness)

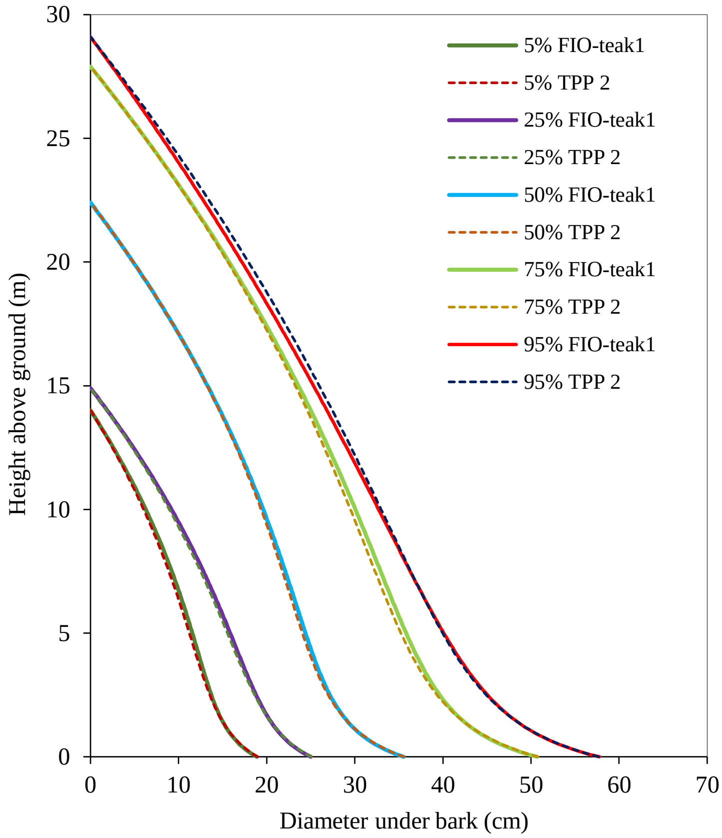

Figure 6. Comparison of model calibration of the predicted diameter under bark as percentiles. (%=percentile of DBH under bark)

and Little, 2012). However, Figure 5 indicates that the teak trees sampled from Thong Pha Phum plantation had a relatively thicker bark compared to the ones sampled from Northern Thailand. This may be because teak trees in Western Thailand grow in moist environments experiencing a tropical monsoon climate (Am), with an annual rainfall between 1,600-2,000 mm/year, compared to the north where the environment is of a dry tropical savanna (Aw) type with an annual rainfall measured in the range of 1,000-1,400 mm/year. According to a study related to the structure and function of tree barks done by Rosell (2016), it was reported that for trees growing under moist conditions in a tropical climate, the investment in a thicker bark occurs because transpiration and photosynthesis can be activated when the tree gets enough water. As such, the secondary phloem, which is the main structure of the inner tree bark, is produced by the vascular cambium. Moreover, a secondary phloem can produce phloem parenchyma to increase the storage of water and photosynthates and also transport food to other parts of a tree (Ryan and Asao, 2014). Therefore, such a cell division can result in a thicker tree bark.

4. CONCLUSIONS

Thong Pha Phum plantation, Kanchanaburi Province, Thailand was selected as a representative area for the development of suitable taper model calibrations for the volume estimation of teak growing in Western Thailand. The plantation is the largest teak plantation in the region and is also intensively managed. From the 12 taper model calibrations developed, TPP 2 was selected as the most suitable taper model calibration for teak growing in Western Thailand as it had the best overall performance (validation index=5.454 and adjusted R^2=0.98423). This calibration can predict the diameter under bark, tree height, and log volume with sufficient accuracy, especially in the lower bole, which is a more valued section of a teak tree. Comparison of TPP 2 with teak taper model (FIO-teak1) and bark equations, developed previously for teak trees in Northern Thailand, indicated that the trees growing in the two regions have similar stem shapes, but the teak trees grown in Western Thailand tend to have a thicker bark. For general usage, TPP 2 will be encoded in the Farm Forestry Toolbox software package and named FIO-teak2 for recommended application to optimize the log product value of standing teak trees in the plantations of Western Thailand based on log grade specifications, commonly used during the inventory process. Furthermore, using the under bark taper equations, regional differences in bark thickness can be an important factor in the teak inventory and will be investigated further.

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REFERENCES

Beck H, Zimmermann N, McVicar T, Vergopolan N, Berg A, Wood E. Present and future Köppen-Geiger climate classification maps at 1-km resolution. Scientific Data 2018;5:180214.

Brooks J, Jiang L-C, Iii A. Compatible stem taper, volume and weight equations for young longleaf pine plantations in Southwest Georgia. Southern Journal of Applied Forestry 2007;31:187-91.

Fonweban J, Gardiner B, Macdonald E, Auty D. Taper functions for scots pine (*Pinus sylvestris* L.) and sitka spruce (*Picea sitchensis* (Bong.) Carr.) in Northern Britain. Forest 2011;84:49-60.

Forest Industry Organization (FIO). Forest Management Optimization Using Farm Forestry Toolbox. Lampang, Thailand: Forest Industry Organization Regional Office; 2013.

Forest Industry Organization (FIO). Thong Pha Phum Forest Plantation Management Summary. Kanchanaburi, Thailand: Thong Pha Phum Forest Plantation Office; 2016.

Forest Industry Organization (FIO). Business Plan 2018. Bangkok, Thailand: Policy Planning and Strategy Bureau; 2018.

Gomat H, Deleporte P, Moukini R, Mialounguila G, Ognouabi N, Saya A, et al. What factors influence the stem taper of *Eucalyptus*: Growth, environmental conditions, or genetics? Annals of Forest Science 2011;68:109-20.

Goodwin A. A cubic tree taper model. Australian Forestry 2009;72:87-98.

Hansen O, Changtragoon S, Ponoy B, Kjær E, Minn Y, Finkeldey R, et al. Genetic resources of teak (*Tectona grandis* Linn. f.)-strong genetic structure among natural populations. Tree Genetics and Genomes 2014;11:1-16.

Hastie T, Tibshirani R, Friedman J. The Elements of Statistical Learning: Data Mining, Inference and Prediction. 2nd ed. New York, USA: Springer; 2013.

Huang S, Yang Y, Wang Y. A critical look at procedures for validating growth and yield models. In: Amaro A, Reed D, Soares P, editors. Modelling Forest Systems. Wallingford, UK: CABI Publishing; 2003. p. 271-94.

Kollert W, Kleine M. The Global Teak Study Analysis, Evaluation and Future Potential of Teak Resources. Vienna, Austria: International Union of Forest Research Organizations (IUFRO); 2017.

Klos RJ, Wang GC, Dang QL, East EW. Taper equations for five major commercial tree species in Manitoba, Canada. Western Journal of Applied Forestry 2007;22:163-70.

Kozak A, Smith JHG. Standards for evaluating taper estimating systems. Forest Chronicle 1993;69:438-44.

Kozak A, Kozak R. Does cross validation provide additional information in the evaluation of regression models? Canadian Journal of Forest Research 2003;33:976-87.

Kuželka K, Marušák R. Use of nonparametric regression methods for developing a local stem form model. Forest Science 2014;60:464-71.

López-Martínez J, Larreta B, Calderon O, Aguirre-Calderon C, Macario P, Martinez-Salvador M, et al. Compatible taper-volume systems for major tropical species in Mexico. Forestry 2019;93:56-74.

Miguel Sd, Mehtätalo L, Shater Z, Kraid B, Pukkala T. Evaluating marginal and conditional predictions of taper models in the absence of calibration data. Canadian Journal of Forest Research 2012;42:1383-94.

Morley T, Little K. Comparison of taper functions between two planted and coppiced eucalypt clonal hybrids, South Africa. New Forests 2012;43:129-41.

Nigh G, Smith W. Effect of climate on lodgepole pine stem taper in British Columbia, Canada. Forestry: An International Journal of Forest Research 2012;85(5):579-87.

Noda I, Himmapan W. Erratum to "Effects of silvicultural alternatives on model-based financial evaluation of teak (*Tectona grandis* L.) farm forestry management for small-scale farmers in Northeast Thailand". Open Journal of Forestry 2014;4:558-69.

Ryan MG, Asao S. Phloem transport in trees. Tree Physiology 2014;34:1-4.

Rosell J. Bark thickness across the angiosperms: More than just fire. New Phytologist 2016;211:90-102.

Sabatia C, Burkhart H. On the use of upper stem diameters to localize a segmented taper equation to new trees. Forest Science 2014;61:411-23.

Sumida A, Miyaura T, Torii H. Relationships of tree height and diameter at breast height revisited: Analyses of stem growth using 20-year data of an even-aged *Chamaecyparis obtusa* stand. Tree Physiology 2013;33(1):106-18.

Tasissa G, Burkhart H. An application of mixed effects analysis to modeling thinning effects on stem profile of loblolly pine. Forest Ecology and Management 1998;103:87-101.

Thai Meteorological Department. Annual weather summary [Internet]. 2020 [Cited 2020 Mar 5]. Available from: https://www.tmd.go.th/en/climate.php?FileID=5.

Vanclay JK. Optimum Sampling of Sample Trees for Volume Equations. Research Note No. 35. Brisbane, Australia: Department of Forestry; 1982.

Wang Y, Baker T. A regionalised growth model for *Eucalyptus globulus* plantations in south-eastern Australia. Australian Forestry 2007;70:93-107.

Warner AJ, Jamroenprucksa M, Puangchit L. Development and evaluation of teak (*Tectona grandis* L.f.) taper equations in Northern Thailand. Agriculture and Natural Resources 2016;50:362-7.

Warner AJ, Jamroenprucksa M, Puangchit L. Buttressing impact on diameter estimation in plantation teak (*Tectona grandis* L.f.) sample trees in Northern Thailand. Agriculture and Natural Resources 2017;51:520-5.

Westfall J, Scott C. Taper models for commercial tree species in the Northeastern United States. Forest Science 2010;56:515-28.

Yang Y, Huang S. Suitability of five cross validation methods for performance evaluation of nonlinear mixed-effects forest models-a case study. Forestry 2014;87(5):654-62.

Zheng C, Wang Y, Jia L, Mason E, We S, Sun C, et al. Compatible taper-volume models of *Quercus variabilis* Blume forests in North China. iForest 2017;10:567-75

Diversity and Habitat Use of Terrestrial Mammals in the Area Proposed for Water Resource Development in Khao Soi Dao Wildlife Sanctuary, Thailand

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ABSTRACT

The Khlong Ta Liu dam construction plan was re-proposed to be constructed in the forest area of Khao Soi Dao Wildlife Sanctuary in the Ta-riu tributary without a biodiversity impact assessment. Five camera traps were mounted at the hotspot points for terrestrial mammals next to the main trail for 376 trap nights from the forest edge to the forest interior. Fifteen species of terrestrial mammals were found. Two species found were categorized as having endangered status, while seven have vulnerable status. Grazers and browsers, i.e., Sambar, Gaur, Northern Red Muntjac, and Asian Elephant were mostly detected at the forest edge, while omnivores and frugivores, i.e., Wild Boar, Greater Hog Badger, and Northern Pig-tailed Macaque were largely detected in the forest interior. Dhole should be a carnivore species specific to the forest edge while Clouded Leopard should be in the forest interior. The Normalized Difference Vegetation Index (NDVI) may relate to species of terrestrial mammals detected at each habitat. Among the five habitats, three would be destroyed upon construction of the dam, including the habitat with the highest diversity of terrestrial mammals. The habitat that would likely be least impacted had the lowest species richness of terrestrial mammals.

1. INTRODUCTION

Khao Soi Dao Wildlife Sanctuary (745 km^2) is a part of the Cardamom Mountains rain forests ecoregion. It is the headwater of four sub-basins in eastern Thailand, with some water also flowing to Tonlé Sap Lake in Cambodia. Based on 2019 Thai population data from the Department of Provincial Administration, these four sub-basins provide water for at least 349,925 Thai people. Although an ecosystem service of Khao Soi Dao Wildlife Sanctuary is water provision, the wildlife sanctuary has been continuously encroached. By analyzing LANDSAT 8 satellite image from the U.S. Geological Survey using QGIS 3.10 program, the forest area covered was 581 km^2 in 2019 or 78% of the wildlife sanctuary area. The largest part of the forest area (246 km^2) is the headwater of Mae Nam Chanthaburi sub-basin which provides water for at least 129,392 people in Chanthaburi city and another two districts. Within this largest part of the forest area, the Ta-riu tributary (74 km^2) is the largest headwater and is comprised of the North and South Ta-riu sub-tributaries (30 km^2 and 44 km^2, respectively). In 1989, construction of the Khlong Ta Liu Dam was recommended in the Ta-riu tributary for irrigation (JICA, 1989). It should be noted that the Royal Irrigation Department uses the name "Ta Liu" while the Department of National Parks, Wildlife and Plant Conservation and the Royal Survey Department use the name "Ta-riu", but both names refer to the same area. The proposed Khlong Ta Liu Reservoir has a capacity of 30 million m^3. By using QGIS 3.10 program to simulate the reservoir area from this capacity, at least 1.6 km^2 of the Ta-riu tributary would be inundated, including 1.2 km^2 in the North and 0.4 km^2 in South Ta-riu sub-tributaries (Figure 1). Although the dam proposal was rejected when it was originally proposed, it was later re-proposed by the Royal Irrigation Department in 2017 for flood regulation purpose (Kateworachai, 2017). This re-proposal was again rejected by the Department of National Parks, Wildlife

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and Plant Conservation. Although the Khlong Ta Liu reservoir can enhance control of water in the Mae Nam Chanthaburi sub-basin, the potential negative impact on biodiversity has never been assessed.

Biodiversity is the core of ecosystem services, i.e., provisioning, regulating, supporting and cultural. While the reservoir can enhance control of water provision and flood regulation services, other ecosystem services of this area would be lost if the biodiversity were to be destroyed by the dam construction. Terrestrial mammals are an important part of the biodiversity and help to support the ecosystem. Moreover, certain species are the keystone species in food webs. Negative impacts on the diversity of terrestrial mammals can in turn affect its supporting service which can consequently affect other ecosystem services. Camera traps are an effective tool for surveying mammals. Data on species identification, habitat use, time of usage, behavior, and the number of individuals can be collected. Using camera traps, surveys on diversity and the habitat use of terrestrial mammal can effectively illustrate the potential negative impacts on biodiversity if the dam is constructed.

2. METHODOLOGY

2.1 Camera trap survey

The North Ta-riu sub-tributary was selected as the study site for two reasons. First, most of the inundated area will be in this sub-tributary. Second, there were high levels of cooperation between the local Non-Timber Forest Products (NTFPs) collectors and the author during a community-based conservation project to conserve an endangered Pileated Gibbon (*Hylobates pileatus*) that was conducted between 2009 and 2012 (Kolasartsanee and Srikosamatara, 2014). With their participation, the survey was designed according to their local experiences and the camera traps were unlikely to be destroyed or damaged by them. Five passive infrared-triggered camera traps, Bushnell 119837C (Bushnell Outdoor Products, Kansas, USA), were mounted at the hotspots of terrestrial mammals, i.e., salt lick and passageway, next to the main trail of the North Ta-riu sub-tributary from the forest edge to the forest interior (Figure 1). Locations of terrestrial mammals' hotspots were selected based on the experience of the late Mr. Wang Chomdee, the senior NTFPs collector who used to collect NTFPs in this sub-tributary for over thirty years and who was a key person during the community-based conservation project. At each camera trap station, a camera trap was mounted on a tree with a metal sling. The camera traps were pointed in directions perpendicular to the expected directions of mammals. For wide field of views, camera traps were mounted approximately 5 m from where the terrestrial mammals were expected to be. The installation and maintenance of the camera traps was conducted by the author with support from the Ta-riu wild elephant guarding team which is the self-established local conservation team extended from the community-based conservation project for Pileated Gibbons. All inter-trap distances were over 1 km (Table 1). This is the minimum recommended distance when the target organism's home range size is unknown (Wearn and Glover-Kapfer, 2017). Camera traps were set to take three still pictures after detection of terrestrial mammals, with a one second recovery rate. Camera traps were 24-h operated from 26 October 2018 to 5 November 2019 (376 trap nights). The wet season started in May, resulting in 187 trap nights during the dry season and 189 trap nights during the wet season. Some camera traps electronically malfunctioned which reduced the number of trap nights.

Table 1. Trap night of each camera trap's location in each season, type of camera trap station and distance from the forest edge

Camera trap's location	1	2	3	4	5
Trap night in dry season	187	156	142	186	186
Trap night in wet season	189	Aborted	135	188	188
Total trap night	**376**	**156**	**277**	**374**	**374**
Type of camera trap station	SL	PW	PW	SL	SL
Distance from the forest edge (m)	0	2058	3475	5180	6280

SL=salt lick and PW=passageway

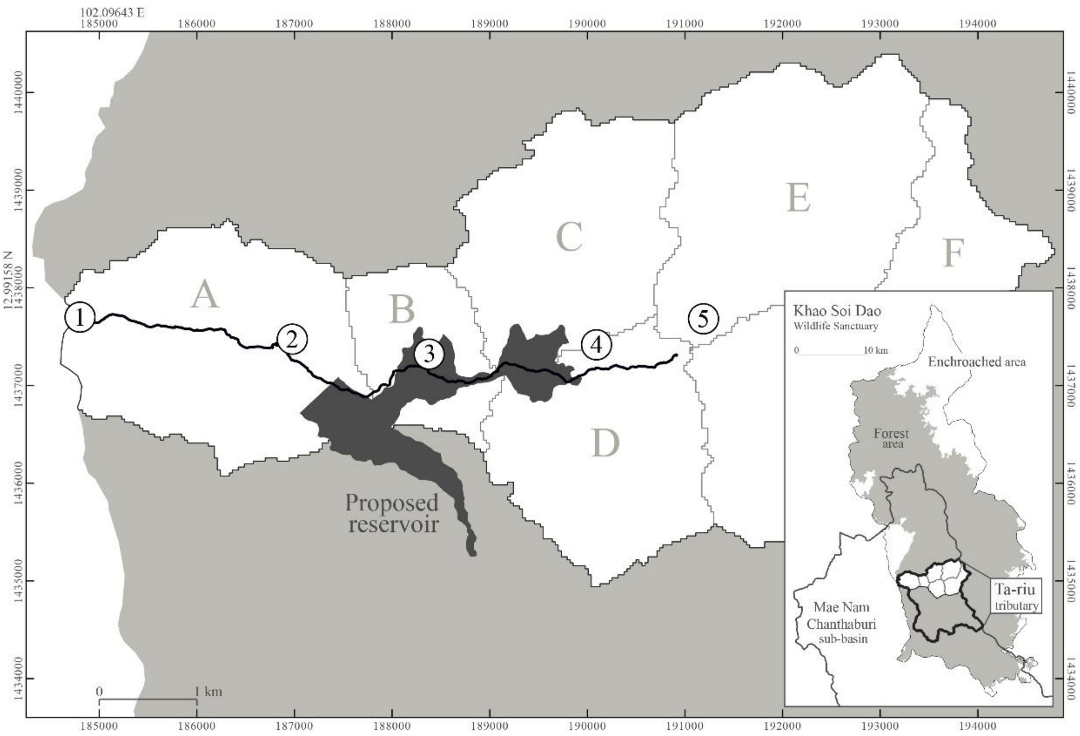

Figure 1. The North Ta-riu sub-tributary which is composed of six watersheds (watershed A to F). Numbers in white circles showed the locations of camera trap stations. Black line showed the main trail of North Ta-riu sub-tributary. The proposed reservoir showed in dark grey area (Adapted from JICA, 1989). (Projection: UTM; Datum: WGS84; Zone: 48P)

2.2 Data analysis

The time interval between independent detection was set as 30 min (Kitamura et al., 2010). The Relative Abundance Index (RAI) which is the number of detections per 100 trap nights sampling were calculated for each species at each camera trap for each season, as in the following equation.

$$\text{Relative Abundance Index (RAI)} = \frac{\text{Number of detection}}{\text{Total trap night}} \times 100$$

The RAI of each species from five camera traps were used to analyze the distribution of each species using the index of dispersion test, i.e., goodness-of-fit of the Poisson distribution (Krebs, 1999) as in the following equations.

$$\text{Index of dispersion(I)} = \frac{\text{Variance of RAI}}{\text{Mean of RAI}}$$

Then; $\chi 2 = \text{I(Number of camera traps} - 1)$

If $\chi 2$ is higher than $\chi 2_{\ 0.025}$, the distribution will significantly resemble a clumped pattern. If $\chi 2$ is lower than $\chi 2_{\ 0.975}$, the distribution will significantly resemble a uniform pattern. If $\chi 2$ is between $\chi 2_{\ 0.975}$ and $\chi 2_{\ 0.025}$, the distribution will significantly resemble a random pattern.

The RAI of each terrestrial mammal at each camera station in each season was used to plot the Lognormal rank abundance graph to illustrate the diversity of terrestrial mammals between each camera trap station.

Elevation, terrain slope, distance from forest edge, annual mean of Normalized Difference Vegetation Index (NDVI) and standard deviation of NDVI between months were the habitat characteristics around the camera trap stations that were used to analyze their relationships with the RAI of each terrestrial mammal species. The Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (U.S. Geological Survey) was used to extract elevation and terrain slope was calculated using the slope tool in QGIS 3.10 program. LANDSAT 8 satellite images (U.S. Geological Survey) in November 2018, January 2019, March 2019, and November 2019 were used to extract the NDVI. Satellite images from the other months during the survey period were full of clouds and so could not be used for analysis. The satellite images were atmospherically corrected by the dark Object Subtraction 1 (DOS1) method using the semi-automatic classification plugin in QGIS 3.10 program. The atmospheric corrected images were calculated for NDVI using the raster calculation tool in QGIS 3.10

program. A 500 m radius area surrounding each camera trap station was made using the buffer tool in QGIS 3.10 program to indicate the habitat area surrounding each camera trap station. The mean elevation, slope, and NDVI of these areas were extracted using the zonal statistic tool in QGIS 3.10 program. Correlations between characteristics of habitat and RAI of each terrestrial mammal species were analyzed by the Pearson correlation test using R 4.0.3 program.

3. RESULTS AND DISCUSSION

None of camera traps were destroyed or damaged by local people. Fifteen species of terrestrial mammals were found in this study. Two species have endangered status and seven have vulnerable status (Table 2; IUCN (2020)). Sambar was only found at camera 1 while Leopard Cat, Crab-eating Mongoose and Clouded Leopard were only found at camera 4 (Table 3). The distribution of Wild Boar was significantly clumped to the forest interior in both seasons. The distribution of Sambar was significantly clumped to the forest edge in both seasons. At least four male Sambars were found, three of which were adults, and one was a sub-adult with one-point antlers. The distribution of Gaur was significantly clumped to the forest edge during the dry season. Two adult males, one adult female, one sub-adult male, and two sub-adult females were found. Two adult males were mostly found at camera 1 while the females were found only at camera 3. The distribution of Northern Red Muntjac was significantly clumped to the forest edge during the wet season. The distribution of Greater Hog Badger was significantly clumped to the forest edge during the dry season.

Table 2. Common name, scientific name, IUCN status (IUCN, 2020) and total Relative Abundance Index (RAI) of terrestrial mammals found in this study.

Common name	Scientific name (IUCN status)	Total RAI
Wild Boar	*Sus scrofa* (LC)	6.17
Sambar	*Rusa unicolor* (VU)	5.65
Northern Pig-tailed Macaque	*Macaca leonina* (VU)	4.62
Gaur	*Bos gaurus* (VU)	3.92
Northern Red Muntjac	*Muntiacus vaginalis* (LC)	3.60
Greater Hog Badger	*Arctonyx collaris* (VU)	3.08
Malayan Porcupine	*Hystrix brachyura* (LC)	1.16
Asian Elephant	*Elephas maximus* (EN)	1.16
Asiatic Black Bear	*Ursus thibetanus* (VU)	0.45
Common Palm Civet	*Paradoxurus hermaphroditus* (LC)	0.45
Leopard Cat	*Prionailurus bengalensis* (LC)	0.32
Sun Bear	*Helarctos malayanus* (VU)	0.13
Dhole	*Cuon alpinus* (EN)	0.13
Crab-eating Mongoose	*Herpestes urva* (LC)	0.06
Clouded Leopard	*Neofelis nebulosa* (VU)	0.06

Table 3. The Relative Abundance Index (RAI) at each camera trap in each season.

Common name	Season	RAI at each camera					Distribution
		1	2	3	4	5	
Wild Boar	Dry		1.28	4.93	9.68	13.98	I
	Wet		-	2.96	3.72	17.02	I
Sambar	Dry	17.65					E
	Wet	29.10	-				E
Northern Pig-tailed Macaque	Dry	2.14	1.28	8.45	3.76	6.45	
	Wet	6.35	-	8.15	3.72	2.66	

Table 3. The Relative Abundance Index (RAI) at each camera trap in each season (cont.).

Common name	Season	RAI at each camera					Distribution
		1	2	3	4	5	
	Wet	6.35	-	8.15	3.72	2.66	
Gaur	Dry	26.20		2.11			E
	Wet	2.65	-	1.48	1.06		
Northern Red Muntjac	Dry	2.67	1.92	2.82	0.54	2.69	
	Wet	18.52	-	1.48		0.53	E
Greater Hog Badger	Dry		0.64	2.82	1.61	3.23	E
	Wet	2.65	-	9.63	4.26	4.26	
Malayan Porcupine	Dry	0.53	5.77		1.61		
	Wet	0.53	-	2.96			
Asian Elephant	Dry	4.28	1.28	0.70			
	Wet	3.17	-	0.74			
Asiatic Black Bear	Dry	0.53	1.28	0.70		1.08	
	Wet		-		0.53		
Common Palm Civet	Dry		0.64	2.11	0.54		
	Wet		-		1.06		
Leopard Cat	Dry				1.08		
	Wet		-		1.60		
Sun Bear	Dry			0.70		0.54	
	Wet		-				
Dhole	Dry	0.53					
	Wet		-	0.74			
Crab-eating Mongoose	Dry				0.54		
	Wet		-				
Clouded Leopard	Dry						
	Wet		-		0.53		

RAI: Blank=0; – =not surveyed
Distribution: I=significantly clumped at forest interior; E=significantly clumped at forest edge; Blank=significantly random distribution

The lognormal rank abundance plot of terrestrial mammals that used each habitat in each season is shown in Figure 2. In both seasons, the habitat with the highest species richness and most evenly distributed $\log_{10}$ RAI, i.e., the log normal distribution, was the habitat around camera 3, so it can be inferred that this habitat was used by highest diversity of terrestrial mammals in both seasons. Habitats located further from camera 3 at both the forest edge and interior directions tended to have lower species richness and lesser evenly distributed $\log_{10}$ RAI, i.e., the dominance preemption model, so it can be inferred that these habitats were used by a lower diversity of terrestrial mammals.

Characters of habitat around each camera trap station are shown in Table 4. There were some significant correlations among habitat characteristics. Distance from forest edge was significantly correlated with SD of NDVI between months and mean elevation. Habitats in the forest interior had significantly lower SD of NDVI between months (Pearson correlation coefficient=-0.94; p-value=0.02) and significantly higher mean elevation (Pearson correlation coefficient=0.97; p-value=0.01) than habitats at the forest edge. Mean elevation and SD of NDVI between months were also significantly correlated with each other (Pearson correlation coefficient=-0.93; p-value=0.02). The RAI of Asian Elephant in both seasons and Gaur in the wet season were significantly higher in habitats at the forest edge, low elevation and high SD of NDVI between months, than habitats in the forest interior. The RAI of Wild Boar in the dry season was significantly lower in habitats at the forest edge than habitats in the forest interior (Table 5).

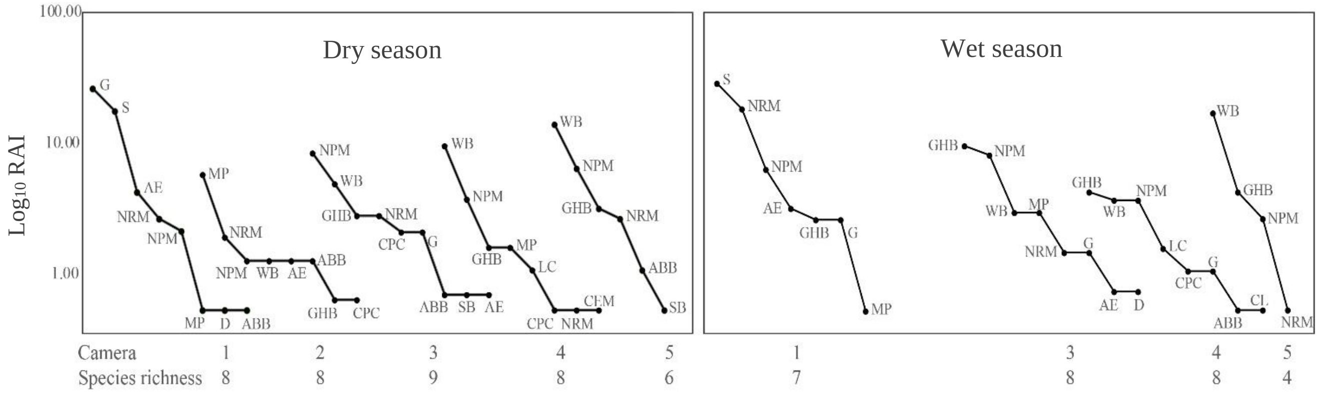

Figure 2. Lognormal rank abundance plot of terrestrial mammals that used each habitat in each season with the abbreviation of each species; ABB: Asiatic Black Bear, AE: Asian Elephant, CEM: Crab-eating Mongoose, CPC: Common Palm Civet, CL: Clouded Leopard, D: Dhole, G: Gaur, GHB: Greater Hog Badger, LC: Leopard Cat, MP: Malayan Porcupine, NPM: Northern Pig-tailed Macaque, NRM: Northern Red Muntjac, S: Sambar, SB: Sun Bear, WB: Wild Boar.

Table 4. Characters of habitat around each camera trap station

Camera trap's location	1	2	3	4	5
Mean elevation (m MSL)	162	218	239	266	333
Mean terrain slope (degree)	20	17	12	9	13
Distance from the forest edge (m)	0	2058	3475	5180	6280
Annual mean of NDVI	0.77	0.80	0.80	0.79	0.80
SD of NDVI between months	0.08	0.06	0.05	0.06	0.05

Table 5. Significant correlations between habitat characters and the RAI of terrestrial mammals

Dry season	Habitat character	Coefficient	p-value
Asian Elephant	Distance	-0.92	0.03
	NDVI SD	0.95	0.01
Wild Boar	Distance	0.96	0.01
	Elevation	0.96	0.01
Wet season	Habitat character	Coefficient	p-value
Asian Elephant	Distance	-0.97	0.03
	NDVI SD	0.96	0.04
Gaur	Distance	-0.97	0.03
	Elevation	-0.99	<0.01

At the forest edge, grazers and browsers were mostly found. The habitat around camera 1 had a unique pattern of mean NDVI between months that favored Gaur and Asian Elephant during the dry season. In March 2019, the mean NDVI of habitat around camera 1 decreased more than the other habitats. This was the only habitat that had a mean NDVI lower than 0.7 and Gaur and Asian Elephant were frequently detected only at this habitat around that time (Figure 3). Since NDVI can reflect the amount of chlorophyll at the canopy, a low NDVI can imply leaf senescence or shedding at the canopy, resulting in higher light penetration to the ground. This condition can result in the graminoids to thrive, which are the main diet of Gaur and Asian Elephant. During the wet season when the NDVI increased, Sambar and Northern Red Muntjac began to be detected more often than Gaur and Asian Elephant. Northern Red Muntjac and Sambar were the main prey of Dhole (Intaraprasit et al., 2017; Kamler et al., 2020), so Dhole should be one of the carnivores that is specific to the forest edge, especially during the wet season. One point of concern is that Dhole may potentially catch certain diseases from domestic dogs at the forest edge, since Dhole is susceptible to Canine Distemper (Sillero-Zubiri et al., 2004), a lethal disease among domestic dogs which is prevalent in the villages.

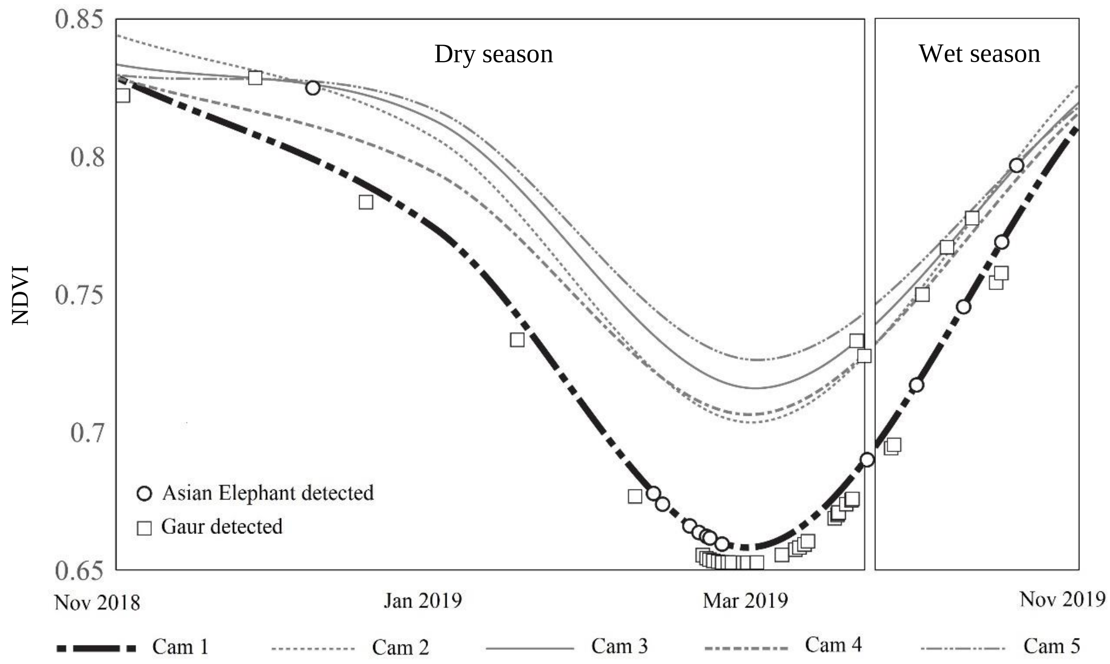

Figure 3. Trendlines of NDVI at each habitat and dates that Asian Elephant and Gaur were detected.

In the forest interior, Wild Boar, Northern Pig-tailed Macaque and Greater Hog Badger were most detected in both seasons (Figure 2). These terrestrial mammals are omnivores and frugivores. The lower SD of NDVI between months in the forest interior may make these habitats less favored to grazers and browsers than at the forest edge. The leaf canopy in the forest interior should be more evergreen than at the forest edge which makes less light penetrate to the ground. This condition should be more suitable for the shade-tolerant understory plants to thrive rather than the graminoids. Clouded Leopard was found once at camera 4 during the wet season. Wild Boar, Northern Pig-tailed Macaque and Greater Hog Badger were the most detected species of prey for Clouded Leopard (Davies, 1990; Ngoprasert et al., 2012). In April 2010, the author directly found a Clouded Leopard which had hunted on a Greater Hog Badger in the area near camera 5. According to the distribution of these three most detected species, Clouded Leopard should be one of the carnivores that is specific to the forest interior. The study at Khlong Saeng - Khao Sok Forest Complex, Thailand showed the same trend. The estimated density of Clouded Leopard in the core area was higher than in the edge area (Petersen et al., 2020). According to the geographic range of Clouded Leopard in the IUCN Red List of Threatened Species database, it was present in the Khao Angruenai Wildlife Sanctuary but was absent in the Khao Soi Dao Wildlife Sanctuary (Grassman et al., 2016). Thus, the results from this study can be a new record of its occurrence (Figure 4).

The results from this study reveal that the North Ta-riu sub-tributary is not degraded forest and is regularly used by a diverse range of terrestrial mammals. Further, greater distance from the forest edge does not appear to correlate with a higher diversity of terrestrial mammals, since each habitat had unique characters. Habitat at the forest edge (camera 1) had a unique NDVI pattern which favored grazers and browsers. Meanwhile, habitat located in between forest edge and the forest interior (camera 3) was used by the highest diversity of terrestrial mammals. Additionally, habitats in the forest interior (camera 4 and 5) were mostly used by omnivores and frugivores. According to the dam construction plan (JICA, 1989), the habitat around camera 3 would be inundated (Figure 1). The forest outside the inundated area could also be destroyed during the dam construction process. The rock-filled dam would be constructed at watershed A using rocks quarried from a mountain between watersheds B and D. The habitat around camera 1 would be the filter and drain area. Habitats around cameras 1, 2, and 3 would be destroyed, including the area of highest terrestrial mammal species diversity around camera 3. The terrestrial mammals that specifically use these habitats include Sambar, Gaur, Northern Red Muntjac, Asian Elephant, and Dhole. Among these species, Asian Elephant and Dhole have endangered status. The

Figure 4. Clouded Leopard found in this study.

habitat around camera 4 would have indirect negative impacts and the habitat around camera 5, which was used by the lowest species richness of terrestrial mammals, would be the least impacted by the dam construction. From the perspective of the Pileated Gibbon conservation, the Khao Soi Dao Wildlife Sanctuary is an important habitat for the Cardamom Mountains rain forests population in Thailand. The North Ta-riu sub-tributary has been a historic study site for Pileated Gibbon since 1979 (Srikosamatara, 1980; Srikosamatara, 1984) and conservation evidence has only been found at this sub-tributary (Kolasartsanee, 2014; Kolasartsanee and Srikosamatara, 2014; Kolasartsanee, 2016). Pileated Gibbon was not only found at watersheds E and F (camera 5) but also at watersheds C and D (camera 4) (Kolasartsanee and Srikosamatara, 2014). During this study, watershed B (camera 3) was found to be a new colonizing area of Pileated Gibbon (Kolasartsanee and Srikosamatara, 2019), meaning that dam construction would negatively affect the recovery of Pileated Gibbon in this sub-tributary. From both national and global scale policy perspectives, the dam should not be constructed within the protected forest. At the national policy scale, the national forest policy aims to prevent forest loss and seeks to increase forest areas to 40% of the country's area. At the global policy scale, the Aichi target 5 aims to reduce forest loss and fragmentation, while target 11 aims to protect 17% of terrestrial land and inland water areas. From diversity and habitat use of terrestrial mammals, community-based conservation on Pileated Gibbon and policy perspectives, water resource development projects outside the wildlife sanctuary area would be the best solution and can ensure synergy between wildlife sanctuary ecosystem services and water management.

4. CONCLUSION

The detected terrestrial mammals were unique between habitat at the forest edge and the forest interior. Sambar, Northern Red Muntjac, Gaur and Asian Elephant which are grazers and browsers were mostly detected at the forest edge, while Wild Boar, Greater Hog Badger and Northern Pig-tailed Macaque, which are omnivores and frugivores, were mostly detected in the forest interior. Based on distribution of prey, Dhole should be one of the carnivores that is specific to the forest edge while Clouded Leopard should be in the forest interior. North Ta-riu sub-tributary was regularly used by diverse terrestrial mammals. Dam construction will permanently destroy the habitats, especially at the habitat around camera 3 which was used by the highest diversity of terrestrial mammals, and habitat around camera 1 which its unique characters favored grazers and browsers.

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REFERENCES

Davies R. Sighting of a clouded leopard (*Neofelis nebulosa*) in a troop of pigtail macaques (*Macaca nemestrina*) in Khao Yai National Park, Thailand. Natural History Bulletin of the Siam Society 1990;28:95-6.

Grassman L, Lynam A, Mohamad S, Duckworth JW, Bora J, Wilcox D, et al. *Neofelis nebulosa* the IUCN red list of threatened species 2016 [Internet]. 2016 [cited 2020 Sep 7]. Available from: https://www.iucnredlist.org/species/14519/97215090.

Intaraprasit S, Sukmasuang R, Duengkae P. Abundance and prey selection of dhole (*Cuon alpinus*) in Huai Kha Khaeng Wildlife Sanctuary, Uthai Thani Province. Journal of Wildlife in Thailand 2017;24:63-74 (in Thai).

International Union for Conservation of Nature (IUCN). The IUCN red list of threatened species [Internet]. 2020 [cited 2020 Sep 7]. Available from: https://www.iucnredlist.org/.

Japan International Cooperation Agency (JICA). The Feasibility Study on the Agricultural Water Development Project of Chanthaburi River Basin. Japan: Japan International Cooperation Agency; 1989.

Kamler J, Thatdokkham K, Rostro-García S, Bousa A, Caragiulo A, Crouthers R, et al. Diet and prey selection of dholes in evergreen and deciduous forests of Southeast Asia. Journal of Wildlife Management 2020;84:1396-405.

Kateworachai S. Using the king's philosophy to extend the Bhakti Rambhai Canal [Internet]. 2017 [cited 2020 Sep 7]. Available from: https://www.dailynews.co.th/agriculture/578620 (in Thai).

Kitamura S, Thong-Aree S, Madsri S, Poonswad P. Mammal diversity and conservation in a small isolated forest of Southern Thailand. Raffles Bulletin of Zoology 2010;58:145-56.

Kolasartsanee I. Networking Non-Timber Forest Product (NTFP) Collectors for the Population Recovery of Pileated Gibbon (*Hylobates pileatus*) [dissertation]. Bangkok, Mahidol University; 2014.

Kolasartsanee I, Srikosamatara S. Applying "Diffusion of innovation" theory and social marketing for the recovery of pileated gibbon *Hylobates pileatus* in North Ta-riu watershed, Khao Soi Dao Wildlife Sanctuary, Thailand. Conservation Evidence 2014;11:61-5.

Kolasartsanee I. Patrol area determination using the prediction from pileated gibbon (*Hylobates pileatus*) distribution in Ta-riu watershed, Khao Soi Dao Wildlife Sanctuary, Thailand. Srinakharinwirot Science Journal 2016;32:152-60.

Kolasartsanee I, Srikosamatara S. Evidence of pileated gibbons *Hylobates pileatus* recolonization in an area proposed for water resource development in Khao Soi Dao Wildlife Sanctuary, Thailand. Asian Primates Journal 2019;8:41-4.

Krebs C. Ecological Methodology. California, USA: Addison-Wesley; 1999.

Ngoprasert D, Lynam A, Sukmasuang R, Tantipisanuh N, Chutipong W, Steinmetz R, et al. Occurrence of three felids across a network of protected areas in Thailand: prey, intraguild, and habitat associations. Biotropica 2012;44:810-7.

Petersen W, Steinmetz R, Sribuarod K, Ngoprasert D. Density and movements of mainland clouded leopards (*Neofelis nebulosa*) under conditions of high and low poaching pressure. Global Ecology and Conservation 2020;23:e01117.

Sillero-Zubiri C, Hoffmann M, Macdonald DW. Canids: Foxes, Wolves, Jackals and Dogs. Status Survey and Conservation Action Plan. Gland, Switzerland and Cambridge, UK: IUCN/SSC Canid Specialist Group; 2004.

Srikosamatara S. Ecology and Behavior of the Pileated Gibbon (*Hylobates pileatus*) in Khao Soi Dao Wildlife Sanctuary, Thailand [dissertation]. Bangkok, Mahidol University; 1980.

Srikosamatara S. Ecology of pileated gibbons in South-east Thailand. In: Preuschoft H, Chivers D, Brockelman W, Creel N, editors. The Lesser Apes: Evolutionary and Behavioural Biology. Edinburgh: Edinburgh University Press; 1984. p. 242-57.

Wearn O, Glover-Kapfer P. Camera-trapping for Conservation: A Guide to Best-practices. UK: World Wildlife Fund; 2017.

Effect of COVID-19 Lockdown on Air Quality: Evidence from South Asian Megacities

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ABSTRACT

Anthropogenic activities were greatly restricted in many South Asian cities during the COVID-19 (Coronavirus disease-2019) pandemic creating an opportunity to observe source reduction of air pollutants. This study analyzed the change in columnar nitrogen dioxide (NO_2) and particulate matter ($PM_{2.5}$, aerodynamic diameter ≤2.5 μm) in five megacities of South Asian countries (Delhi, Dhaka, Kathmandu, Kolkata, and Lahore) from April 1 - May 31 over the previous three years (2018-2020). The Dutch-Finnish Ozone Monitoring Instrument (OMI) provided satellite-based daily tropospheric columnar NO_2 values for this study. Ground-based hourly $PM_{2.5}$ data were collected from the World's Air Pollution: Real-time Air Quality Index Project. The study observed a decrease of tropospheric columnar NO_2 in selected cities in 2020 compared to 2018 and 2019 from April 1 - May 31. The mean daily reading of $PM_{2.5}$ was 36.56% and 45.44% less in Delhi; 12.67% and 23.46% less in Dhaka; in Kathmandu 28.32% and 37.42% less; in Kolkata 41.02% less in 2020 than 2018 and 34.08% less in 2019 during April 1 - May 31. The $PM_{2.5}$ was 44.26% less in 2020 than in 2019 during April 9 - May 31 in Lahore. The daily mean difference in concentration during April 1 - May 31, 2018-2020 was significantly lower at α=0.01 level for both pollutants. Introducing appropriate mitigation measures would provide safer environments and reduce future air pollution in South Asian cities.

1. INTRODUCTION

1.1 Coronavirus disease (COVID-19) pandemic

The world was reminded of environmental determinism in December 2019 by a new strain of Coronavirus (COVID-19). The virus appeared to have originated in Wuhan, China (Chen et al., 2020). This respiratory illness spread worldwide and led to a global pandemic. COVID-19 pandemic has impacted many aspects of human life and the global economy. A reduction of pollution has occurred due to limited social and economic activities despite the negative impacts of COVID-19 in many aspects of daily life (Dutheil et al., 2020). Most countries have tried to contain the spread of the highly contagious virus with massive COVID-19 screening tests, social distancing public policies, travel restrictions, and lockdown. The South Asian countries of Bangladesh, India, Nepal, and Pakistan restricted movements from the mid of March 2020 to mitigate the COVID-19 pandemic (Shrestha et al., 2020; Mahato et al., 2020; Nayeem et al., 2020).

The Bangladesh government reported the first three known cases on March 8, 2020 (IEDCR, 2020). To protect the population from this outbreak, the government declared a countrywide lockdown from March 23 to May 30, 2020 (Nayeem et al., 2020). Heavy vehicles (long road trucks) and diesel buses were restricted during the daytime in Dhaka during these weeks.

India identified the first case of COVID-19 on January 30, 2020; by July 7, 2020, India had the third-highest number of confirmed cases after the United States and Brazil (Kulkarni, 2020). The Indian government imposed a nationwide lockdown on

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March 24, 2020, for 21 days to control this outbreak extending it to May 31, 2020. The government restricted vehicle movements (except emergency services) in Delhi and Kolkata to comply with the social distancing policy.

Nepal reported the first COVID-19 positive patient on January 23, 2020, when a 31-year-old student returned to Kathmandu from Wuhan, China. In response, the Nepal government suspended on-arrival tourist visas for all countries from March 14 - April 30, 2020. After that, a countrywide lockdown came into effect on March 24, 2020, which ended on July 21, 2020 (Pradhan, 2020). The government also closed the land border entry points for third-country nationals and canceled all mountain climbing expeditions, including Mount Everest. Enforcement of these restrictions was from March 14 - April 30, 2020 (Himalayan Times, 2020).

Pakistan reported the first confirmed case on February 26, 2020. As a result, the Pakistan government closed shopping malls, markets, parks, and public gathering places. The government declared a 14-day lockdown from March 24 - April 6, later extended to April 30 (Sipra et al., 2020). The government shut down all land borders and canceled international and domestic flights.

With all these restraints in these four countries, only emergency services such as medical, healthcare, logistics, food supply chain, power sector, and banking were allowed to be carried on in a limited way. Therefore, less vehicle movement on the roads, restricted construction, and industrial activities has led to an emission reduction of various gases and particulate matter in the atmosphere (Nadzir et al., 2020).

1.2 Sources apportionment of air pollution over different cities

A study carried out in Delhi during the winter of 2013-2014, and the summer of 2014 identified the source apportionment of $PM_{2.5}$ as road dust (38%), vehicular pollution (20%), domestic sources (12%), industrial sources (11%), concrete batching (6%), and 13% from other sources (Nagar et al., 2017). Vehicular emission (51.4%), followed by industrial sources (24.5%) and road dust (21.1%) were identified as the significant sources of air pollution in Kolkata (Haque and Singh, 2017). In Dhaka, previous studies have identified brick kilns located near the city, uncontrolled open burning of trash, and vehicle exhaust as significant sources of $PM_{2.5}$ (Nayeem et al., 2020). Primary sources of $PM_{2.5}$ in Lahore are diesel emission and two-stroke vehicles (36%), biomass burning (15%), coal combustion (13%), and industrial activities (Dutkiewicz et al., 2009; Raja et al., 2010; Stone et al., 2010). Brick kilns (40%), motor vehicles (37%) biomass/garbage burning (22%), and soil dust (1%) have been identified as contributing sources in the Kathmandu Valley (Kim et al., 2015).

1.3 COVID-19 and air pollution

One of the significant environmental problems of developing countries is air pollution, mostly seen in urban areas due to exhaust from vehicles, brick kilns, industrial and construction activities, unsustainable farming, open waste dumping, and combustion of fossil fuels (Majumder et al., 2020; Nayeem et al., 2019; Razib et al., 2020; Nadzir et al., 2020; Hossain et al., 2019). These emissions are responsible for the release of several gaseous compounds such as carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), sulfur dioxide (SO_2), and particulate matter (coarse and fine particles) into the atmosphere. Among these compounds, the concentrations of nitrogen dioxide (NO_2) and fine particulate matter ($PM_{2.5}$) are monitored continuously in urban areas since these compounds have adverse impacts on human health (Latif et al., 2012; Banan et al., 2012; Nadzir et al., 2018). Increased levels of these pollutants may cause acute and chronic diseases resulting in 5.5 million unnecessary deaths annually (WHO, 2016).

Many satellite and ground-based air pollution studies have addressed the impacts of COVID-19 pandemic. A study reported that three cities in central China (Wuhan, Jingmen, and Enshi) had recorded total reductions of air pollutants of $PM_{2.5}$ by 30.1% and of NO_2 by 61.4% during the pandemic (Xu et al., 2020). The average air quality index (AQI) for these three cities decreased significantly compared to 2017-2019. In another study, the Copernicus Atmosphere Monitoring Service (CAMS) was used to observe the concentration of particulate matter ($PM_{2.5}$) in China and found a 20-30% reduction throughout lockdown compared to the previous three years of 2017, 2018, and 2019 during the same months (Zambrano et al., 2020). In one study over the peninsular Malaysia region, the concentration of $PM_{2.5}$ was found to be reduced by 58.4% during the lockdown (Abdullah et al., 2020). A study in Barcelona, Spain, using Copernicus Tropospheric Monitoring Instrument, reported a 51.0% reduction of tropospheric columnar NO_2 during the lockdown than the month before the lockdown (Tobías et al., 2020). A sharp declining trend of NO_2 concentrations was also observed in developed countries such as France, Germany, Italy, and Spain (ESA, 2020).

According to the 2019 IQAir report, Bangladesh (1st), Pakistan (2nd), India (5th), and Nepal (8th) are some of the world's most polluted countries for $PM_{2.5}$ exposure with high urban growth rates (UNCTAD, 2020), Delhi topped the list of the world's most polluted capital cities followed by Dhaka (IQAir, 2019). Since India ranks as the second-most populous country, Kolkata, a very crowded city just adjacent to Bangladesh surrounded by numerous coal power plants, is also worthy of being evaluated (Vadrevu et al., 2020). While Islamabad, the capital city of Pakistan, ranked 14th, $PM_{2.5}$ exposure data is not available. This study considered, a relative nearby alternative Lahore (270 km), where a strict lockdown was imposed and is a significant polluted city according to the US Air Quality Index (Sipra et al., 2020). In Nepal, Kathmandu has the 6th highest $PM_{2.5}$ value of any capital being analyzed (IQAir, 2019). As several studies found that atmospheric pollution is a transboundary issue (Shehzad et al., 2020; Rana et al., 2016), only the research on a regional scale can identify issues. According to the Koppen climate classification scheme, part of Delhi and Lahore are considered Bsh (semi-arid), other parts of Delhi and Kathmandu are in a Cwa (humid subtropical) climatic zone, and Kolkata and Dhaka fall in a Aw (tropical wet-and-dry) zone (Lohmann et al., 1993) and these cities are also part of the regional wind system. This study chose these five megacities of four neighboring countries since they are cities in member countries of the regional forum SAARC (South Asian Association of Regional Cooperation). We have carried out this study to observe the impacts of COVID-19 lockdown on air quality in those five polluted megacities of South Asia. The objective of this study was to analyze the variations in satellite-derived tropospheric columnar NO_2 and ground-based $PM_{2.5}$ concentration in selected South Asian megacities: Delhi, Dhaka, Kathmandu, Kolkata, and Lahore for the three years (2018-2020) at the same period of April 1 - May 31.

2. METHODOLOGY

2.1 Tropospheric NO_2 Vertical Column Densities (VCDs)

The Dutch-Finnish Ozone Monitoring Instrument (OMI), a UV-Visible wavelength spectrometer on the polar-orbiting NASA Aura satellite (https://so2.gsfc.nasa.gov/no2/no2_index.html), provided daily tropospheric columnar NO_2 values. This OMI sensor measures direct and atmospheric backscattered sunlight in the ultraviolet-visible (UV-Vis) zone ranging from 270 to 500 nm (Levelt et al., 2006). The normal spatial resolution is 24 × 13 km^2 in nadir and was zoomed into 13 × 13 km^2 to monitor urban scale pollution sources (Boersma et al., 2004). In this study, level 2 data were collected as comma-separated value (CSV) files to detect tropospheric columnar NO_2 in five megacities of South Asian countries during the COVID-19 pandemic compared to 2018 and 2019 during the same months (April-May). The 1 × 1 degree grid boxes surrounding each city was calculated to be: Delhi (76.709N 28.1139E 77.709N 29.1139E); Dhaka (89.9201N 23.308E 90.9201N 24.308E); Kathmandu (84.824N 27.2172E 85.824N 28.2172E); Kolkata (87.9001N 22.0667E 88.9001N 23.0667E), and Lahore (73.8436N 31.0497E 74.8436N 32.0497E). We retrieved average spatial maps of tropospheric columnar NO_2 in the troposphere with 0.25° × 0.25° resolution from the GIOVANNI online platform (GIOVANNI, 2020).

2.2 Ground level $PM_{2.5}$

$PM_{2.5}$ data were gathered from April 1 - May 31 over the last three years (2018-2020) from four selected Southeast Asian cities: Dhaka, Kolkata, Delhi, and Kathmandu. Data from April 9 - April 30, 2019, and May 9 - May 31, 2020 were used for Lahore since other data was lacking (Figure 1). We obtained hourly readings of $PM_{2.5}$ from the publicly available air quality data at World's Air Pollution: Real-time Air Quality Index Project (Air Now, 2020). Ground-based $PM_{2.5}$ monitoring stations, located at or near the US embassies and consulates of each country, record data. Several researchers have used this data source to determine compliance with air quality standards, simulate model, forecast air quality, study epidemiology, and assess health risk (Diao et al., 2019; Bulto, 2020; Yousefian et al., 2020; Roy et al., 2020). In the global village, using open-access air quality data helps develop integrated actions to control air pollution.

2.3 Data analysis

SPSSv20 and Microsoft Excelv10 were used for data processing, analysis, and preparing tables and graphs. Tukey's post hoc multiple comparison test was conducted to determine the significant level of changes

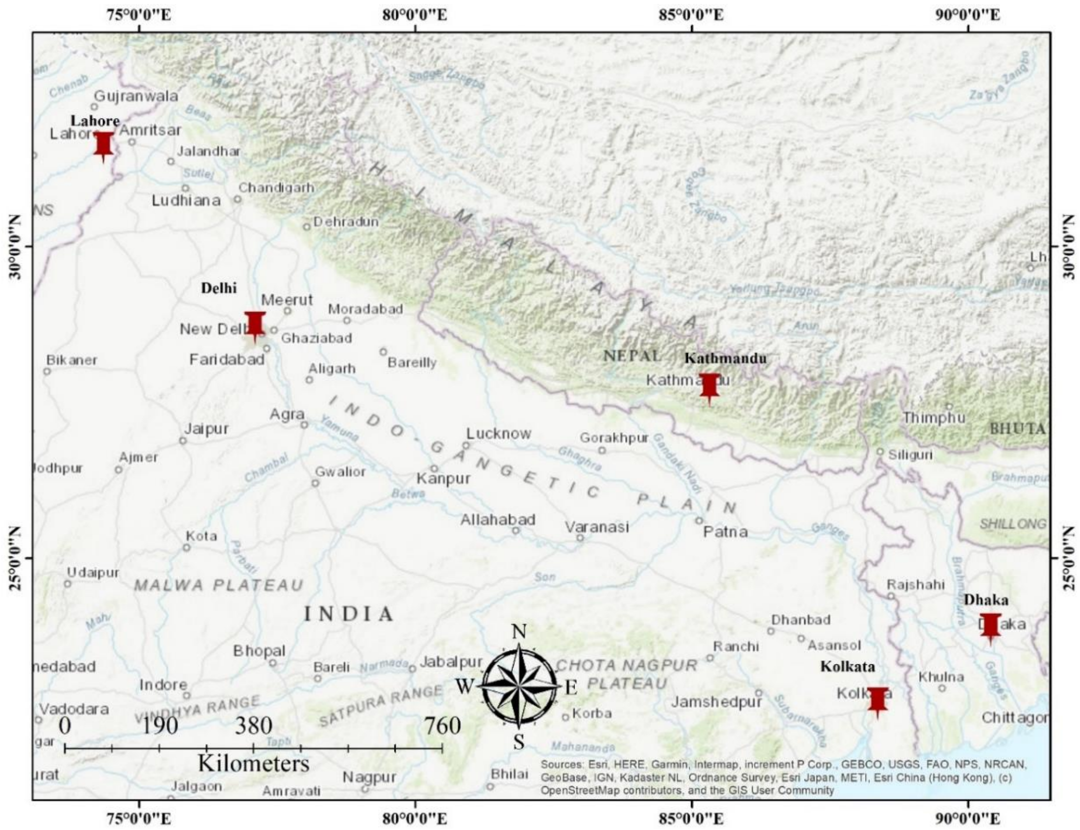

Figure 1. Geographical distribution of the selected cities in South Asian countries

in the selected years for both $PM_{2.5}$ concentration and tropospheric columnar NO_2. ArcGIS 10.2.1 was used to visualize the study area map.

3. RESULTS AND DISCUSSION

3.1 Tropospheric NO_2 Vertical Column Densities (VCDs) measured by OMI

The tropospheric columnar NO_2 observed from space through OMI denote emissions of nitrogen oxides ($NOx = NO + NO_2$) formed from fossil fuel combustion in industries, biomass burning, fires, and lightning. The wind direction and speed transport the NO_2 away from its sources. Many of these anthropogenic pollution sources were inactive since Bangladesh, India, Nepal, and Pakistan implemented strict traffic restrictions and self-quarantine measures to control the expansion of the COVID-19 pandemic (Shrestha et al., 2020). Significant air pollution changes in Delhi, Dhaka, Kathmandu, Kolkata, and Lahore resulted. This study observed a decreasing trend of tropospheric columnar NO_2 compared to previous years during the same months in these selected cities of South Asia (Figure 2). Tropospheric columnar NO_2 values were much higher in 2018 in Delhi, Dhaka, Kolkata, and Lahore. In Kathmandu, the highest value observed was in 2019. Table 1 shows the daily average of tropospheric columnar NO_2 in the selected cities from 2018-2020 during April and May. Delhi observed a dramatic reduction in the daily tropospheric columnar NO_2 during the COVID-19 period of 48% and 45.6% compared to 2018 and 2019. In Dhaka, the daily average tropospheric columnar NO_2 was 4.36, 3.47, and 2.57 molecules/cm^2 in 2018, 2019, and 2020, respectively. The tropospheric columnar NO_2 values in 2020 were 41.0% and 25.9% lower relative to 2018 and 2019 during the lockdown. The rate was reduced in Kolkata by 24.7% and 17.6% in 2020 compared to the previous two years.

In Lahore, the daily average tropospheric columnar NO_2 concentration was 36.0% and 25.0% lower in 2020 during the COVID-19 period compared to 2018 and 2019. In Kathmandu, the 2020 tropospheric columnar NO_2 is 8.7% lower than in 2018 and 15.0% than in 2019. Other studies showed that Delhi had a significant tropospheric columnar NO_2 reduction during the lockdown period (Vadrevu et al., 2020; Shehzad et al., 2020). Kolkata, as a coastal city, saw less reduction (Vadrevu et al., 2020). Additionally, in Kolkata, most coal power plants were not closed during the pandemic, which may have contributed to less reduction (Vadrevu et al., 2020).

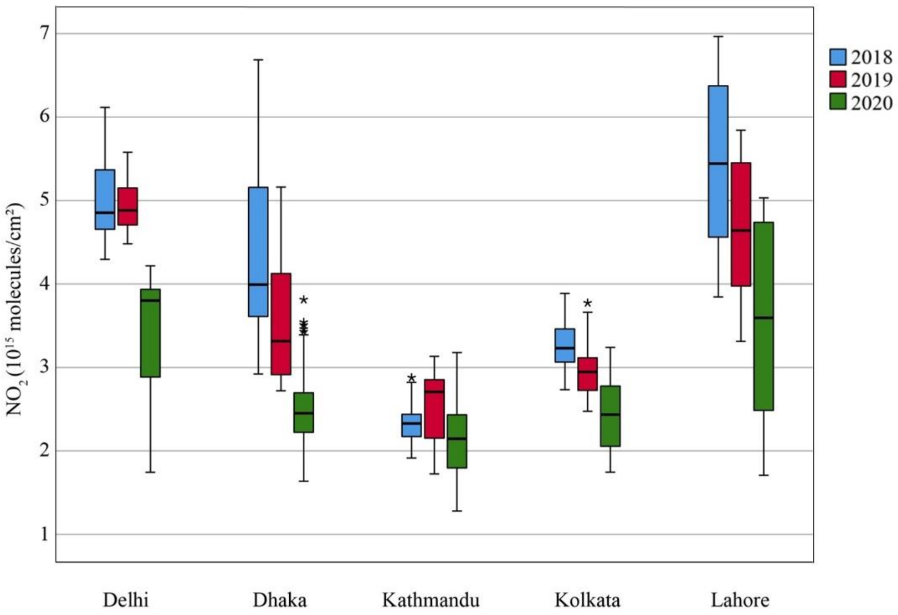

Figure 2. The whisker box plot shows the daily average of OMI derived tropospheric columnar NO_2 (10^{15} molecules/cm^2). A horizontal black line within the box marks the median; the lower boundary of the box indicates the 25th percentile, the upper boundary of the box indicates the 75th percentile. The whisker represents the maximum (upper whisker) and minimum value (lower whisker). Points above the whiskers indicate outliers.

Table 1. Daily Mean of Tropospheric Columnar NO_2 (10^{15} molecules/cm^2) with Relative Changes (%)

Location	Month	2018	2019	2020	A	B
Delhi	April	4.73	4.96	2.86	-65.5	-73.3
	May	5.32	4.94	3.92	-35.7	-26.0
	Average	5.03	4.95	3.40	-48.0	-45.6
Dhaka	April	5.06	4.03	2.67	-47.2	-33.7
	May	3.69	2.93	2.40	-34.8	-18.1
	Average	4.36	3.47	2.53	-41.0	-25.9
Kathmandu	April	2.48	2.26	2.20	-11.3	-2.5
	May	2.18	2.83	2.05	-6.1	-27.5
	Average	2.33	2.55	2.13	-8.7	-15.0
Kolkata	April	3.36	3.16	2.74	-18.4	-13.4
	May	3.15	2.78	2.17	-31.0	-21.9
	Average	3.25	2.97	2.45	-24.7	-17.6
Lahore	April	4.49	4.03	2.49	-44.4	-38.1
	May	6.36	5.22	4.60	-27.6	-11.9
	Average	5.44	4.64	3.57	-36.0	-25.0

Note: A=2020 vs 2018; B=2020 vs 2019

The reduction in Kathmandu may have occurred because of wildfires in the first half of April, open garbage burning, and cross border pollution haze (Nepal Times, 2020). Thermal inversions trap pollutants during the winter season, making conditions worse in this valley (Mahapatra et al., 2019).

Atmospheric NO_2 concentration has decreased in some developed countries during the COVID-19 outbreak. The readings from the Copernicus Sentinel-5P satellite showed a significant decrease of tropospheric columnar NO_2 concentrations during lockdown over Rome, Madrid, and Paris (Zambrano et al., 2020). The most substantial reduction of NO_2 was estimated at 51% in Barcelona (Tobías et al., 2020). Dhaka, Bangalore, Beijing, Bangkok, Delhi, and Nanjing experienced lower tropospheric columnar NO_2. Several major trade centers such as New York, London, Paris, Seoul, Sydney, and Tokyo experienced reduced atmospheric NO_2 levels (Roy et al., 2020, Shrestha et al., 2020). The Tukey post hoc test, as shown in Table 2, displays the significant changes in the daily tropospheric columnar NO_2 data in 2020. The mean differences are significantly lower (at α=0.01 level) in 2020 compared to 2018 and 2019 for the same period for all selected cities. Major cities of all selected countries are shown in Figure 3 comparing satellite measurements of background tropospheric columnar NO_2, supplied by OMI in 2018-2020. Analyses show that the tropospheric columnar NO_2 concentration reduced significantly during the lockdown. Combustion processes such as diesel and gasoline combustion from road traffic, manufacturing, power generation, and shipping industry release urban NO_2 (Tobías et al., 2020); most of these sectors ceased or reduced operations during the lockdown. In India, the average concentrations of tropospheric columnar NO_2 decreased by 45.99% in industrial areas and 50.61% in traffic-dominated locations (Mahato et al., 2020).

Table 2. Summary of Tukey's post hoc multiple comparisons between tropospheric columnar NO_2 and years

Location	(I) Year	(J) Year	Mean difference (I-J)	Std. Error
Delhi	2020	2018	-1.63[a]	0.09
		2019	-1.55[a]	0.09
Dhaka	2020	2018	-1.83[a]	0.14
		2019	-0.94[a]	0.14
Kathmandu	2020	2018	-0.21[b]	0.07
		2019	-0.43[a]	0.07
Kolkata	2020	2018	-0.80[a]	0.06
		2019	-0.52[a]	0.06
Lahore	2020	2018	-1.81[a]	0.18
		2019	-1.07[a]	0.18

[a] The mean difference is significant at α=0.001
[b] The mean difference is significant at α=0.01

3.2 Concentration of $PM_{2.5}$

Vehicle emissions, biomass burning, brick kilns, and construction activities generate $PM_{2.5}$, defined as fine particulate matter less than 2.5 microns. Many of these emission sectors were shut down worldwide during the COVID-19 induced lockdown. The whisker box plots in Figure 4 shows that Delhi, Dhaka, and Kathmandu had higher pollution levels in 2019 compared to 2018, showing the decreasing trend of $PM_{2.5}$ during the lockdown in five megacities of South Asia. During lockdown in 2020, the pollution level decreased noticeably in all the selected cities compared to the previous two years.

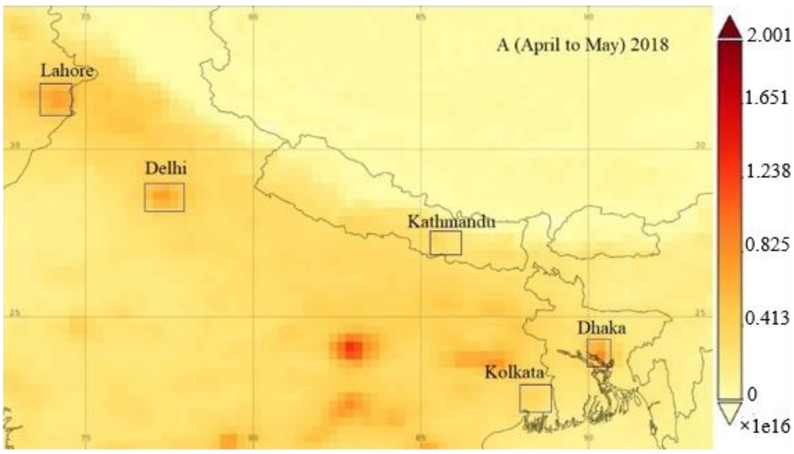

Figure 3. Spatial distribution of tropospheric columnar NO_2 in Delhi (76.709N, 28.1139E, 77.709 N, 29.1139E); Dhaka (89.9201N 23.308E 90.9201N 24.308E); Kathmandu (84.824N 27.2172E 85.824N 28.2172E); Kolkata (87.9001N 22.0667E 88.9001N 23.0667E) and Lahore (73.8436N 31.0497E 74.8436N 32.0497E) from 2018-2020 (Average of April-May)

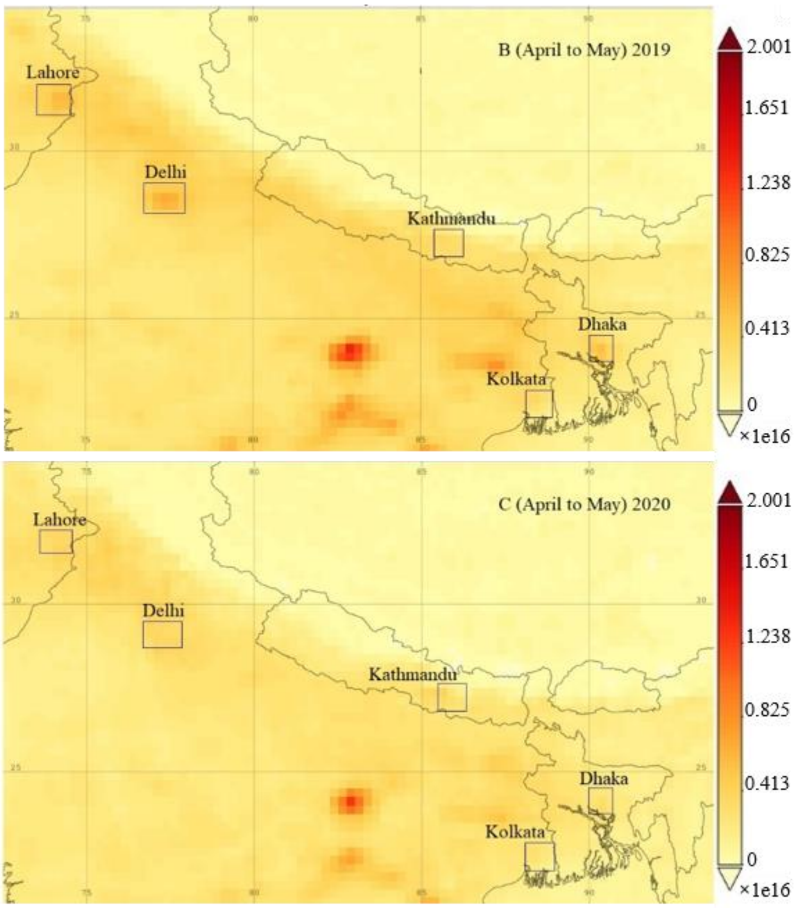

Figure 3. Spatial distribution of tropospheric columnar NO_2 in Delhi (76.709N, 28.1139E, 77.709 N, 29.1139E); Dhaka (89.9201N 23.308E 90.9201N 24.308E); Kathmandu (84.824N 27.2172E 85.824N 28.2172E); Kolkata (87.9001N 22.0667E 88.9001N 23.0667E) and Lahore (73.8436N 31.0497E 74.8436N 32.0497E) from 2018-2020 (Average of April-May) (cont.)

The daily mean of $PM_{2.5}$ concentration in five cities from 2018-2020 is in Table 3. Delhi's air contained 72.02, 83.74, and 45.69 µg/m^3 of $PM_{2.5}$ in 2018, 2019, and 2020 from April 1 - May 31. $PM_{2.5}$ concentration decreased during the COVID-19 period in 2020 in Delhi, reducing 36.6% compared to 2018 and 45.4% compared to 2019. Nagar et al. (2017) found the $PM_{2.5}$ levels in Delhi resulted from a regional problem caused by contiguous urban agglomerations.

In Dhaka, the mean concentration was 56.91 µg/m^3 in 2018, 64.93 µg/m^3 in 2019, and 49.70 µg/m^3 in 2020 from April 1 - May 31. The $PM_{2.5}$ concentration reduced by 12.7% compared to 2018 and 23.5% compared to 2019 during the lockdown in those months. Dhaka experienced less $PM_{2.5}$ reduction than other cities because construction of the Mass Rapid Transit (MRT) continued during COVID-19 lockdown (Nayeem et al., 2020). Other factors may have been meteorological characteristics (Mofijur et al., 2020), higher population density, greater dependence on fossil fuel for cooking, and reopening of industry. Market and shopping malls were open, allowing private vehicle movement inside the city (Nayeem et al., 2020).

In Kolkata, the daily concentration of $PM_{2.5}$ in 2020 decreased by 41.0% compared to 2018 and 34.1% relative to 2019. The $PM_{2.5}$ in Kathmandu was 28.3% less in 2020 than in 2018 and 37.4% less than in 2019. The Kathmandu valley geography causes large diurnal variability in temperature and relative humidity resulting in a corresponding gas-aerosol phase partitioning of NH_3, HNO_3, and HCl and aerosol solution affecting the pH (Islam et al., 2020).

In Lahore, only a comparison with the concentration of 2019 was available. $PM_{2.5}$ decreased by 44.26% in 2020 compared to 2019, more than in other cities. The $PM_{2.5}$ reduction in Delhi and Kolkata was more than in other cities during the lockdown. The restriction in social contact, the closing of restaurants, shops, and many commercial and administrative centers, reduced these air pollutants.

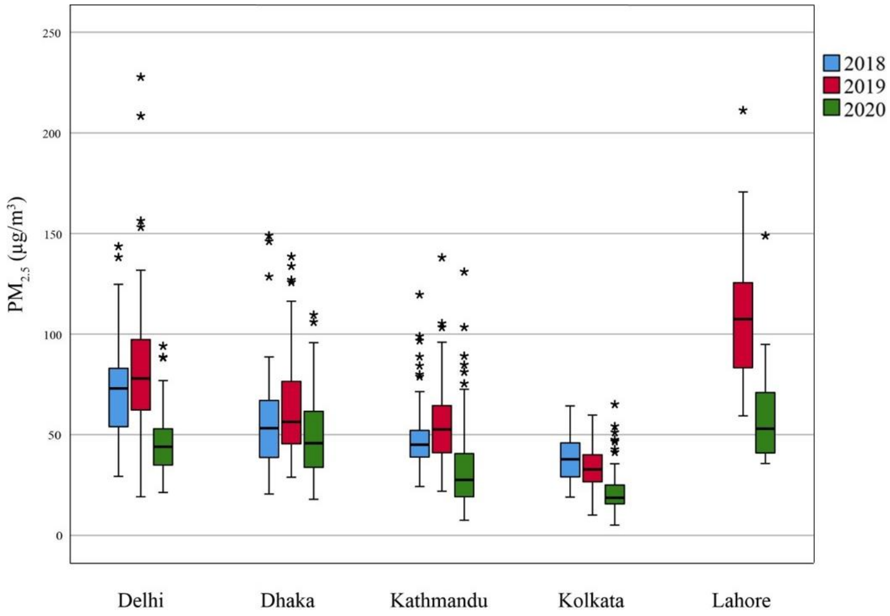

Figure 4. The whisker box plot shows the daily average of ground-level $PM_{2.5}$ (µg/m^3) concentration. A horizontal black line marks the median. The lower boundary of the box indicates the 25th percentile. The upper boundary of the box indicates the 75th percentile. The whisker represents the maximum (upper whisker) and minimum value (lower whisker). Points above the whiskers indicate outliers.

Table 3. Daily mean of $PM_{2.5}$ (µg/m^3) with relative changes (%)

Location	Month	2018	2019	2020	A	B
Delhi	April	71.47	75.13	40.72	-43.03	-45.80
	May	72.56	92.06	50.51	-30.39	-45.13
	Average	72.02	83.74	45.69	-36.56	-45.44
Dhaka	April	70.71	70.82	52.24	-26.12	-26.24
	May	43.55	59.04	46.52	-6.82	-21.21
	Average	56.91	64.93	49.70	-12.67	-23.46
Kathmandu	April	58.84	50.46	47.08	-19.99	-6.70
	May	40.13	62.34	24.02	-40.14	-61.47
	Average	49.33	56.50	35.36	-28.32	-37.42
Kolkata	April	41.60	34.37	28.06	-32.55	-18.36
	May	33.73	33.04	16.56	-50.90	-49.88
	Average	37.66	33.69	22.21	-41.02	-34.08
Lahore	May	DNA	109.14	60.84	DNA	-44.26
	Average	DNA	109.14	60.84	DNA	-44.26

Note: A=2020 vs 2018; B=2020 vs 2019; DNA=Data Not Available

Table 4 shows Tukey's post hoc analysis to test the significant changes in the daily average of $PM_{2.5}$ data based on 2020 with an equal sample size. The mean differences of daily $PM_{2.5}$ concentration between the year 2019 and 2020 during the lockdown period were significantly lower (at α=0.01) during the same time in Delhi, Dhaka, Kathmandu, and Kolkata. The mean differences of daily $PM_{2.5}$ concentration between 2020 and 2018 were also significantly lower in all those cities except Dhaka.

Figure 5 depicts the diurnal changes of $PM_{2.5}$ in selected cities from 2018-2020 at the same time of April and May. The nighttime air pollution (8 pm-6 am) is higher than during the day in all cities except Kolkata. Restriction of the heavy vehicle (long road trucks) occurs only throughout the day in Delhi, Dhaka, and Lahore year around (Nagar et al., 2017; Nayeem et al., 2020; Rasheed et al., 2015; Gorai et al., 2018). The primary cause of higher pollution levels at night in these cities may be heavy vehicle traffic. Since there is little restriction on heavy traffic in Kolkata, $PM_{2.5}$ is similar during the day and night (Bera et al., 2020). The pollution levels increase at night in

Kathmandu because of the slopes and orientation of the mountains (Mahapatra et al., 2019).

Table 5 shows the mean differences of diurnal $PM_{2.5}$ concentration between 2019 and 2020, and 2018 and 2020 were also significantly lower (at α=0.01) according to Tukey's post hoc comparison. During the COVID-19 lockdown in these cities, nighttime entry to the central city was open for these vehicles. The mean differences were not significant at night (8 pm-6 am) in Delhi, Dhaka, and Lahore, possibly because the traffic conditions were similar to previous years. The study found pollutant levels high at nighttime in the Kathmandu valley because of the surrounding mountains (Mahapatra et al., 2019).

Table 4. Summary of Tukey's post hoc multiple comparisons between hourly $PM_{2.5}$ and years

Location	(I) Year	(J) Year	Mean difference (I-J)	Std. Error
Delhi	2020	2018	-26.3[a]	4.9
		2019	-38.1[a]	4.9
Dhaka	2020	2018	-7.2	4.6
		2019	-15.2[b]	4.6
Kathmandu	2020	2018	-13.9[b]	3.9
		2019	-21.2[a]	3.9
Kolkata	2020	2018	-15.4[a]	2.2
		2019	-11.5[a]	2.2

[a] The mean difference is significant at α=0.001
[b] The mean difference is significant at α=0.01

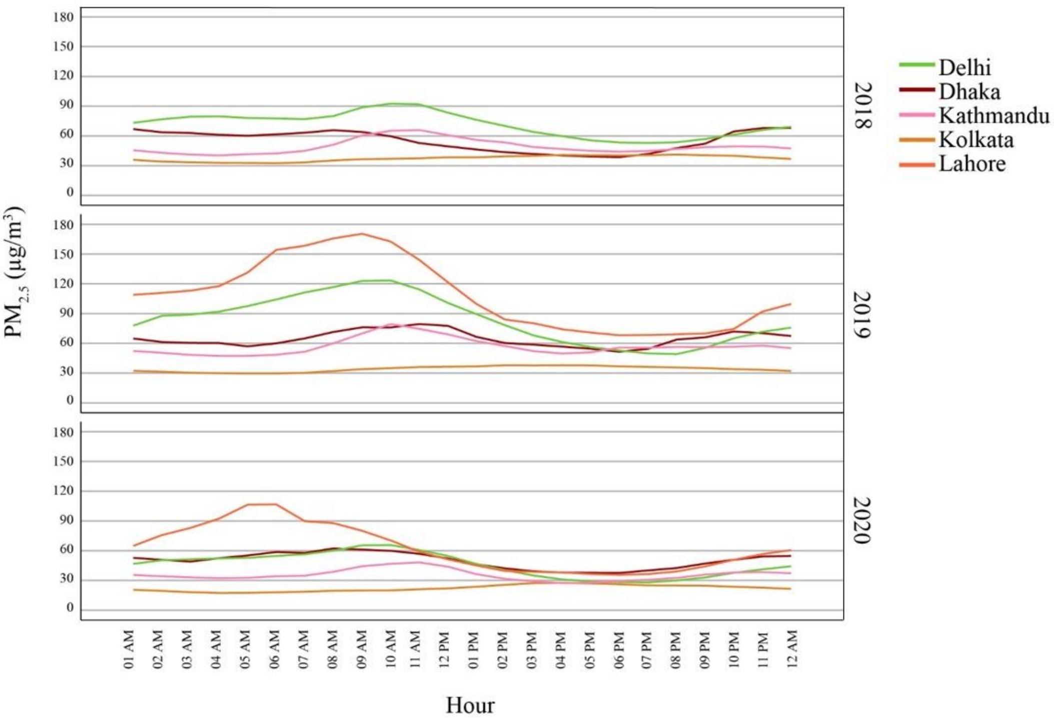

Figure 5. Diurnal changes of $PM_{2.5}$ in different cities from 2018-2020 at same time (April-May)

Table 5. Summary of Tukey's post hoc multiple comparisons between diurnal $PM_{2.5}$ and years

Location		(I) Year	(J) Year	Mean difference (I-J)	Std. Error
Delhi	Night (8 pm-6 am)	2020	2018	-11.42	4.47
			2019	-4.51	4.47
	Day (6 am-8 pm)	2020	2018	-35.11[a]	5.21
			2019	-37.62[a]	5.21

Table 5. Summary of Tukey's post hoc multiple comparisons between diurnal $PM_{2.5}$ and years (cont.)

Location		(I) Year	(J) Year	Mean difference (I-J)	Std. Error
Dhaka	Night (8 pm-6 am)	2020	2018	-3.18	4.37
			2019	-7.70	4.36
	Day (6 am-8 pm)	2020	2018	-17.01[b]	5.20
			2019	-14.56[a]	5.11
Kathmandu	Night (8 pm-6 am)	2020	2018	-9.70	3.70
			2019	-6.25	3.72
	Day (6 am-8 pm)	2020	2018	-17.88[a]	2.48
			2019	-21.90[a]	2.49
Kolkata	Night (8 pm-6 am)	2020	2018	-15.39[a]	2.21
			2019	-7.86[a]	2.17
	Day (6 am-8 pm)	2020	2018	-6.74	3.39
			2019	-7.36	3.28

[a] The mean difference is significant at α=0.001
[b] The mean difference is significant at α=0.01

Air pollution concentrations in the Kathmandu valley increased gradually after sunset (Shrestha et al., 2002). In Kolkata, the nighttime mean differences for both the cases (2018-2020 and 2019-2020) were significantly lower (at α=0.01). No restriction on vehicle movement and the emission from the nearby coal power plant of Kolkata might be the reasons for high pollution in the daytime (Bera et al., 2020).

4. CONCLUSION

The present study found a significant reduction of daily tropospheric columnar NO_2 and $PM_{2.5}$ concentrations in all the cities compared to previous years during the same timeline.

- The tropospheric columnar NO_2 values were reduced between 9% and 48% in the cities studied.
- The daily mean $PM_{2.5}$ values were reduced between 13% and 46% in the cities studied.
- The diurnal pattern of $PM_{2.5}$ showed significant improvement of between 15% and 38% during the day in Delhi, Dhaka, and Kathmandu due to traffic restrictions.

Abatement of tropospheric columnar NO_2 and $PM_{2.5}$ occurred because of the restrictive actions imposed to reduce the population's mobility and shut down many commercial establishments and industries. The temporary decrease in the concentrations of pollutants is not a sustainable way to improve the environment. The effect of the lockdown on air pollution provided a unique opportunity to analyze the effects of various emission sources and further assess air quality policies. Traffic was significantly less during the lockdown in each of the selected cities. Air quality can be improved by increasing mass transit or restricting vehicles in certain areas of each city. The closing of companies resulted in emissions reduction from manufacturing and industrial facilities. Introducing more fuel-efficient transportation systems and improved pollution strategies for industries would improve air quality permanently. Improvement in industrial emission standards could assist in these cities reaching similar air quality during normal operations. This study was not able to compare overpass sensor data to tropospheric columnar NO_2 sensor data. In addition, a single monitoring station of $PM_{2.5}$ cannot represent an entire city. This study indicates the relative impact on tropospheric columnar NO_2 and $PM_{2.5}$ resulting from the COVID-19 lockdown.

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REFERENCES

Abdullah S, Mansor AA, Napi NN, Mansor WN, Ahmed AN, Ismail M, et al. Air quality status during 2020 Malaysia Movement Control Order (MCO) due to 2019 novel coronavirus pandemic. Science of the Total Environment 2020;729:1-5.

Air Now. Air quality index data [Internet]. 2020 [cited 2020 Jun 2]. Available from: https://www.airnow.gov/?city=Dhaka& country=BGD.

Air Quality Information (IQAir). World air quality report, region and city $PM_{2.5}$ ranking [Internet]. 2019 [cited 2020 Jun 1]. Available from: https://www.iqair.com/us/world-most-polluted-cities.

Banan N, Latif MT, Juneng L, Ahamad F. Characteristics of surface ozone concentrations at stations with different backgrounds in the Malaysian Peninsula. Aerosol and Air Quality Research 2012;13(3):1090-106.

Bera B, Bhattacharjee S, Shit PK, Sengupta N, Saha S. Significant impacts of COVID-19 lockdown on urban air pollution in Kolkata (India) and amelioration of environmental health. Environment, Development and Sustainability 2020;28:1-28.

Boersma KF, Eskes HJ, Brinksma EJ. Error analysis for tropospheric NO_2 retrieval from space. Journal of Geophysical Research: Atmospheres 2004;109:1-26.

Bulto TW. Impact of open burning refuse on air quality: In the case of “Hidar Sitaten” at Addis Ababa, Ethiopia. Environmental Health Insights 2020;14:1-11.

Chen M, Fan Y, Wu X, Zhang L, Guo T, Deng K, et al. Clinical characteristics and risk factors for fatal outcome in patients with 2019-coronavirus infected disease (COVID-19) in Wuhan, China. Lancet 2020;7:1-9.

Diao M, Holloway T, Choi S, O’Neill SM, Al-Hamdan MZ, Van Donkelaar A, et al. Methods, availability, and applications of $PM_{2.5}$ exposure estimates derived from ground measurements, satellite, and atmospheric models. Journal of the Air and Waste Management Association 2019;69(12):1391-414.

Dutheil F, Baker JS, Navel V. COVID-19 as a factor influencing air pollution? Environmental Pollution 2020;263:1-3.

Dutkiewicz VA, Alvi S, Ghauri BM, Choudhary MI, Husain L. Black carbon aerosols in urban air in South Asia. Atmospheric Environment 2009;43:1737-44.

European Space Agency (ESA). Setinel 5P data [Internet]. 2020 [cited 2020 Jun 10]. Available from: https://www.esa.int/ Applications/Observing_the_Earth/Copernicus/ Sentinel-5P.

Gorai AK, Tchounwou PB, Biswal SS, Tuluri F. Spatio-temporal variation of particulate matter ($PM_{2.5}$) concentrations and its health impacts in a mega city, Delhi in India. Environmental Health Insights 2018;12:1-9.

Geospatial Interactive Online Visualization and Analysis Infrastructure (GIOVANNI) [Internet]. 2020 [cited 2020 Jun 14]. Available from: https://giovanni.gsfc.nasa.gov/giovanni/.

Hossain MM, Majumder KA, Islam M, Nayeem AA. Study on ambient particulate matter ($PM_{2.5}$) with different mode of transportation in Dhaka City, Bangladesh. American Journal of Pure and Applied Science 2019;1(4):12-9.

Haque M, Singh RB. Air pollution and human health in Kolkata, India: A case study. Climate 2017;5(4):1-16.

Himalayan Times. Coronavirus hits Nepal-China trade [Internet]. 2020 [cited 2020 Aug 12]. Available from: https:// thehimalayantimes.com/business/coronavirus-hits-nepal-china-trade/.

Institute of Epidemiology Disease Control and Research (IEDCR). Distribution of confirmed cases in Bangladesh. Institute of Epidemiology, Disease Control and Research [Internet]. 2020 [cited 2020 Jun 8]. Available from: https://iedcr.gov.bd/.

Islam M, Jayarathne T, Simpson IJ, Werden B, Maben J, Gilbert A, et al. Ambient air quality in the Kathmandu Valley, Nepal, during the pre-monsoon: Concentrations and sources of particulate matter and trace gases. Atmospheric Chemistry and Physics 2020;20(5):2927-51.

Kulkarni S. India becomes third worst affected country by coronavirus, overtakes Russia. Deccan Herald [Internet]. 2020 [cited 2020 Jul 5]. Available from: https://www. deccanherald.com/national/india-set-to-overtake-russia-as-third-worst-hit-country-by-covid-19-857110.html.

Kim BM, Park JS, Kim SW, Kim H, Jeon H, Cho C, et al. Source apportionment of PM_{10} mass and particulate carbon in the Kathmandu Valley, Nepal. Atmospheric Environment 2015;123:190-9.

Latif MT, Huey LS, Juneng L. Variations of surface ozone concentration across the Klang Valley, Malaysia. Atmospheric Environment 2012;61:434-45.

Levelt PF, Van Den Oord GH, Dobber MR, Mälkki A, Visser H, de Vries J, et al. The ozone monitoring instrument. IEEE Transactions on Geoscience and Remote Sensing. 2006;44(5):1093-101.

Lohmann U, Sausen R, Bengtsson L, Cubasch U, Perlwitz J, Roeckner E. The Köppen climate classification as a diagnostic tool for general circulation models. Climate Research 1993;3:177-93.

Mahapatra PS, Puppala SP, Adhikary B, Shrestha KL, Dawadi DP, Paudel SP, et al. Air quality trends of the Kathmandu Valley: A satellite, observation and modeling perspective. Atmospheric Environment 2019;201:334-47.

Mahato S, Pal S, Ghosh KG. Effect of lockdown amid COVID-19 pandemic on air quality of the megacity Delhi, India. Science of the Total Environment 2020;29:1-23.

Majumder AK, Nayeem AA, Patoary MN, Carter WS. Temporal variation of ambient particulate matter in Chattogram City, Bangladesh. Journal of Air Pollution and Health 2020;5(1): 33-42.

Mofijur M, Rizwanul Fattah IM, Saiful Islam AB, Uddin MN, Ashrafur Rahman SM, Chowdhury MA, et al. Relationship between weather variables and New Daily COVID-19 cases in Dhaka, Bangladesh. Sustainability 2020;12(20):1-10.

Nadzir MS, Ashfold MJ, Khan MF, Robinson AD, Bolas C, Latif MT, et al. Spatial-temporal variations in surface ozone over Ushuaia and the Antarctic region: Observations from in situ measurements, satellite data, and global models. Environmental Science and Pollution Research 2018; 25(3):2194-210.

Nadzir MS, Ooi MC, Alhasa KM, Bakar MA, Mohtar AA, Nor MF, et al. The impact of movement control order (MCO) during pandemic COVID-19 on local air quality in an urban area of Klang Valley, Malaysia. Aerosol and Air Quality Research 2020;20(6):1237-48.

Nagar PK, Singh D, Sharma M, Kumar A, Aneja VP, George MP, et al. Characterization of $PM_{2.5}$ in Delhi: Role and impact of secondary aerosol, burning of biomass, and municipal solid waste and crustal matter. Environmental Science and Pollution Research 2017;24(32):25179-89.

Nayeem AA, Hossain MS, Majumder AK, Carter WS. Spatiotemporal variation of brick kilns and it’s relation to ground-level $PM_{2.5}$ through MODIS image at Dhaka District, Bangladesh. International Journal of Environmental Pollution and Environmental Modelling 2019;2(5):277-84.

Nayeem AA, Majumder AK, Carter WS. The impact of coronavirus induced general holiday on air quality in urban area. International Journal of Human Capital and Urban Management 2020;5(3):207-16.

Nepal Times. Nepal sees drop in wildfires during lockdown [Internet]. 2020 [cited 2020 Nov 10]. Available from: https://www.nepalitimes.com/latest/nepal-sees-drop-in-wildfires-during -lockdown/.

Pradhan TR. Government decides to lift the four-month-long coronavirus lockdown, but with conditions [Internet]. 2020 [cited 2020 Sep 10]. Available from: https://kathmandupost.com/national/2020/07/21/government-decides-to-lift-the-four-month-long-coronavirus-lockdown-but-with-conditions.

Raja S, Biswas KS, Husain L, Hopke PK. Source apportionment of the atmospheric aerosol in Lahore, Pakistan. Water, Air and Soil Pollution 2010;208:43-57.

Rana M, Mahmud M, Khan MH, Sivertsen B, Sulaiman N. Investigating incursion of transboundary pollution into the atmosphere of Dhaka, Bangladesh. Advances in Meteorology 2016:1-11.

Rasheed A, Aneja VP, Aiyyer A, Rafique U. Measurement and analysis of fine particulate matter ($PM_{2.5}$) in urban areas of Pakistan. Aerosol and Air Quality Research 2015;15(2):426-39.

Razib, Nayeem AA, Hossain MS, Majumder AK. $PM_{2.5}$ concentration and meteorological characteristics in Dhaka, Bangladesh. Bangladesh Journal of Science and Industrial Research 2020;58(2):89-98.

Roy S, Saha M, Dhar B, Pandit S, Nasrin R. Geospatial analysis of COVID-19 lockdown effects on air quality in the South and Southeast Asian region. Science of the Total Environment 2020;21:1-20.

Shehzad K, Sarfraz M, Shah SG. The impact of COVID-19 as a necessary evil on air pollution in India during the lockdown. Environmental Pollution 2020;266:1-5.

Shrestha AM, Shrestha UB, Sharma R, Bhattarai S, Tran HN, Rupakheti M. Lockdown caused by COVID-19 pandemic reduces air pollution in cities worldwide. Eartharxi 2020:1-27.

Shrestha ML, Kaga A, Kondo A, Inoue Y, Sapkota B. Diurnal variation of air pollution concentration during winter in Kathmandu Valley. WIT Transactions on Ecology and the Environment 2002;24:1-10.

Sipra H, Aslam F, Syed JH, Awan TM. Investigating the implications of COVID-19 on $PM_{2.5}$ in Pakistan. Aerosol and Air Quality Research 2020;20:1-24.

Stone E, Schauer J, Qureshi TA, Mahmood A. Chemical characterization and source apportionment of fine and coarse particulate matter in Lahore, Pakistan. Atmospheric Environment 2010;44:1062-70.

The United Nations Conference on Trade and Development (UNCTAD). Total and urban population [Internet]. 2020 [cited 2020 Nov 7]. Available from: https://stats.unctad.org/handbook/Population/Total.html.

Tobías A, Carnerero C, Reche C, Massagué J, Via M, Minguillón MC, et al. Changes in air quality during the lockdown in Barcelona (Spain) one month into the SARS-CoV-2 epidemic. Science of the Total Environment 2020:1-4.

Vadrevu KP, Eaturu A, Biswas S, Lasko K, Sahu S, Garg JK, et al. Spatial and temporal variations of air pollution over 41 cities of India during the COVID-19 lockdown period. Scientific Reports 2020;10(1):1-5.

World Health Organization (WHO). Mortality and burden of disease from ambient air pollution [Internet]. 2016 [cited 2020 Aug 21]. Available from: https://www.who.int/gho/phe/outdoor_air_pollution/burden/en/.

Xu K, Cui K, Young LH, Wang YF, Hsieh YK, Wan S, et al. Air quality index, indicatory air pollutants and impact of COVID-19 event on the air quality near Central China. Aerosol and Air Quality Research 2020;20:1204-21.

Yousefian F, Faridi S, Azimi F, Aghaei M, Shamsipour M, Yaghmaeian K, et al. Temporal variations of ambient air pollutants and meteorological influences on their concentrations in Tehran during 2012-2017. Scientific Reports 2020;10(1):1-11.

Zambrano MA, Ruano MA, Sanchez-Alcalde L. Indirect effects of COVID-19 on the environment. Science of the Total Environment 2020;728:138813.

Incorporating the Ecological, Socio-economic and Institutional Conceptual Model Framework for Sustainable Management of Small-scale Mud Crab *(Scylla serrata)* Fishery in Western Seram Regency, Indonesia

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ABSTRACT

Mud crab *Scylla serrata* of Kotania Bay and Pelita Jaya Bay of Western Seram District, has been harvested by local fishermen for more than 25 years. The mud crab has high economic value, and there is always a market for this fishery. The economic dependence of the fishermen forces them to harvest this resource extensively. No existing management strategy and extensive exploitation leads to unsustainable conditions of this fishery. With inadequate data condition, the Driver-Pressure-State-Impact-Response (DPSIR) model constructs an ecological, social-economy, and institutional conceptual model framework for sustainable management of this fishery. The driving force (D) in this fishery comes from the local fishers harvesting the mud crab. The two most sensitive attributes that affected mud crab sustainability from Rapfish analysis were used as state-level of DPSIR methodology. The result shows that the most sensitive variables from ecological, socio-economy, and institution were: caught before maturity, mud crab size, consumer attitude towards sustainability, just management, government quality, and monitoring and reporting, respectively. It was concluded that this conceptual model allows a better understanding of how the mud crab *S. serrata* system works and management actions taken at different system components. This conceptual model framework can be a useful tool to incorporate the participation of stakeholders, managers, and scientists in the process of a sustainable management plan.

1. INTRODUCTION

The Bay of Kotania and Pelita Jaya of Western Seram Regency, Eastern Indonesia is a productive area with many fish resources like skipjack tuna, mackerel, anchovy, grouper, sea cucumber, and mud crab (Wouthuyzen and Sapulete, 1994; Siahainenia, 2016; Huliselan et al., 2017). The bay is considered as a semi enclosed estuary ecosystem covered with three important tropic ecosystems, mangrove, seagrass bed, and coral reef, among which mangrove ecosystem is the dominant one. Because of its productivity, in 1989 the Government of Indonesia designated this area as a part of the Seram Integrated Economic Development Area (KAPET Seram).

Among some economic fish resources, mud crab (*Scylla* spp.) is one of the most valuable crustacean species caught by local fishers in Western Seram Regency, Maluku Province. Three species of mud crab are commonly found in this area, *Scylla olivacea, S. paramamosain*, and *S. serrata* (Tetelepta and Makatita, 2012; Tetelepta et al., 2018), with *S. serrata* being the dominant species. The mud crab *S. serrata* which is generally known also as green crab or black crab is the crab from the genus of *Scylla* found living mostly in the mangrove ecosystem of tropical and subtropical waters of Indo Pacific region (Keenan, 1999; Jirapunpipat, 2008; Shelley, 2008).

The fishery in this area has been conducted for

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many years mostly by local fishers with most being artisanal fishermen. These fisheries represent an important socio-economic and cultural aspect of coastal communities, and their impact on coastal reefs and vulnerable mega-fauna may be significant. The 'small' in small-scale fisheries refers to the size of the fishing boat and the size of the crew on the boat. Small-scale can be misleading, however, since although the size of the fishing unit is small, the extent and prevalence of this type of fishery on a global scale is not. About 95% of fishers worldwide are small-scale fishers (Fujita et al., 2018; Smith and Basuro, 2019).

There are approximately 40 mud crab fishers in this rea, each having about 20 mud crab pots which operate every day, except Friday. Some mud crab fishermen from Wael Village have extended their fishing area to Manipa Island since the catch in this area has decreased (personal communication). Field observation also shows that the local people use hard coral for building material and mangrove trees for mud crab fences, burning fuel, and materials for floating cage mariculture. This condition if not managed properly will lead to more unsustainable fisheries management.

Interviews with local mud crab fishers indicate that the mud crab fishery in Western Seram, Maluku Province started from early 1980 with very few fishermen compared to recent years. According to the fishers, almost no fishery management has been applied to this crab fishery up to the present time. The study by Tetelepta and Makatita (2012), Tetelepta et al. (2017) at Pelita Jaya Village, Western Seram showed a sign of mud crab resource depletion. Both number and body size of mud crab harvested have decrease in the last 15-20 years. A recent study by Tetelepta et al. (2018) on *S. serrata* revealed that the overall sustainability of this species was 46.92% of 100% sustainable scale and was considered as less sustainable according to the Ecosystem Approach to Fisheries Management (EAFM) (Pitcher et al., 2013).

The core element in managing the fisheries is human behavior, meaning social and economic understanding are important considerations apart from the bio-ecology aspect of the resources. Incorporating the socio-economic aspect to the ecological aspect in fisheries management is important to understand the complexity of the fisheries system (Barclay et al., 2017; Sobocinski et al., 2017). Support for the implementation of EAFM has long been compelled through a range of global declarations and policy instruments, however, progress in the implementation of this approach at national and regional levels has been slow, partly due to fisheries managers lacking the relevant skills and experience to apply such an integrated and holistic approach (FAO, 2008; Staples et al., 2014; Voyer et al., 2017).

An ecosystem approach requires more parameters to be put into the system and most often there are fewer data available apart from imprecise parameter estimation and this produces noisy data which will later lead to an unsuitable model (Plaganyi, 2007; Staples et al., 2014; Voyer et al., 2017). Since its inception, EAFM has been evolving globally, and in the late 2000s, Indonesia adopted EAFM to guide national and regional fishery planning. For ground-level implementation, however, it will be within the remit of Fisheries Management Council (FMC) and the respective provinces to lead the way in EAFM planning and implementation in their regions. According for the Ministry of Marine Affairs and Fisheries (MMAF) Republic of Indonesia to achieve this, considerable capacity-building support will be necessary (MMAF et al., 2018). Maluku, in particular, is still in an infancy stage and still evolving, regardless of its complexity.

For the local mud crab fisher, the sustainability of the mud crab is important, however, information available for sustainable management of *S. serrata* in Western Seram, Maluku Province is considered very limited. The human system and ecosystems are linked by forming a socio-ecological system in which the social and biophysical interact on multiple spatial and temporal scales (Díaz et al., 2018). Fisheries management in the ecosystem approach should incorporate this relationship. The quantitative model for this relationship is scarce and difficult to model (Dambacher et al., 2009; Sobocinski et al., 2017; Barclay et al., 2017). Qualitative modeling, also known as loop analysis may be used when quantitative data is lacking, as it requires only the signs of interactions between model variables i.e., positive, negative or zero (Harvey et al., 2016; Sobocinski et al., 2017). This technique uses feedback to investigate the impacts of perturbation on system stability and produce predictions of change in ecological, socio-economic, and institutional aspects of systems. The qualitative modeling, therefore, can be useful to aid the development of a framework for EAFM (Smith et al., 2014; Barclay et al., 2017; Sobocinski et al., 2017; Rosellon-Druker et al., 2019).

An essential step of the integrated ecosystem assessment framework is the development of conceptual models. These models allow the integration of intrinsically linked social, environmental, and biological components of marine ecosystems that is pivotal to address unsolved questions in fisheries management (Rosellon-Druker et al., 2019). Conceptual models have become an essential tool for identifying knowledge gaps, informing research needs, and developing EAF objectives and strategies (Harvey et al., 2016, Zador et al., 2017). Conceptual models facilitate the selection of ecological and socio-economic ecosystem indicators, and they emerge as the basis for risk assessments and quantitative ecosystem models (Harvey et al., 2016, Ingram et al., 2018; Rosellon-Druker et al., 2019).

The Driver-Pressure-State-Impact-Response (DPSIR) framework has been indicated as a useful approach in analyzing problems concerning human and natural systems by the European Environment Agency because it provides a relatively simple and generic structure for linking cause-effect relationships (Martin et al., 2018). DPSIR is valuable in identifying cause-and-effect relationships between society and the ecosystem and joining scientific and place-based knowledge. DPSIR can also integrate information regarding intensities of identified relationships (Ingram et al., 2018). DPSIR framework is also seen as a useful adaptive management tool for analyzing and identifying solutions to environmental problems (Gari et al., 2015). DPSIR has found broad application in environmental assessments of terrestrial and aquatic ecosystems due to its ability to improve communication between policymakers, stakeholders, and scientists facilitating collaborative model development (Kelble et al., 2013; Zador et al., 2017; Díaz et al., 2018; Balzan et al., 2019; Mozumder et al., 2019).

The conceptual model framework developed through the DPSIR approach can be used as a tool in developing the sustainable management of mud crab fishery. With the condition and management practices on mud crab fishery in Kotania Bay and Pelita Jaya Bay, the DPSIR conceptual model framework can be a very suitable approach in addressing the conditions and problems of mud crab fishery and proposing a sustainable management strategy for mud crab fishery. The economic dependence of the local mud crab fishers from this area on the mud crab causes the mud crab fishery to become a driving force in the DPSIR conceptual model framework. Therefore, the objectives of this research are to analyze variables that contribute most to mud crab fishery sustainability and to produce a conceptual model framework for the sustainable management of mud crab *S. serrata* fishery based on EAFM principles.

2. METHODOLOGY

2.1 Study site

This study was conducted at Kotania Bay and Pelita Jaya Bay of Western Seram Regency (Figure 1) from April to August 2019. These areas have unique and comparative characteristics in terms of ecology and economy. The three most important tropical ecosystems, namely mangrove, seagrass bed, and coral reef, are found in this area with mangrove ecosystem being the dominant one. Mangrove forest in the coastal waters of these areas mainly consists of *Rhizophora* spp. and *Sonneratia* spp. with the predominant substrates being fine sand, mud, and crushed shell (Siahainenia et al., 2016).

2.2 Data collection

Data for ecological, socio-economy, and institutional conceptual framework for sustainable management of the mud crab *S. serrata* was obtained through in-depth interviews with local mud crab fishermen from the study site. Interview topics focused on ecological, socio-economy, and institutional dimensions for sustainability analysis following Pitcher et al. (2013). A questionnaire with 35 closed questions concerning variables corresponding to each domain was also distributed to 30 local mud crab fisher to obtain their perceptions about the particular variables. The local fishermen's ages ranged from 28-53 years old with an average of 38 years. Their experience on mud crab fishery varied but was on average above 15 years.

All the data collected were then tabulated and pooled for leverage analysis. A focus group discussion (FGD) with 10 mud crab fishermen was also conducted during the research to obtain their perception about the condition of mud crab fishery and other socio-economic issues.

2.3 Data analysis

Leverage analysis from the Rapfish method (Pitcher and Preikshot, 2001; Kavanagh and Pitcher, 2004) was used to determine the most sensitive variables that contribute to mud crab sustainability. To simplify the interaction and connectivity among variables in the conceptual model framework, only two variables from each dimension with high sensitivity

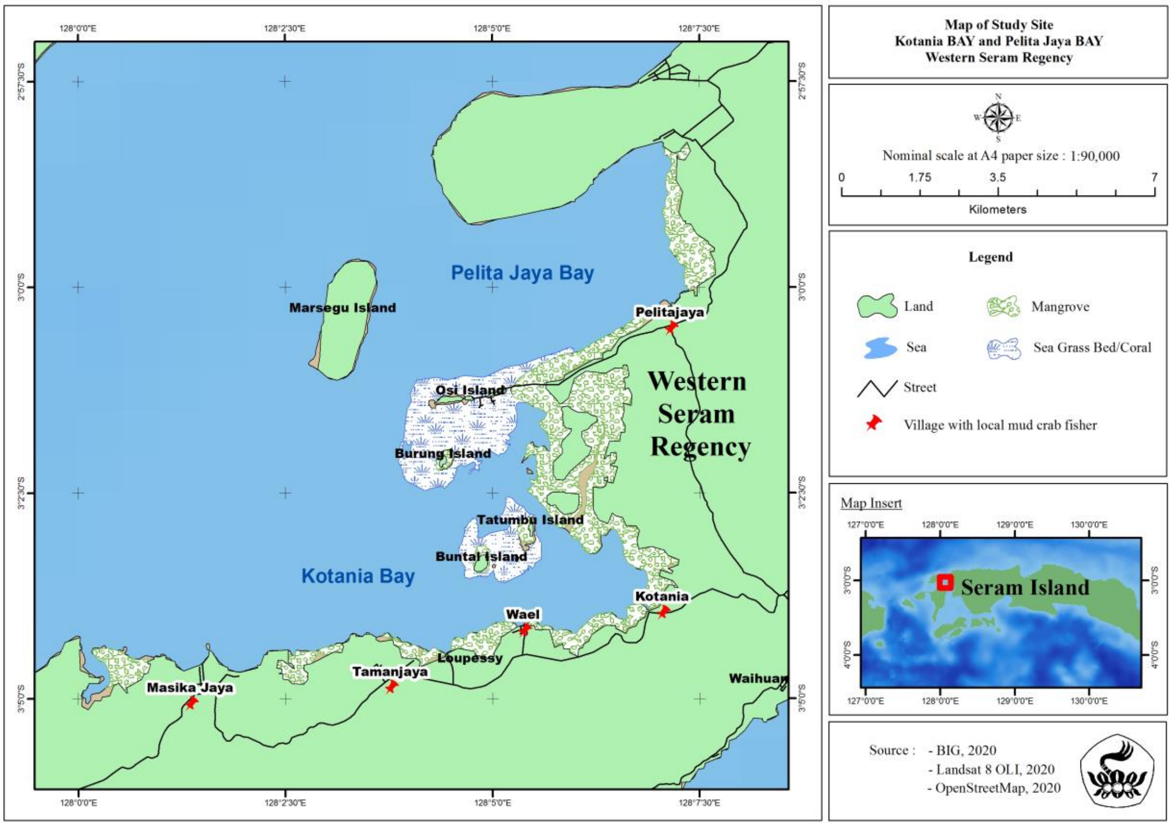

Figure 1. Map of Kotania and Pelita Jaya Bay showing study site

were used to construct the model. Two variables with the highest Root Mean Square (RMS) values from ecology, social-economy, and institutional dimension were then used as State variables of DPSIR to construct a conceptual model framework for the management instruments (Díaz et al., 2018; Balzan et al., 2019). Driving forces (D) can be a physical, chemical, or biological factor that causes a change in the system which in this study is the mud crab fishery. Pressure (P) which cascades from D in this study is the fishing gear, a traditional mud crab pot called *bubu* that affects the integrity of the system (ecology, socio-economic, and institutional). State (S) is the existing condition of the component of an ecosystem which results from the P. In this study the S is the most sensitive attribute affect the sustainability of mud crab. The impact (I) component is the condition of the organism and/or the system trigger by the pressure and can be in the form of population decline, a decrease of economy revenue, social conflict, etc (Kell and Luckhurst, 2018; Mozumder et al., 2019; Balzan et al., 2019). The response (R) component is the attempt conducted by the community in the form of a program or strategy to overcome the impact and it can be at the level of D, P, or S.

Cause-effect diagrams were developed and broken down into the different elements within the DPSIR framework. Each element was studied in detail, based on the finding and deep search in the literature, including every cause or factors that interacted with the element (Zador et al., 2017; Elliott et al., 2017; Mozumder et al., 2019). Identification according to the DPSIR framework was done to establish at which level of the framework the elements were found (driving forces, pressures, states, or impacts). Every management action associated with mud crab fishery was identified and broken down into different parts, introducing them in the conceptual framework and connecting as responses to the driving forces, pressures, states, or impacts (Zador et al., 2017; Elliott et al., 2017).

3. RESULTS AND DISCUSSION

3.1 Sensitive atribute

Sustainability analysis of mud crab *S. Serrata* of the ecology, social-economy, and institutional dimension incorporates 34 variables that form the system of this fishery. All variables interact with one another and have an impact on the sustainability of this fishery with different degrees of sensitivity. Table 1 shows all variables from the three dimensions analyzed with its sensitivity level measured by the RMS. This table shows the two most sensitive variables from the ecology dimension was 'catch before maturity' and 'mud crab size.' The study by Tetelepta and Makatita (2012) shows that the majority (70-80%) of the female mud crab harvested was in their reproductive status with different gonad maturity index. The average carapace width of mud crab harvested in 2012 was 14.79 cm and declined to 13.68 cm in 2018, the average weight also decreased from 575.52 g in 2012 to 477.72 g in 2018 (Tetelepta and Makatita, 2012; Tetelepta et al., 2019).

Table 1. Variables of each dimension with its sensitivity value, RMS (Root Mean Square)

Ecology	RMS	Socio-Economy	RMS	Institutional	RMS
Catch before maturity	4.80	Consumer attitude towards sustainability	3.86	Government quality	3.78
Mud crab size	3.80	Just management	3.33	Monitoring and reporting	3.64
Discard	3.72	Change in fishing practices	2.19	Management plan	3.08
By catch	3.40	Equity of fishing benefit	1.93	Protection	2.99
Change in size	2.30	Other source of income	0.89	Village by law	2.48
Migratory range	2.25	Strength of social network	0.88	Legality	2.37
Sex ratio	2.23	Marketing system	0.84	Regulation	2.16
Exploiation status	1.50	Subsides	0.83	Regulation implemented	1.98
Vulneralbility index	0.66	Local environment knowledge	0.56		
Range of collapse	0.45	Commoditization	0.39		
Species change	0.37	Socialization in fishing	0.38		
		Benefit transfer	0.19		
		Change in fishing benefit	0.16		
		Equity of economic benefit	0.12		
		Poverty index	0.12		

Leverage analysis for sensitivity variable of socio-economy dimension shows that of 15 attributes of this dimension, 2 attributes, 'consumer attitude towards sustainability' and 'just management,' were the most sensitive attribute towards mud crab sustainability (Table 1). This study shows that consumers, mud crab fishers, and local trade collectors have not considered sustainable fisheries principles whatsoever. Mud crab of small sizes and berried females trapped inside the mud crab pot were taken and sold to local mud crab collectors.

EAFM emphasizes the need for effective participation of all stakeholders in the management system. Objectives and targets in the management system should be agreed upon by all stakeholders (Pitcher et al., 2009; Staples et al., 2014; Fortnam, 2019). This study reveals that there was favoritism in the fishery where mud crab fishers having a close relationship with the chief of the village and/or government personnel will more likely get support compared to other fishermen. This condition could produce a conflict in the fishery which will lead to unsustainable management. A study on EAFM in the small-scale fishery in Indonesia reveals the need to increase co-management substantially among all stakeholders for better EAFM management (Courtney et al., 2017).

From eight attributes analyzed, the two most sensitive attributes from institutional dimensions were government quality and monitoring and reporting (Table 1). Government quality assesses the overall quality or capacity enabling conditions for legal, regulated, reported, and protected fisheries as indicated by the government. Monitoring is connected to reporting which assesses accurate, transparent reporting of fisheries activity and extraction of fish to government board either at local, regional, or national levels (Pitcher et al., 2009; Pitcher et al., 2013; Angel et al., 2019). The fish resources management system is comprehensive and inclusive, based on reliable data and knowledge and uses for the adaptive management approach (Pitcher et al., 2009). This study shows that government quality is very poor and no data is collected on monitoring and reporting for this fishery.

3.2 Ecological DPSIR framework for mud crab fishery

Fishing activities and gear types affect the marine environment and target species in many different ways. This study shows that the two most sensitive attributes towards the ecological sustainability of mud crab arise from mud crab pot use were catch before maturity and mud crab size (Table 1). Approximately 68.42% of female mud crabs caught were in their reproductive status with various levels of gonad maturity index. The study of Tetelepta et al. (2017) at Pelita Jaya shows that the majority (53.20%) of mud crabs caught ranged between 12-14 cm carapace widths. Furthermore, Tetelepta et al. (2019) in their study at Kotania Bay showed the same result with an average carapace width of mud crabs caught of 13.68 cm, a size prohibited by the Ministry of Marine and Fisheries Affairs of the Republic of Indonesia directive Nr. 1/2015 and Nr. 56/2016.

In practice, three processes link a stock at a given time to the stock at a future date: recruitment, growth, and mortality. These processes are interconnected to one another and not isolated (Diekert, 2012). The fish stock even in a manageable state can also be depleted. Ample evidence has shown that global fisheries and natural resources are depleting much faster than those that can replenish themselves (Froese, 2004; Thorpe et al., 2019; Pauly and Zeller, 2017; Gough et al., 2020). This depleting process is called overfishing and usually consists of two components: (i) diminishing the ability of fish to reproduce, called recruitment overfishing; and (ii) catching them before they can fully realize their growth potential, called growth overfishing (Froese, 2004; Diekert, 2012; Ordines et al., 2019). Some variables related to overfishing either growth overfishing or recruitment overfishing are high fishing mortality, low spawning stock, and environmental variability. The exact causes and mechanisms of recruitment collapse are poorly known, although often a combination of those three variables is indicated and ecological interactions are suspected (Pauly, 1994; Froese, 2004; Diekert, 2012).

This study has revealed that the two most sensitive variables contributing to the ecological sustainability of mud crab are catch before maturity and catch size which refers to body size. The ecological conceptual model (Figure 2) shows the DPSIR, a causal loop diagram, describing the existing condition of mud crab fishery at the study site and management actions that should be taken for sustainable management of this fishery. An example of management action taken at different levels of this system are fattening and grow out of small mud crab size caught (Aquino, 2018; Khoa and Harrison, 2019), mud crab bank (Thiammueang et al., 2012; Chap et al., 2012; Jöhl, 2013), and harvest control rules (HCR) (Kvamsdal et al., 2016; PEW, 2016). In HCR, the manager (government) can impose either input control on gear use, size harvested, season, etc. or output control on the number and size of resources taken (Tetelepta et al., 2018; Grubert et al., 2019). Crab fattening and grow out has the potential to be developed because it only requires small capital, short cultivation time, and simple technology (Karim et al., 2017). A study by Natan (2014) on this species has shown an increase in biomass from average biomass of 100-325 g/individual to 499-523.3 g/individual within 4 months grow out.

3.3 Social-economy DPSIR framework for mud crab fishery

There are 15 socio-economy attributes used in the analysis of mud crab sustainability. This socio-economy attribute can foster or inhibit the biological sustainability of mud crab. From leverage analysis, it was found that the two most sensitive attributes (attribute with the highest RMS) which affect the socio-economy sustainability of mud crab are consumer attitude towards sustainable management and just management (Table 1).

Consumer attitude towards sustainability assesses how a social attitude of consumers has an impact through a demand on what the fishing community delivers to the market and can foster sustainability (Pitcher et al., 2013). The attitude can be in the form of sustainable fishing practices, eco-labels, provenance information, sustainable sources of fish for restaurants, and fishery improvement plan. All of these attributes are not considered by the consumer in the study area and outside. Studies in Europe and South Korea showed a positive relationship between consumer attitude towards fishery products with certified eco-labels (Zander and Feucht, 2018; Yi, 2019). The mud crab fishers, mud crab brokers, and local consumers in the study site, for example, do not consider sustainable fisheries management principles. The second most sensitive attribute, just management, assess the inclusion of fishermen in the management

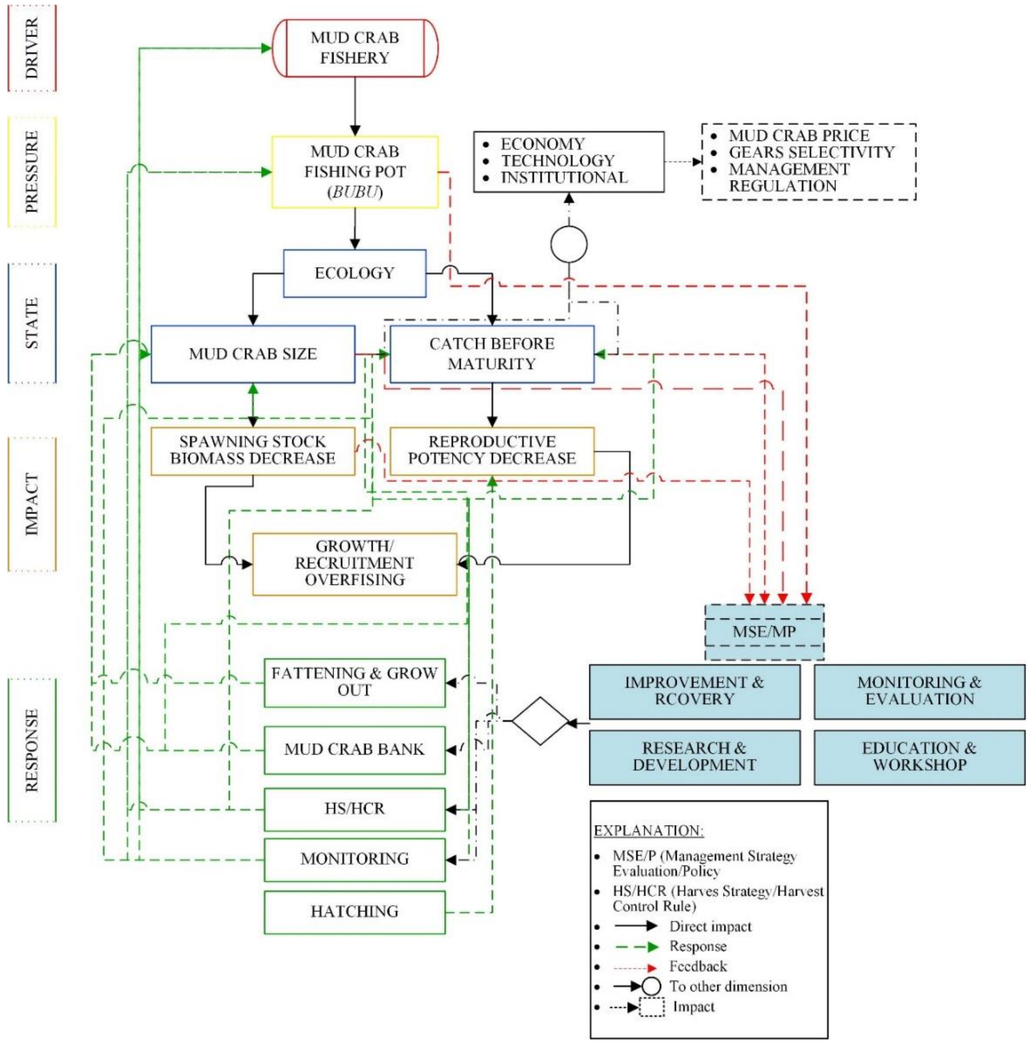

Figure 2. Ecological conceptual model framework for sustainable mud crab fishery management

and governance of the fishery. No inclusion of fishers in the management will lead to a bad impact on sustainability, while co-management with all parties having equal roles will have a good impact on sustainability (Rapfish Group, 2006; Pitcher et al., 2013).

With this kind of consumer attitude, the economic dependency of mud crab fishers on the mud crab, and continuous demand for this resource will lead to a high fishing intensity, and if not managed properly will lead to an overfishing situation. The fishery of mud crab in this area started in early 1980 and is still practiced up to the present time. Interviews with local fishers in FGD revealed that almost no fishery management is exercised towards this fishery. Production numbers and the individual size of mud crabs harvested have been decreasing recently (Tetelepta et al., 2019).

Fisheries co-management is defined as a relationship between a resource-user group (local fishers) and another entity (e.g., government agency or non-government organization) in which management responsibilities and authority are shared (Quimby and Levine, 2018; Tilley et al., 2019; Waithaka et al., 2020). This management concept has been considered as a good management approach in ensuring sustainable fisheries. With the involvement of local governance in Timor Leste, for example, the *tara bandu*, an indigenous knowledge co-management, has shown a positive impact on small-scale fisheries management (Tilley et al., 2019). Co-management in fisheries resources in the Naivasha Lake in Kenya has shown a positive impact on sustainable fisheries (Waithaka et al., 2020). Indigenous knowledge in fisheries management termed *sasi* in Maluku, Indonesia, has been considered as useful co-management (Warawarin et al., 2017; Persada et al., 2018; Soselisa, 2019). This co-management approach is not practiced in this site but could be an optional strategy management for this fishery.

In terms of just management, there should be an equal sharing of responsibility among stakeholders. There was some inclusion of fishers in the management but more on technical support and it went only to some fishers having a relation to the chief of the village. On one occasion there was a conflict between mud crab fishers from two different villages towards mud crab fishing ground. This poor quality of just management in the long term will affect mud crab sustainability. Figure 3 shows a socio-economy conceptual model framework describing the current situation of mud crab fishery and a series of management strategy which should be taken at a different level of the system to respond to the situation in this fishery which will lead to sustainable management.

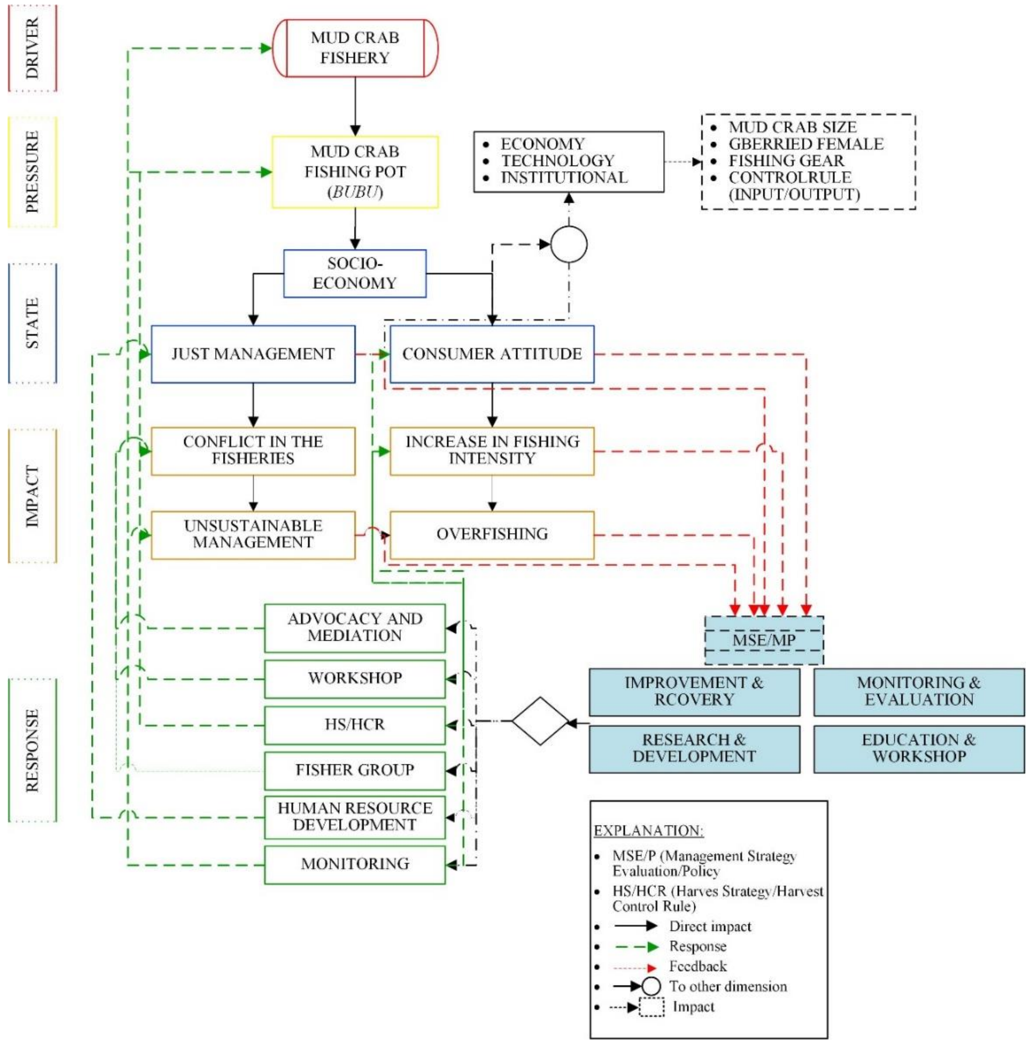

Figure 3. Socio-economy conceptual model framework for sustainable mud crab fishery management

3.4 Institutional DPSIR framework for mud crab fishery

In theory, sustainability should include social, cultural, institutional, and ethical dimensions of fisheries, but frequently the scope of sustainability in fisheries is limited to a small set of biological and economic considerations (Stephenson et al. 2018; Foley et al., 2018; Angel et al., 2019). The institutional field in sustainability analysis encompasses both governance (quality and legality) and management (regulation, reporting, monitoring, and protection) of fisheries. It focuses on organizational practices, established and enforced by formal rules of behavior, and their efficacy, as governed by both legal and cultural systems of accepted codes of conduct or norms (Pitcher et al., 2013; Stephenson et al., 2018). Fisheries Department of Queensland (DAF), for example, has been undertaking monitoring on fisheries for almost 30 years covering data on catch, size, effort, age, socio-economy indicators, legality (compliance), and used the data for the fisheries management plan (DAF, 2017). Marine Stewardship

Council (MSC) also develop monitoring and evaluation program to measure the achievement of MSC objectives through the assessment of results, effectiveness, improved processes, and performance within both MSC certified entities and the environments in which they operate (MSC, 2019).

Eleven attributes were used in the institutional sustainability analysis of mud crab *S. serrata* fishery. From these 11 attributes, the two most sensitive attributes towards mud crab sustainability are government quality and reporting and monitoring (Table 1). Monitoring assesses accurate, transparent reporting of fishing activities and fish extracted to national authority or local. This report then will be used in evaluation for the basis of the fisheries management plan. This study shows that there is no such monitoring and reporting taken in this fishery as a basis for the management plan. This will result in poor data situations which will lead to mismanagement and overfishing in the long run.

In sustainable fishery, management uses the best scientific evidence as a basis for management regulation. The regulation includes EAFM, multispecies attempts, precautionary approach, an ecosystem approach to management, monitoring and assessment, and adapting to change (Pitcher et al., 2013; Angel et al., 2019; Fortnam, 2019). In relation to EBFM/EAFM, the government of Indonesia already agrees to implement EAFM and there are also two specific regulations issued concerning the management of mud crab *Scylla* spp., but in the field, this is not the case. This study shows that none of these are implemented at the study site, hence will lead to unsustainable management. Figure 4 describes the conceptual model framework of the institutional domain of mud crab fisheries and series of responses which should be taken at a different level in this system in order to achieve sustainable mud crab fishery at the study site.

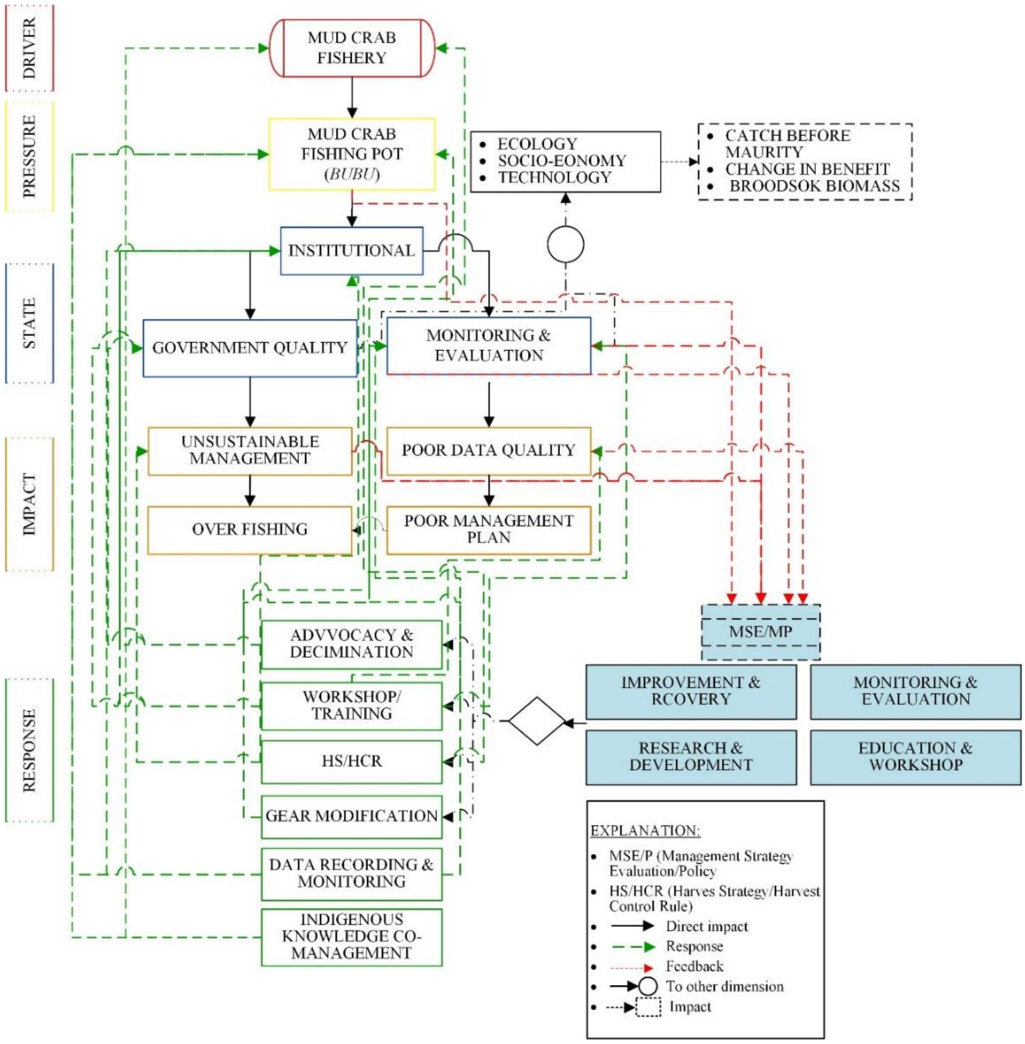

Figure 4. Institutional conceptual model framework for mud crab fishery management

The DPSIR is based on the idea that anthropogenic activities will impact the environment adversely and are considered as “Driving Forces” and “Impacts”. Under DPSIR, environmental problems and solutions are simplified into variables that stress the cause-effect relationships between human activities that exert pressures on the environment, the condition of the environment and society’s response to the condition. The DPSIR approach has been used in many different fields like an assessment of climate change (Salehi and Zebardast, 2016; Mozumder et al., 2019), the sustainability of fish in fisheries (Gebremedhin et al., 2018), environmental impacts will then drive humans to control the pressures. It introduces two new concepts: human welfare and environmental quality and societal behavior and economic pressures affecting the environment, incorporating assessing spatial-temporal differences of water quality, coastal management, marine protected area, and fisheries management (Patrício et al., 2016; Liu et al., 2019).

Conceptual models do not quantify restoration outcomes. This conceptual model framework summarizes the current understanding of how the ecosystem works, so they can assist in qualitative predictions and provide a key foundation for the development of benefits metrics, monitoring plans, and performance measures (Salehi and Zebardast, 2016; Elliott et al., 2017; Díaz et al., 2018). The conceptual model framework resulting from the DPSIR approach developed in this study was proposed as a first step to define the condition of the mud crab fishery of the study site, enabling the use of further and more accurate tools for the sustainable management of this fishery.

Information on mud crab fishery in Pelita Jaya and Kotania Bay for sustainable management is very scarce. The conceptual model framework combined with the DPSIR approach help to understand how the mud crab system works and its status. These three domains of the conceptual model framework in this study describe a series of responses that should be taken for sustainable management of mud crab *S. serrata* of Kotania Bay and Pelita Jaya Bay. Small size mud crab harvested could be improved through grow-out inside a fence to achieve more economical price and the berried female could be grown-out (Natan, 2014) as well to a mature stage and then transferred to a high salinity area to hatch. Harvest strategy through HCR can be imposed to manage the appropriate number of fishing units operated (input control) or amount of mud crab which could be taken (output control) for this fishery (Kvamsdal et al., 2016; Tetelepta et al., 2017).

In the ecosystem approach to fisheries management, these three domains do not stand separately, but they are connected as a system. Mud crab size at the ecological domain, for example, have a relation to the socio-economy domain in term of mud crab price, to the institutional domain in term of regulation, to technology domain in term of gear effect and gear modification and so forth. When management strategies have been taken according to responses shown by the conceptual model framework, monitoring, reporting, and evaluation should be followed afterward. The result of the evaluation will become a basis for new management strategies. Henceforth, the conceptual model framework will be changed or become adaptive management and this is a continuous process.

4. CONCLUSION

The DPSIR configuration of variables is a flexible framework that can be adapted to the necessities of specific programs to identify the different actors and processes affecting the system and in this case the mud crab *S. serrata* fishery at the study site. This conceptual model allows a better understanding of how the mud crab *S. serrata* system works and management actions taken at different system components (e.g., age at first maturity, spawning biomass, fishing intensity, etc.). Its structure can be used to select indicators as is being done in the implementation of, for example, Marine and Fishery Affairs of Republic Indonesia Directive on the mud crab fisheries management. Furthermore, it can be a very effective tool to incorporate the participation of stakeholders, managers, and scientists in the process of establishing a sustainable management plan.

REFERENCES

Angel E, Edwards DN, Hawkshaw S, Wor C, Parlee CE. An indicator framework to support comprehensive approaches to sustainable fisheries management. Ecology and Society 2019;24(4):1-34.

Aquino JIL. Promoting responsible aquaculture for the sustainable production of soft-shell crabs. Fish and People 2018;10(3): 46-51.

Balzan MV, Pinheiro AM, Mascarenhas A, Morán-Ordóñez A, Ruiz-Frau A, Carvalho-Santos C, et al. Improving ecosystem assessments in Mediterranean social-ecological systems: DPSIR analysis. Ecosystem and People 2019;15(1):136-55.

Barclay K, Michelle V, Mazur N, Payne, AN, Mauli S, Kinh J, et al. The importance of qualitative social research for effective fisheries management. Fisheries Research 2017;186(2):426-38.

Chap S, Meng K, Tep C, Joffre O. Crab Fisheries in Cambodia and the Development of Crab Banks. Phnom Penh, Cambodia: The Learning Institute and the World Fish Centre; 2012.

Courtney CA, Pomeroy R, De Alessi M, Adhuri D, Yuni C, Halim A. Marine tenure and small-scale fisheries: Learning from the Indonesia experience. Washington, DC: USAID Tenure and Global Climate Change Program and USAID Indonesia Sustainable Ecosystems Advanced Project; 2017.

Dambacher JM, Gaughan DJ, Rochet MJ, Rossignol PA, Trenkel VM. Qualitative modelling and indicators of exploited ecosystems. Fish and Fisheries 2009;10(3):305-22.

Department of Agiculture and Fisheries (DAF). Queensland Sustainable fisheries Strategy 2017-2027 [Internet]. 2017 [cited 2020 Aug 20]. Available from: https://cabinet.qld.gov.au/documents/2017/Jun/FishPol/Attachments/Strategy.pdf.

Díaz ME, Figueroa R, Alonso MLS, Vidal-Abarca MR. Exploring the complex relations between water resources and social indicators: The Biobío Basin (Chile). Ecosystem Service 2018;31:84-92.

Diekert FK. Growth overfishing: The race to fish extends to the dimension of size. Environmental and Resource Economics 2012;52:549-72.

Elliot M, Burdon D, Atkins JP, Borja A, Cormier M, de Jonge VN, et al. "And DPSIR begat DPSI(W)R(M)!"-A unifying framework for marine environmental management. Marine Pollution Bulletin 2017;118(1-2):27-40.

Foley P, Okyere DA, Mather C. Alternative environmentalities: Recasting the assessment of Canada's first Marine Stewardship Council-certified fishery in social terms. Ecology and Society 2018;23(3):37(1-10).

Food and Agriculture Organization (FAO). Workshop on Toolbox for the Ecosystem Approach to fisheries. FAO Fisheries and Aquaculture Report. Nr. 884. FIFM/R884(En) [Internet]. 2008 [cited 2020 Jan 20]. Available from: http://www.fao.org/tempref/docrep/fao/012/i0946e/i0946e.pdf.

Fortnam MP. Forces opposing sustainability transformations: Institutionalization of ecosystem-based approaches to fisheries management. Ecology and Society 2019;24(4):33(1-15).

Froese R. Keep it simple: Three indicators to deal with overfishing. Fish and Fisheries 2004;5:86-91.

Fujita R, Cusack C, Karasik R, Takade-Heumacher H, Baker C. Technologies for Improving Fisheries Monitoring. San Fransisco, USA: Environmental Defense Fund; 2018.

Gari SR, Newton A, Icely JD. A review of the application and evolution of the DPSIR framework with an emphasis on coastal social-ecological systems. Ocean and Coastal Management 2015;103:63-77.

Gebremedhin S, Getahun A, Anteneh W, Bruneel S, Goethals P. A drivers-pressure-state-impact-responses framework to support the sustainability of fish and fisheries in Lake Tana, Ethiopia. Sustainability 2018;10(8):1-20.

Gough CLA, Dewar KM, Godley BJ, Zafindranosy E, Broderick AC. Evidence of overfishing in small-scale fisheries in Madagascar. Frontiers in Marine Science 2020;7:1-17.

Grubert MA, Walters CJ, Brown RC, Penny SS. Simple modeling to inform harvest strategy policy for a data-moderate crab fishery. Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science 2019;11(2):125-38.

Harvey CJ, Reum JC, M. Poe MR, Williams GD, Kim SJ. Using conceptual models and qualitative network models to advance integrative assessments of marine ecosystems. Coastal Management 2016;44(5):486-503.

Huliselan NV, Wawo M, Tuapattinaja MA, Sahetapy D. Present status of grouper fisheries at waters of Kotania Bay, Western Seram Regency Maluku Province. IOP Conference Series Earth and Environmental Science 2017;89(1):012002.

Ingram RJ, Oleson KL, Gove JM. Revealing complex social-ecological interactions through participatory modeling to support ecosystem-based management in Hawai'i. Marine Policy 2018;94:180-8.

Jirapunpipat K. Population structure at size of maturity of the orange mud crab *Scylla olivacea* in Klong Ngao mangrove swamp, Ranong Province, Thailand Kasetsart Journal: Natural Science 2008;42(1):31-40.

Jöhl A. Crab Banks: A Literature Review. Bangkok, Thailand: IUCN; 2013.

Karim MY, Azis HY, Muslimin, Tahya AM. Physiological response: survival, growth, and nutrient content of the mud crabs (*Scylla olivacea*) which cultivated in mangrove area with different types of feed. AACL Bioflux 2017;10(5):1534-9.

Kavanagh P, Pitcher TJ. Implementing Microsoft Excel Software for Rapfish: A Technique for the Rapid Appraisal of Fisheries Status. Vancouver, Canada: University of British Columbia Fisheries Centre Research; 2004.

Keenan CP. The fourth species of *Scylla*. In: Keenan CP, Blackshaw A, editors. Proceedings of an International Scientific Forum; 1997 Apr 21-24; ACIAR Proceedings No. 78, Darwin: Australia; 1999. p. 48-58.

Kelble CR, Loomis DK, Lovelace S, Nuttle WK, Peter Ortner PB, Fletcher P, et al. The EBM-DPSER conceptual model: Integrating ecosystem services into the DPSIR framework. PLOS ONE 2013;8(8):e70766.

Kell LT, Luckhurst BE. Extending the indicator-based ecosystem report card to the whole ecosystem: A preliminary example based on the Sargasso Sea. Collective Volumes of Scientific Paper ICCAT 2018;75(2):258-75.

Khoa TND, Harrison FS. Development of mud crab breeding technology for conservation and communal livelihoods in the Setiu Wetlands, Terengganu, Malaysia. Asian Journal of Agriculture and Biology 2019;Special Issue:11-6.

Kvamsdal SF, Eide A, Ekerhovd A, Enberg K, Gudmundsdottir A, Hoel AH, et al. Harvest control rules in modern fisheries management. Elementa: Science of the Anthropocence 2016;4:1-22.

Liu W, Sun C, Zhao M, Wu Y. Application of a DPSIR modelling framework to assess spatial-temporal differences of water poverty in China. Journal of the American Water Resources Association 2019;55(1):259-73.

Marine Stewardship Council (MSC). Monitoring and evaluation framework. Certified Sustainable Seafood [Internet]. 2019 [cited 2020 Aug 19]. Available from: https://www.msc.org/what-we-are-doing/our-collective-impact/monitoring-and-evaluating.

Martin DM, Piscopo AN, Chintala MM, Gleason TR, Berry W. Developing qualitative ecosystem service relationships with the Driver-Pressure-State-Impact-Response framework: A case study on Cape Cod, Massachusetts. Ecology Indicator 2018;84:404-15.

Ministry of Marine Affairs and Fisheries (MMAF), Republic of Indonesia, and USAID Sustainable Ecosystems Advanced (SEA) Project. State of the Sea: Indonesia, Volume One: An Overview of Marine Resource Management for Small-Scale Fisheries and Critical Marine Habitats in Indonesia. Jakarta, Indonesia; 2018.

Mozumder MMH, Phyla A, Wahab MdA, Darkki S, Schneider P, Islam MM. Understanding social-ecological challenges of a small-scale Hilsa (*Tenualosa ilisha*) fishery in Bangladesh. International Journal of Environment Research and Public Health 2019;16:1-24.

Natan Y. Fattening of small mud crab *Scylla serrata* harvested by local fisher from Wael Village, Sub-Regency Piru, Western Seram Regency. Jurnal Perikanan (Journal of Fisheries Science) 2014;15(2):79-87 (in Indonesian).

Ordines F, Lloret J, Tugores P, Manfredi C, Guijarro B, Jadaud A, et al. A new approach to recruitment overfishing diagnosis based on fish condition from survey data. Scientia Marina 2019;83S1:223-33.

Pauly D. From growth to malthusian overfishing: Stages of fisheries resources misuse. SPC Traditional Marine Resource Management and Knowledge Information Bulletin 1994;3:7-14.

Pauly D, Zeller D. The best catch data that can possibly be? Rejoinder to Ye et al. “FAO's statistic data and sustainability of fisheries and aquaculture. Marine Policy 2017;81:406-10.

Patrício J, Elliott M, Mazik K, Papadopoulou KN, Smith CJ. DPSIR-Two Decades of trying to develop a unifying framework for marine environmental management. Frontiers in Marine Science 2016;3:177(1-14).

Persada NPR, Fachrudin M, Mangujjaya, Tobing ISL. *Sasi* as a natural conservation culture in Maluku Islands. Jurnal Ilmu dan Budaya 2018;41(59):6869-900 (in Indonesia).

PEW Charitable Trusts. Management strategy evaluation for fisheries: Informing the selection of harvest strategies [Internet]. 2016 [cited 2020 Jan 20]. Available from: https://www.pewtrusts.org/-/media/assets/2019/07/harvest-strategies/hs_mse_update. pdf.

Pitcher TJ, Kalikoski D, Short K, Varkey D, Pramoda G. An evaluation of progress in implementing ecosystem-based management of fisheries in 33 countries. Marine Policy 2009;33:223-32.

Pitcher TJ, Lam ME, Ainsworth C, Martindale A, Nakamura K, Perry RI, et al. Improvements to Rapfish: A rapid evaluation technique for fisheries integrating ecological and human dimensions. Journal of Fish Biology 2013;83:865-89.

Pitcher TJ, Preikshot D. RAPFISH; A rapid appraisal technique to evaluate sustainability status of fisheries. Fisheries Research 2001;49:255-70.

Plaganyi EE. Models for an Ecosystem Approach to Fisheries. FAO Fisheries Technical Papers No. 477. Rome, Italy: FAO; 2007.

Quimby B, Levine A. Participation, power, and equity: Examining three key social dimensions of fisheries comanagement. Sustainability 2018;10:3324(1-20).

Rapfish Group. Standard Attributes for Rapfish Analysis: Evaluation Fields for Ecological, Technological, Economic, Social, and Ethical Status. Vancouver, Canada: Fisheries Centre, University of British Columbia; 2006.

Rosellon-Druker J, Szymkowiak M, Cunningham CJ, Kasperski S, Kruse GH, Moss JH, et al. Development of social-ecological conceptual models as the basis for an integrated ecosystem assessment framework in Southeast Alaska. Ecology and Society 2019;24(3):30(1-18).

Salehi E, Zebardast L. Applicatin of driving force-pressure-state-impact-respones (DPSIR) framework for integrated environmental assessment of the cliamte change in city of Teheran. Pollution 2016;2(1):83-92.

Shelley C. Capture-based aquaculture of mud crabs (*Scylla* spp.). In: Lovatelli A, Holthus PF, editors. Capture-based Aquaculture: Global Overview. FAO Fisheries Technical Paper. No. 508. Rome, Italy: FAO; 2008. p. 255-69.

Siahainenia L, Natan Y, Khouw AS, Pattikawa JA. Size distribution, growth pattern and condition factor of mangrove crab *Scylla serrata* in the coastal waters of Western Seram, Maluku, Indonesia. International Journal of Fisheries and Aquatic Studies 2016;4(2):291-6.

Smith C, Papadopoulou N, Barnard S, Mazik K, Patrício J, Elliott M, et al. Conceptual Mmodels for the Effects of Marine Pressures on Biodiversity. DEVOTES Deliverable; 2014. p. 82.

Smith H, Basurto X. Defining small-scale fisheries and examining the role of science in shaping perceptions of who and what counts: A systematic review. Frontiers in Marine Science 2019;6:236(1-19).

Sobocinski KL, Greene CM, Schmidt MW. Using a qualitative model to explore the impacts of ecosystem and anthropogenic drivers upon declining marine survival in Pacific salmon. Environmental Conservation 2017:45(3):278-90.

Soselisa HL. Sasi Lompa: A critical review of the contribution of local practices to sustainable marine resource management in Central Maluku, Indonesia. IOP Conference Series Earth and Environmental Science 2019;339:012013.

Staples D, Brainard R, Capezzuoli S, Funge-Smith S, Grose C, Heenan A, et al. Essential EAFM: Ecosystem Approach to Fisheries Management Training Course. Volume 1-For Trainees. FAO Regional Office for Asia and the Pacific. Bangkok, Thailand: RAP Publication; 2014.

Stephenson RL, Paul S, Wiber M, Angel E, Benson AJ, Charles A, et al. Evaluating and implementing social-ecological systems: A comprehensive approach to sustainable fisheries. Fish and Fisheries 2018;19(5):853-73.

Tetelepta JMS, Makatita M. An approach to the management of mud crab *Scylla serrata* through the reproductive status of mud crab and socio economy and institutional aspects of the fishermen at Pelita Jaya, Western Seram Regency. Triton Jurnal Manajemen Sumberdaya Perairan 2012;8(1):1-11.

Tetelepta JMS, Khouw AS, Natan Y, Ongkers OTS. Some biological aspects of mud crab *Scylla serrata* (Forskal) Fisheries in Pelita Jaya Bay, Western Seram Regency Indonesia. International Journal of Fisheries and Aquatic Studies 2017;5(5):272-7.

Tetelepta JMS, Natan Y, Ongkers OTS, Pattikawa JA. Some population biology aspects of edible orange mud crab *Scylla olivacea* (Herbst, 1796) of Kotania Bay, Western Seram Regency, Indonesia. AACL Bioflux 2018;11(4):1203-12.

Tetelepta JMS, Natan Y, Pattikawa JA, Pattisina BJ. Fishery of mud crab *Scylla serrata* of Kotania Bay, Western Seram Regency: potency, stock status and sustainable management. IOP Journal Series: Earth and Environmental Science 2019;339:012002.

Thiammueang D, Chuenpagdee R, Juntarashote K. The crab bank project: Lessons from the voluntary fishery conservation initiative in Phetchaburi Province, Thailand. Kasetsart Journal: Natural Science 2012;46:427-39.

Thorpe RB, De Oliveira JAA. Comparing conceptual frameworks for a fish community MSY (FCMSY) using management strategy evaluation-an example from the North Sea. ICES Journal of Marine Science 2019;76(4):813-23.

Tilley A, Hunnam KJ, Mills DJ, Steenbergen DJ, Govan H, Alonso-Poblacion E, et al. Evaluating the fit of co-management for small-scale fisheries governance in Timor Leste. Frontiers in Marine Science 2019;6:392(1-17).

Voyer MA, Barclay K, Mazur N. Using a well-being approach to develop a framework for an integrated socio-economic evaluation of professional fishing. Fish and Fisheries 2017;18(6):1134-49.

Waithaka E, Boera P, Obegi B, Mutie A, Morara G, Loki P, et al. The impacts of co-management towards sustainable development and utilization of fisheries resources in Lake Naivasha, Kenya. Poultry, Fisheries and Wildlife Sciences 2020;8(1):1-6.

Warawarin CY, Cangara H, Muhadar. The symbolic comunication denoting of *sasi* traditional law in marine conservation in Southeasr Maluku District. Jurnal Komunikasi KAREBA 2017;6(1):19 (in Indonesian).

Wouthuyzen S, Sapulete D. Condition of coastal area of Western Seram past and present: A review. Perairan Maluku dan Sekitarnya 1994;7:1-18 (in Indonesian).

Yi S. Determinants of consumers' purchasing behavior for certified aquaculture products in South Korea. Sustainability 2019;11:3840(1-18).

Zador GZ, Gaichas SK, Kasperski S, Ward CL, Blake RE, Ban NC, et al. Linking ecosystem processes to communities of practice through commercially fished species in the Gulf of Alaska. ICES Journal of Marine Science 2017;74(7):2024-33.

Zander K, Feucht Y. Consumers' willingness to pay for sustainable seafood made in Europe. Journal of International Food and Agribusiness Marketing 2018;30(3):251-75.

Spatial Modeling of Forage Crops for Tiger Prey Species in the Area Surrounding Highway 304 in the Dong Phayayen-Khao Yai Forest Complex

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ABSTRACT

Spatial modeling is an analytical procedure that simulates real-world conditions using remote sensing and geographic information systems. The field data in this study were collected from 318 survey plots in the area surrounding highway 304 in the Dong Phayayen-Khao Yai Forest Complex (DPKY-FC) during the 2019 rainy season. Forage-crop biomass was collected from all plots. We focused on sambar deer (*Rusa unicolor*) and gaur (*Bos gaurus*), which are the main prey for tigers in this area. We created spatial models using generalized linear models with stepwise regression. The results indicated that the normalized difference vegetation index (NDVI) varied directly with grass biomass but inversely with shrub biomass ($p<0.05$). Elevation varied directly with forb biomass but inversely with shrub biomass ($p<0.05$). The probability of occurrence of sambar deer varied directly with distance from disturbance variables, distance from the stream, and grass biomass ($p<0.001$), but inversely with NDVI ($p<0.05$). The occurrence of gaur varied directly with NDVI ($p=0.08$), but varied inversely with slope, distance from the road, and distance from the stream ($p<0.05$). Our results demonstrate that spatial modeling can be an effective tool for wildlife habitat management in the area surrounding highway 304.

1. INTRODUCTION

The factors affecting species distributions were first described by Grinnell (1917) and comprise locally measured variables such as food, vegetation, soil, and climate. The advent of geographic information systems and remote sensing have provided spatial data covering large areas that can be used to elucidate the distribution of species. The major contribution of habitat-suitability models (HSMs) to niche theory has been the ability to test the relevance of such variables for species and environmental relationships (Grinnell, 1917; Guisan and Zimmermann, 2000). There are many available methods for generating HSMs. One of the main differences among them is dependence on the quality of data needed. Generalized linear models (GLMs) are a generalization of multiple regression analyses with a binomial distribution and logit link that can fit higher-degree polynomials (Hirzel et al., 2001). GLMs provide good predictions for virtual species distributions because they can deal with many types of predictors (Brotons et al., 2004; Engler et al., 2004). Duangchatrasiri et al. (2019) assessed whether human activity had an impact on the occurrence of wildlife by using the distance from villages and roads because wildlife is sensitive to hunting and a range of other environmental conditions such as disturbance variables inside protected areas (Lynam et al., 2012). In addition, distance to rivers and streams have also been included as covariates that reflect habitat quality near streams (Linkie et al., 2006). Land-cover data have the most diverse influences on ecological niches (Schadt et al., 2002; Sachot et al., 2003; Seoane et al., 2004). The Landsat 8 satellite provides ecologists with

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infrared imagery, which allows computation of the normalized difference vegetation index (NDVI), a proxy for plant biomass (Estrada-Peña et al., 2006).

The Dong Phayayen-Khao Yai Forest Complex (DPKY-FC) in Thailand was declared a UNESCO World Heritage Site in 2005. However, recent reports have shown that tigers in the DPKY-FC were found only in Thap Lan National Park and not in Khao Yai National Park (DNP, 2016; Ash et al., 2020). The last report of tigers in Khao Yai National Park was from September 19th, 1996. Gaur, the main prey for tigers in this area, are still found on both sides of highway 304 (Simcharoen et al., 2018), but they cannot travel between sites. Also, sambar deer, which are found along the forest edge, still do not appear to use the highway 304 wildlife corridor. Therefore, the most important landscape-level issue for the DPKY-FC is the lack (in both quality and quantity) of wildlife habitat. Highway 304 passes through this forest, resulting in threat factors that prevent large wildlife from being able to move safely back and forth across the road.

This study used plot observations from a plant-community survey to investigate habitat composition and factors affecting the quality and quantity of habitat in the DPKY-FC. We used multiple scales, including plot, patch, and landscape (Cushman and McGarigal, 2002), by selecting random points to represent the study area. Information regarding habitat size, fragmentation, and resources provides the baseline for devising appropriate wildlife-management strategies at both the operational and policy levels. This is urgently needed to restore populations of tigers and other endangered wildlife.

2. METHODOLOGY

2.1 Study site

The study was conducted in a 450.35 km^2 area of the DPKY-FC comprising parts of Khao Yai National Park and Thap Lan National Park in Nakhon Ratchasima and Prachin Buri Provinces (14°05′-14°30′N, 101°45′-102°00′E) (Figure 1). The elevation was 38-877 m.a.s.l. Field data were collected from the immediate area surrounding highway 304.

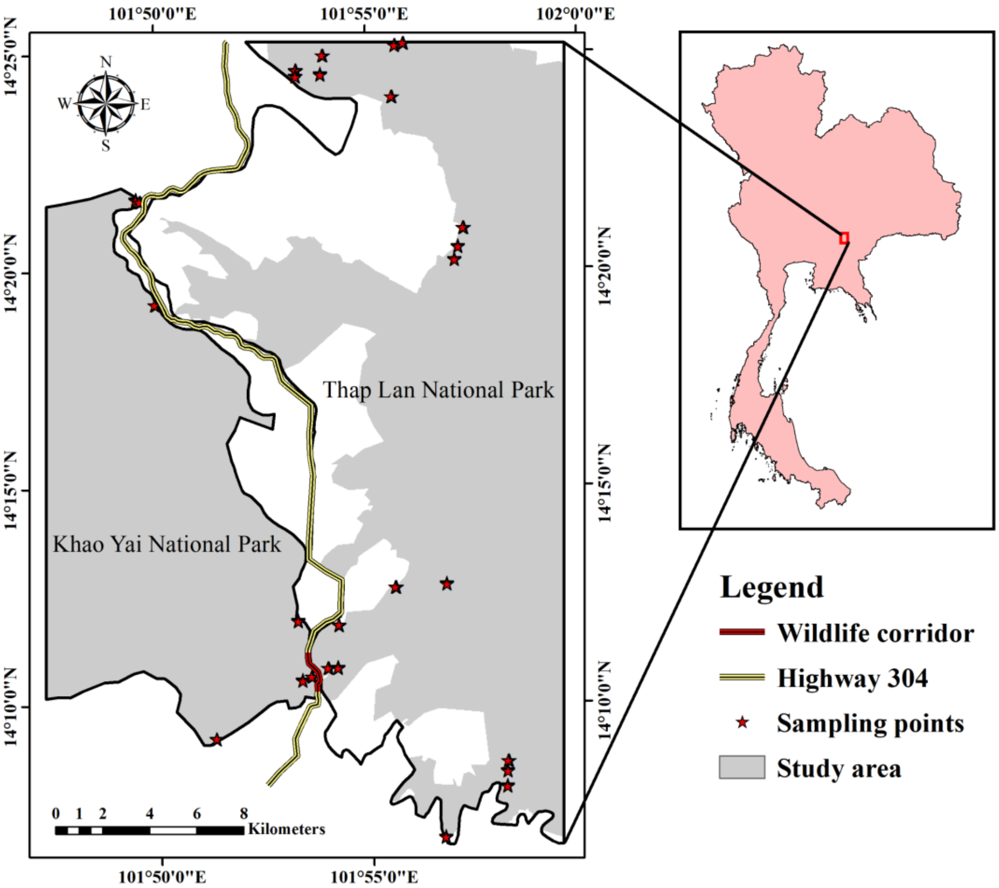

Figure 1. Study area showing the wildlife corridor and sampling points surrounding highway 304 in Khao Yai National Park and Thap Lan National Park.

2.2 Survey design

We surveyed sampling points in 318 plots to study the grasslands according to the abundance of sambar deer and gaur, which are the main prey for tigers. The coordinates of the centers of the plots were recorded as the sampling points. We used tiger and prey occurrence data from the Wildlife Research Division, Department of National Parks, Wildlife and Plant Conservation, to create species distribution models (SDMs) of tigers (*Panthera tigris*) and their main prey species, particularly sambar deer (*Rusa unicolor*), gaur (*Bos gaurus*), and wild boar (*Sus scrofa*). A model was created using the SDMs with maximum entropy (MaxEnt) (Phillips et al., 2006). The coordinates of the sampling points were randomly selected to represent the study area. The following factors were considered for each sampling point: the distribution or occurrence of tigers and prey in the study area, including the density of prey and tiger population; three forest types, including evergreen forest (Ever), deciduous forest (Deci), and mixed deciduous forest (Misc); elevation; and slope. The value of each factor was normalized from 0 to 100. The study area was then divided into 10 clusters according to the scores of each factor using K-means clustering (Table 1). Cluster characteristics can be described according to the scores of various factors as follows: for wildlife habitat suitability, a value of 0 indicated that the area was not suitable, whereas a value of 100 indicated that the area was most suitable; for the forest type, a value of 0 indicated that the area did not have a specific forest type, whereas a value of 100 indicated that the area had a specific forest type; and for elevation and slope, a value of 0 indicated that the area was flat, whereas a value of 100 indicated that the area had a very high elevation and a steep slope.

Table 1. The characteristics of 10 clusters based on the scoring of factors considered at the sample plots.

Clusters	Tiger	Gaur	Sambar deer	Elevation	Slope	Ever	Deci	Misc
1	12.12	0.00	0.00	70.70	100.00	100.00	0.00	0.00
2	100.00	22.45	11.59	100.00	46.83	99.84	0.00	0.19
3	24.96	4.65	11.54	87.23	76.65	0.00	100.00	0.00
4	0.30	23.22	24.81	6.20	29.59	100.00	0.00	0.00
5	8.23	46.40	48.08	79.74	26.59	100.00	0.00	0.00
6	1.66	56.20	54.35	20.06	5.63	0.00	0.00	100.00
7	1.70	100.00	100.00	38.83	0.00	100.00	0.00	0.00
8	0.00	14.78	7.76	0.00	34.21	0.00	100.00	0.00
9	32.74	86.18	97.43	48.76	13.69	0.00	100.00	0.00
10	84.71	78.10	94.91	63.97	7.66	100.00	0.00	0.00

2.3 Field data collection methods

The coordinates of the center point of the sample plots were recorded using the UTM WGS84 coordinate system. Grassland data were collected in four steps: (1) at each sample plot, four sub-plots (1 × 1 m) were created (Figure 2); (2) the density of grass and other plants was measured using a 10 × 10 cm quadrat frame; (3) the height of the grass (from the ground) was measured using a measuring stick to measure the height of the grass that was the closest to the height of the measuring stick by measuring the height of the quadrat frame, not less than 3 frames; and (4) all aboveground biomass was cut and separated into grasses, forbs, and shrubs following Cordova and Wallace (1975) and Holechek (1984). To account for variation in biomass, plant specimens were dried in an oven at a temperature of 70°C for 48 h or until the weight of the specimens was stable. A sample was taken to determine dry weight and calculate the moisture content (percentage) of the biomass following Pattanakiat (1988). In addition, direct sightings, tracks, and fresh dung of sambar deer and gaur were recorded at every sub-plot at each sample plot.

2.4 Statistical analysis

We used Gaussian and Poisson GLMs to relate limiting factors to environmental variables (all variables used a resolution of 30 × 30 m). The logistic regression analysis (GLM with binomial distribution and logit-link function; McCullagh and Nelder, 1989) included limiting factors such as shrub biomass, forb biomass, grass biomass, and occurrence of wildlife (sambar deer and gaur); and environmental variables such as slope (degree), elevation, distance from the road, distance from the stream, distance from villages, and NDVI from the Landsat 8 satellite (Table 2; Figure

4). The analyses were performed using the MASS package (Venables and Ripley, 2002) in R (R Core Team, 2017). We used automatic stepwise selection to select the model with the lowest Akaike Information Criteria (Akaike, 1998). The processing workflow for the spatial modeling is presented in Figure 3.

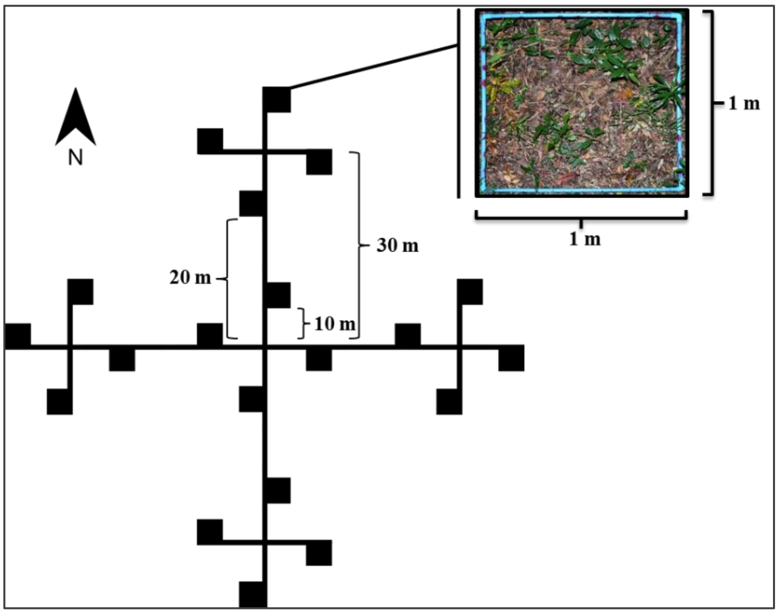

Figure 2. Sub-plots (1 × 1 m) at each sample plot.

Table 2. Variables (predictors) used to generate biomass and the virtual habitat-suitability map.

Type	Predictor	Code
Limiting factors	Shrub biomass	S_wgt
	Forb biomass	F_wgt
	Grass biomass	G_wgt
	Occurrence of wildlife	Sambar deer
		Gaur
Environment variables	Meters above sea level	Elevation
	Slope	Slope
	Normalized difference vegetation index	NDVI
	Distance from the road	Dist_road
	Distance from the stream	Dist_stream
	Distance from villages	Dist_villages

(a)

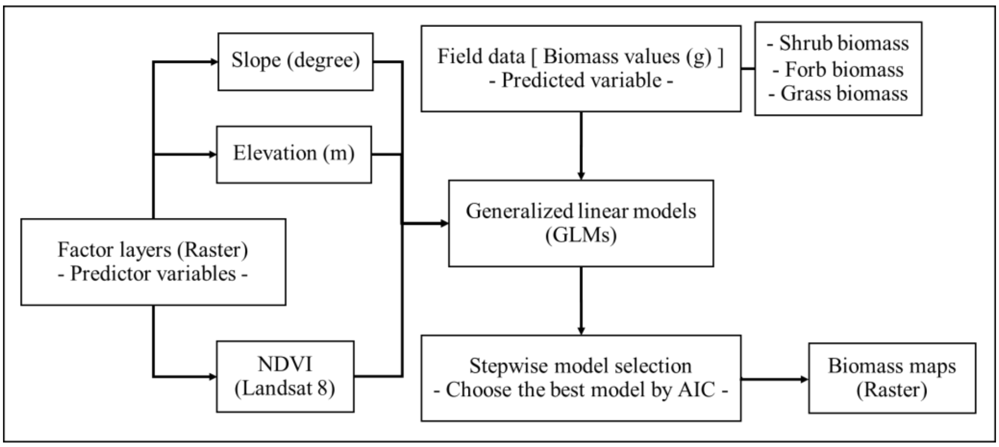

Figure 3. Flowchart of the processing performed for the (a) forage-crop models; and (b) habitat-suitability models.

(b)

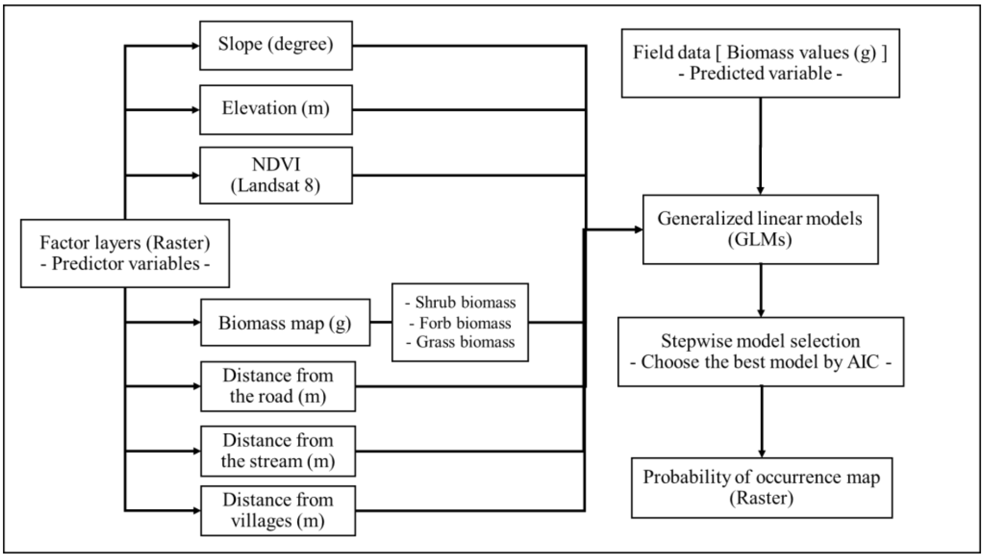

Figure 3. Flowchart of the processing performed for the (a) forage-crop models; and (b) habitat-suitability models (cont.).

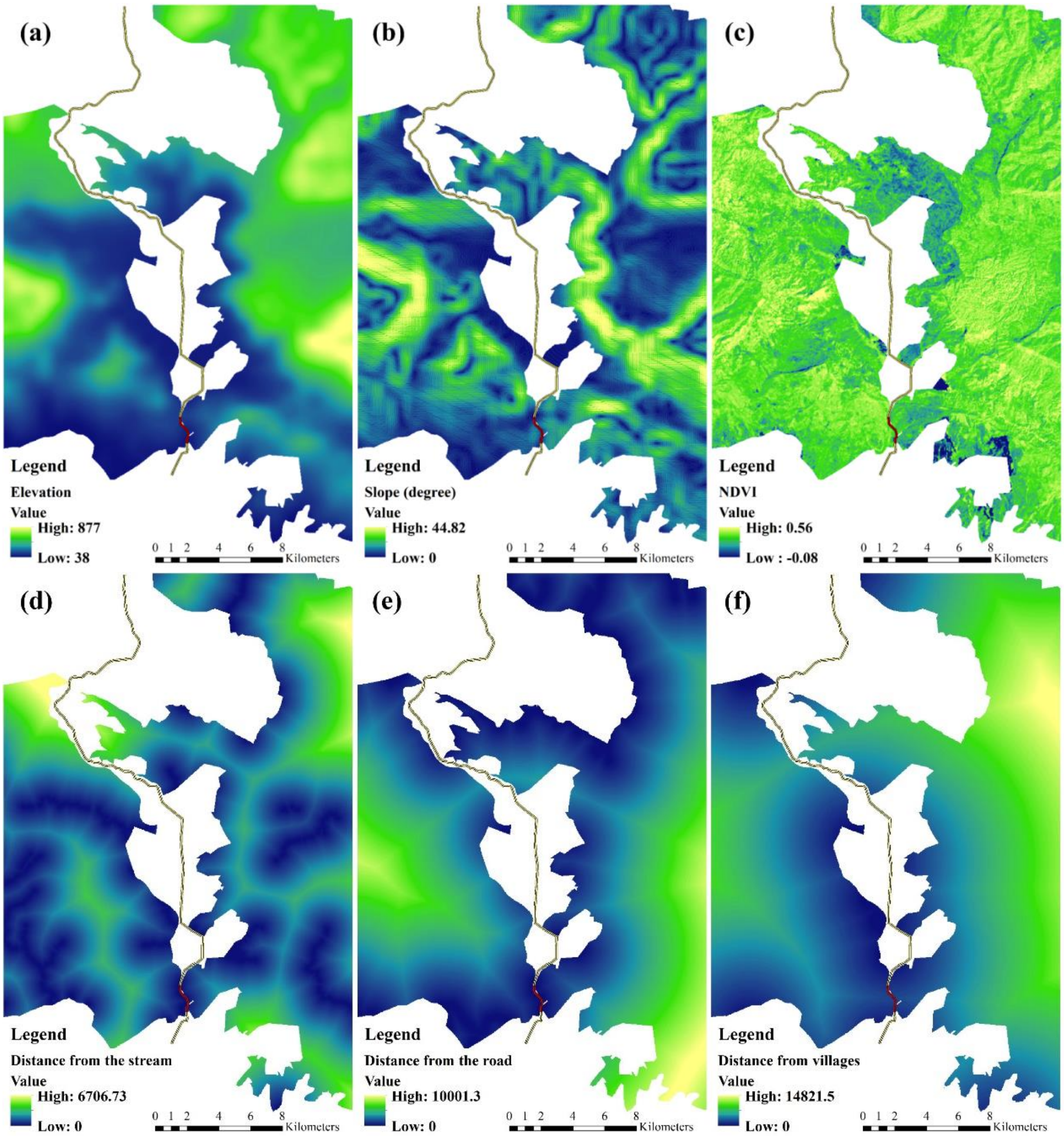

Figure 4. Environment factor layers (raster, resolution 30 × 30 m) including: (a) elevation; (b) slope; (c) NDVI; (d) distance from the stream; (e) distance from the road; and (f) distance from villages.

3. RESULTS AND DISCUSSION

3.1 The forage-crop models

The models were based on 318 1 × 1 m plots from the area surrounding highway 304. The results of the forage-crop model (Table 3) indicated that shrub biomass varied directly with NDVI but inversely with elevation ($p<0.05$) and slope ($p=0.051$). Forb biomass varied directly with elevation ($p<0.001$). Grass biomass varied inversely with NDVI ($p<0.01$). Shrub biomass was 0.001-141.346 g, forb biomass 9.392-51.063 g, and grass biomass 0-124.889 g (Figure 5).

Table 3. Forage-crop models for the generalized linear model with all predictor variables.

Model	Predictor	Coefficient	Standard error	p	AIC
S_wgt ~ Elevation + Slope + NDVI	Intercept	-52.929	33.487	0.115	3562.5
	Slope	1.627	0.831	0.051	
	Elevation	-0.068	0.018	<0.001	
	NDVI	288.485	93.713	<0.05	
F_wgt ~ Elevation	Intercept	7.505	4.816	0.12	3351.8
	Elevation	0.05	0.012	<0.001	
G_wgt ~ NDVI	Intercept	110.98	23.46	<0.001	3373.8
	NDVI	-259.45	62.82	<0.001	

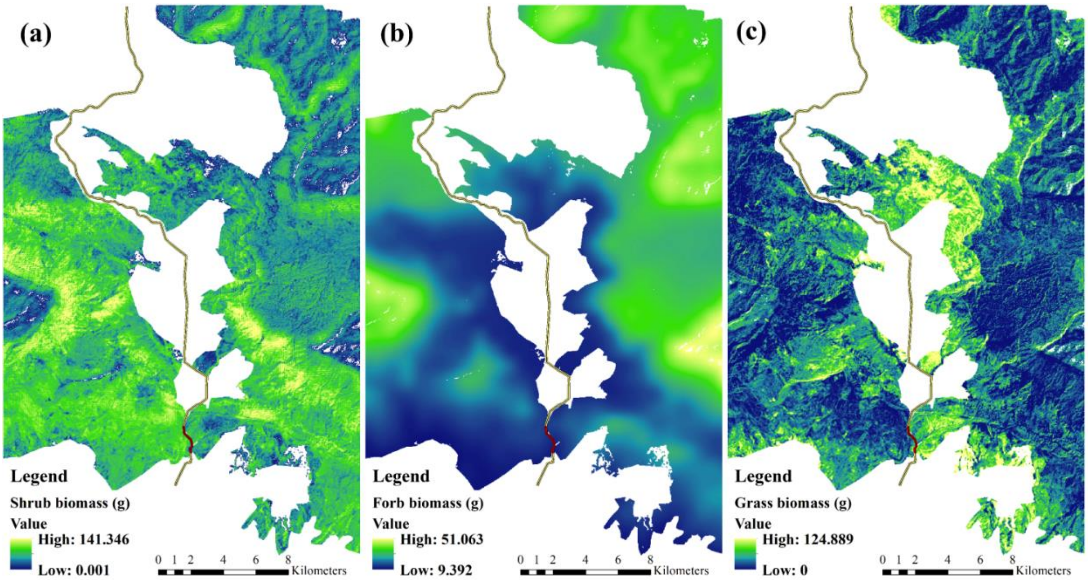

Figure 5. Biomass from the forage-crop models for (a) shrub biomass; (b) forb biomass; and (c) grass biomass in the area surrounding highway 304.

The forage-crop models showed a negative relationship between shrub biomass and elevation. This is consistent with Ensslin et al. (2015), who found that shrub biomass decreased significantly with elevation. Conversely, when tropical elevation (i.e., 100–60 0 m, which is in the range we studied) increases, forest density also increases (Clark et al., 2015). Therefore, higher elevations promote canopy closure. Tropical saplings and species highly associated with gaps (i.e., low-density forests) show a rapid rise in relative growth rate with increasing light level. The inability of light to shine through to the ground is an important factor that influences shrub growth. The model of shrub biomass differed from that of forb biomass. Forb biomass had a positive relationship with elevation because forbs have no persistent woody stem above ground (Mongkhonsin et al., 2019). The height changes when an area has no light or high forest density. The higher shade avoidance, shade tolerance, and specific leaf area of forbs, as well as with their more frequent occurrence under denser canopies, all suggest that the herbaceous climbing-plant strategy is suitable for low-light conditions. Forbs appear to invest in greater shade avoidance and shade tolerance, and they tend to have a slightly higher specific leaf area than co-occurring plants (Bitomský et al., 2019).

Model selection was conducted for models of shrub biomass and grass biomass, which included additive and interactive effects of NDVI. In the forested habitat, the relationship between NDVI and ground vegetation biomass was positive for shrubs and negative for grass because vegetation greenness and photosynthetic capacity have stronger relationships with NDVI for shrubs than for grass (De las Heras et al., 2015). Grassland also has lower NDVI reflectivity. Therefore, models using NDVI show different effects for forest and grassland areas (Borowik et al., 2013). Meanwhile, grass cover decreased as canopy cover increased because of lower transmission of light to understory vegetation, an important factor for the appearance of grass cover (Widenfalk and Weslien, 2009). Both of the conservation areas studied here are intersected by highway 304 and are adjacent to villages (Figure 1). In some areas, forest cover was cleared due to encroachment and livestock has been introduced, resulting in higher grass biomass than in other areas. Therefore, management of these areas affects the type and amount of forage crops. The most important properties were open canopy vs. dense forest cover because light is critical for determining the amount of shrub and grass biomass; however, this did not significantly affect forb biomass.

3.2 The habitat-suitability models

The HSMs showed that the probability of sambar deer occurrence varied directly with distance from the road, distance from the stream, distance from villages, and grass biomass but inversely with NDVI ($p<0.05$). The probability of gaur occurrence varied directly with NDVI ($p=0.084$) but inversely with slope, distance from the road, and distance from the stream ($p<0.05$) (Table 4).

Table 4. The habitat-suitability models for the generalized linear model with all predictor variables.

Model	Predictor	Coefficient	Standard error	p	AIC
Sambar deer ~ G_wgt + Dist_road + Dist_stream + Dist_villages + NDVI	Intercept	-0.762	1.354	0.573	271.7
	G_wgt	1.20E-02	4.43E-03	<0.05	
	Dist_road	3.05E-04	7.62E-05	<0.001	
	Dist_stream	9.29E-04	1.22E-04	<0.001	
	Dist_villages	7.03E-04	1.00E-04	<0.001	
	NDVI	-11.330	3.676	<0.05	
Gaur ~ Slope + Dist_road + Dist_stream + NDVI	Intercept	-1.797	1.839	0.328	253.92
	Slope	-0.258	0.046	<0.001	
	Dist_road	-4.20E-04	1.48E-04	<0.05	
	Dist_stream	-4.39E-04	1.08E-04	<0.001	
	NDVI	9.013	5.220	0.084	

The HSMs showed that the probability of sambar deer occurrence varied positively with grass biomass but negatively with NDVI, and generally corresponded to the model of grass biomass. Although the sambar deer is remarkably flexible in its habitat affinities, it mainly prefers closed canopy and the tallgrass ecotone between dense forest and open canopy, as well as areas relatively free from human disturbance (Kushwaha et al., 2004; O'Brien et al., 2003). The probability of gaur occurrence varied positively with NDVI because gaur can tolerate rugged terrain and dense forest better than other ungulates, as long as there are adequate water sources available (Smith et al., 2010).

Both occurrence models were consistent with Lynam et al. (2012). The results indicated that sambar deer were sensitive to villages and roads (disturbance variables), and places where sambar deer were detected had more open habitat. Sambar deer have suffered poaching pressure and have been targets for market-driven poaching across Thailand. They were found farther away from roads and villages, consistent with the study of Jornburom et al. (2020) in Thailand's Western Forest Complex, suggesting a sensitivity to hunting as well as to a range of other environmental conditions inside protected areas. Distance to the stream had a negative relationship with occurrence of sambar deer. The river itself was likely not the main attractor of sambar deer; rather, the geographic features associated with the valley likely produced a desirable habitat for sambar deer, especially in the area surrounding highway 304 (Simcharoen et al., 2014).

Gaur were not sensitive to roads or slope because they were found mostly in lowland forests. The probability of gaur occurrence was greatest at the forest edge, especially at the wildlife corridor of highway 304 (Figure 6). This information may be useful for managing gaur crossing between the two conservation areas. The gaur HSMs were consistent with Lynam et al. (2012), who also found that gaur showed stronger avoidance of villages than sambar deer. Distance from the stream had a positive relationship with the wildlife corridor, which has a river (Khlong Yang) on the Khao Yai National Park side.

Sambar deer and gaur are considered to be grazers and browsers (Duckworth et al., 2016; Masters and Flach, 2015). The regression coefficient for grass biomass in the sambar deer HSMs was 0.012 (Table 3), indicating that grass biomass had a stronger effect on the occurrence of sambar deer than on that of gaur. The regression coefficients for NDVI in the HSMs of sambar deer and gaur were -11.330 and 9.013, respectively, indicating that sambar deer were more likely to live in open areas than gaur. This corresponded to grass biomass on the edge of the conservation area, which has more open space than in the conservation area (Figure 1). This was consistent with Lamont et al. (2019), whose results showed that ungulates selected grass-covered areas farther from roads. Therefore, increased grass biomass, associated with more open canopy, promotes increased use by ungulates. However, in some areas, ungulates aside from sambar deer and gaur consume large amounts of forbs and shrubs, primarily when green grass is unavailable. These ungulates show a strong avoidance of shrubs high in volatile oils because they lack mechanisms to reduce the toxic effects of these substances (Cappai and Aboling, 2020).

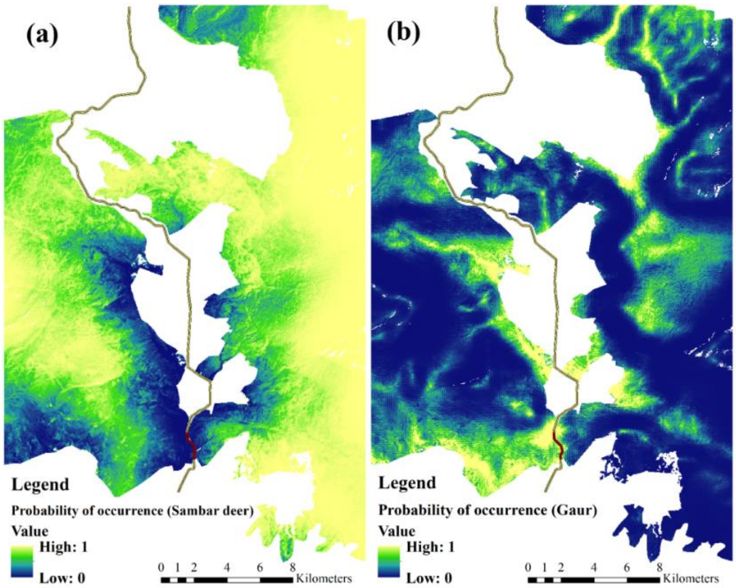

Figure 6. Habitat-suitability models showing the probability of occurrence (0-1) of (a) sambar deer; and (b) gaur.

4. CONCLUSION

We modeled the relationships of shrub biomass and grass biomass with NDVI to facilitate the use of Landsat 8 data for managing the area surrounding highway 304 in Thailand. The forage-crop models can be used to predict HSMs and elucidate the exploitation of sambar deer and gaur. This is critical for wildlife management. Sukmasuang et al. (2020) reported observations of sambar deer and gaur around the wildlife corridor of highway 304 taken with camera traps. Thus, future studies of forage crops could include temporal variations in NDVI at locations where these ungulates have been observed and elucidate disturbance variables affecting the willingness of sambar deer and gaur to cross the forest boundary. Improved management of forage crops and tiger prey species may help tigers from Thap Lan National Park translocate to Khao Yai National Park via the highway 304 wildlife corridor 304.

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REFERENCES

Akaike H. Information Theory and an Extension of the Maximum Likelihood Principle. Selected Papers of Hirotugu Akaike. New York, USA: Springer; 1998.

Ash E, Kaszta Ż, Noochdumrong A, Redford T, Chanteap P, Hallam C, et al. Opportunity for Thailand's forgotten tigers: Assessment of the Indochinese tiger *Panthera tigris corbetti* and its prey with camera-trap surveys. Oryx 2020;27:1-8.

Bitomský M, Mládková P, Cimalová Š, Mládek J. Herbaceous climbers in herbaceous systems are shade-tolerant and magnesium-demanding. Journal of Vegetation Science 2019; 30(5):799-808.

Borowik T, Pettorelli N, Sönnichsen L, Jędrzejewska B. Normalized difference vegetation index (NDVI) as a predictor of forage availability for ungulates in forest and field habitats. European Journal of Wildlife Research 2013;59(5):675-82.

Brotons L, Thuiller W, Araújo MB, Hirzel AH. Presence-absence versus presence-only modelling methods for predicting bird habitat suitability. Ecography 2004;27(4):437-48.

Cappai MG, Aboling S. Toxic or harmful components of aromatic plants in animal nutrition. In: Feed Additives. Massachusetts, USA: Academic Press; 2020.

Clark DB, Hurtado J, Saatchi SS. Tropical rain forest structure, tree growth and dynamics along a 2700-m elevational transect in Costa Rica. PloS One 2015;10(4):e0122905.

Cordova FJ, Wallace JD, editors. Nutritive value of some browse and forb species. Proceedings of the Western Section, American Society of Animal Science; 1975 July 26-30; Colorado, USA: Fort Collins: Colorado State University; p. 1975.

Cushman SA, McGarigal K. Hierarchical, multi-scale decom-position of species-environment relationships. Land-scape Ecology 2002;17(7):637-46.

Department of National Park and Wildlife and Plant Conservation (DNP). Practical plan to improve tiger population 2015-2035 (20 Years). Bangkok, Thailand: Ministry of Natural Resources and Environment, Royal Government of Thailand; 2016.

De las Heras MM, Díaz-Sierra R, Turnbull L, Wainwright J. Assessing vegetation structure and ANPP dynamics in a grassland-shrubland Chihuahuan ecotone using NDVI-rainfall relationships. Biogeosciences Discussions 2015;12(1):51-92.

Duangchatrasiri S, Jornburom P, Jinamoy S, Pattanvibool A, Hines JE, Arnold TW, et al. Impact of prey occupancy and other ecological and anthropogenic factors on tiger distribution in Thailand's western forest complex. Ecology and Evolution 2019;9(5):2449-58.

Duckworth JW, Sankar K, Williams AC, Kumar NS, Timmins RJ. Bos gaurus the IUCN red list of threatened species 2016 [Internet]. 2016 [cited 2020 Aug 12]. Available from: https://www.iucnredlist.org/species/2891/46363646.

Engler R, Guisan A, Rechsteiner L. An improved approach for predicting the distribution of rare and endangered species from occurrence and pseudo-absence data. Journal of Applied Ecology 2004;41(2):263-74.

Ensslin A, Rutten G, Pommer U, Zimmermann R, Hemp A, Fischer M. Effects of elevation and land use on the biomass of trees, shrubs and herbs at Mount Kilimanjaro. Ecosphere 2015;6(3):1-5.

Estrada-Peña A, Venzal JM, Sánchez Acedo C. The tick Ixodes ricinus: Distribution and climate preferences in the western Palaearctic. Medical and Veterinary Entomology 2006; 20(2):189-97.

Grinnell J. Field tests of theories concerning distributional control. The American Naturalist 1917;51(602):115-28.

Guisan A, Zimmermann NE. Predictive habitat distribution models in ecology. Ecological Modelling 2000;135(2-3):147-86.

Hirzel AH, Helfer V, Metral F. Assessing habitat-suitability models with a virtual species. Ecological Modelling 2001;145(2-3):111-21.

Holechek JL. Comparative contribution of grasses, forbs, and shrubs to the nutrition of range ungulates. Rangelands Archives 1984;6(6):261-3.

Jornburom P, Duangchantrasiri S, Jinamoy S, Pattanavibool A, Hines JE, Arnold TW, et al. Habitat use by tiger prey in Thailand's Western Forest Complex: What will it take to fill a half-full tiger landscape? Journal for Nature Conservation 2020:125896.

Kushwaha SP, Khan A, Habib B, Quadri A, Singh A. Evaluation of sambar and muntjak habitats using geostatistical modelling. Current Science 2004:1390-400.

Lamont BG, Monteith KL, Merkle JA, Mong TW, Albeke SE, Hayes MM, et al. Multi-scale habitat selection of elk in response to beetle-killed forest. Journal of Wildlife Management 2019;83(3):679-93.

Linkie M, Chapron G, Martyr DJ, Holden J, Leader-Williams NI. Assessing the viability of tiger subpopulations in a fragmented landscape. Journal of Applied Ecology 2006;43(3):576-86.

Lynam AJ, Tantipisanuh N, Chutipong W, Ngoprasert D, Baker MC, Cutter P, et al. Comparative sensitivity to environmental variation and human disturbance of Asian tapirs (*Tapirus indicus*) and other wild ungulates in Thailand. Integrative Zoology 2012;7(4):389-99.

Masters NJ, Flach E. Chapter 62 - Tragulidae, Moschidae, and Cervidae. In: Miller RE, Fowler ME, editors. Fowler's Zoo and Wild Animal Medicine. 1st ed. St. Louis, USA: Saunders; 2015. p. 611-25.

McCullagh P, Nelder J. Generalized Linear Models. 2nd ed. London, UK: Chapman and Hall; 1989.

Mongkhonsin B, Nakbanpote W, Meesungnoen O, Prasad MN. Adaptive and tolerance mechanisms in herbaceous plants exposed to cadmium. In: Cadmium Toxicity and Tolerance in Plants: From Physiology to Remediation. Amsterdam, USA: Elsevier; 2019.

O'Brien TG, Kinnaird MF, Wibisono HT. Crouching tigers, hidden prey: Sumatran tiger and prey populations in a tropical forest landscape. Animal Conservation 2003;6(2):131-9.

Pattanakiat S. Vegetation Pattern and Soil Relationship in a Tropical Grassland of Khao Yai National Park. Bangkok, Thailand: Kasetsart University; 1988.

Phillips SJ, Anderson RP, Schapire RE. Maximum entropy modeling of species geographic distributions. Ecological Modelling 2006;190(3-4):231-59.

R Core Team. R: A language and environment for statistical computing, R Foundation for Statistical Computing. Vienna, Austria; 2017.

Sachot S, Perrin N, Neet C. Winter habitat selection by two sympatric forest grouse in western Switzerland: implications for conservation. Biological Conservation 2003;112(3):373-82.

Schadt S, Revilla E, Wiegand T, Knauer F, Kaczensky P, Breitenmoser U, et al. Assessing the suitability of central European landscapes for the reintroduction of *Eurasian lynx*. Journal of Applied Ecology 2002;39(2):189-203.

Seoane J, Bustamante J, Dıaz-Delgado R. Competing roles for landscape, vegetation, topography, and climate in predictive models of bird distribution. Ecological Modelling 2004; 171(3):209-22.

Simcharoen A, Savini T, Gale GA, Roche E, Chimchome V, Smith JL. Ecological factors that influence sambar (*Rusa unicolor*) distribution and abundance in western Thailand: Implications for tiger conservation. Raffles bulletin of Zoology 2014;62:100-6.

Simcharoen A, Simcharoen S, Duangchantrasiri S, Bump J, Smith JL. Tiger and leopard diets in western Thailand: Evidence for overlap and potential consequences. Food Webs 2018; 15:e00085.

Smith AT, Xie Y, Hoffmann RS, Lunde D, MacKinnon J, Wilson DE, et al. A Guide to the Mammals of China. Princeton University Press; 2010.

Sukmasuang R, Charaspet K, Panganta T, Pla-ard M, Khioesree N, Thongbanthum J. Diversity, abundance, activity period, and factors affecting the appearance of wildlife around the corridors between Khao Yai-Thap Lan National Parks, Thailand by camera trapping. Biodiversitas Journal of Biological Diversity 2020;21(5):2310-21.

Venables WN, Ripley BD. Modern Applied Statistics with S. 4th ed. New York, USA: Springer; 2002.

Widenfalk O, Weslien J. Plant species richness in managed boreal forests-Effects of stand succession and thinning. Forest Ecology and Management 2009;257(5):1386-94.

Estimation of Nitrogen Loading to Surface Water from Agriculture Based Area and Its Application for Water Pollution Mitigation

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ABSTRACT

Eutrophication of surface water is a globally widespread environmental problem. Similarly, in Thailand, the Nakhon Nayok River (NNR), located in an agriculture-based area, has been markedly affected by eutrophication problems. However, there are limited studies on significant nitrogen (N) sources during agricultural activities in the area. Therefore, this study examined the major sources and key flows of N loading to the surface water by applying material flow analysis (MFA) to the relevant seven subsystems in 2018. The results showed that aquaculture and rice cultivation were the main sources of nitrogen inputs and outputs. Both considerably contributed to the nitrogen loading to the surface water, yet nitrogen released from the aquaculture was five times higher than the rice cultivation. The nitrogen flux found in the study area was 0.11 kg/ha. Accordingly, creating wetlands for aquaculture wastewater treatment that could potentially remove nitrogen by 12% was recommended.

1. INTRODUCTION

Eutrophication is a global problem (WHO and EC, 2002; Smith and Schindler, 2009). Agriculture was reported to have significantly accelerated eutrophication (FAO and IWMI, 2017). For example, fertilizer application doubled the level of global nitrogen fixation (Vitousek et al., 1997) and the excess N from land flowing to surface water can promote algal blooms that affect surface water quality due to hypoxia (oxygen depletion) (Chislock et al., 2013). Drinking water produced from the water contaminated with toxins released from some algae is a risk to human health (WHO and EC, 2002).

There were 34 occurrences of eutrophication reported in the Gulf of Thailand in 2008-2009 (Marine Knowledge Hub, 2020). In 2016, eutrophication killed plenty of fish (MCRC, 2020) and impacted the economy especially for tourism and aquaculture. The NNR basin is in the agriculture-based area and empties into the Bang Pakong River Basin connected to the Gulf of Thailand. The use of N as the eutrophication indicator in the river, suggested by Yang et al. (2008), disclosed that the NNR had a high risk of eutrophication because total N concentration exceeded 300 μg/L (Kammuang, 2010; REO7, 2020). Additionally, the ammonia and nitrite concentrations in groundwater in Nakhon Nayok were greater than the standard (DGR, 2006). Although the nitrate concentration (34 mg/L) was allowable by the drinking water standard, this value higher than 27.4 mg/L in Wisconsin where the blue baby syndrome occurred (Knobeloch and Anderson, 2000).

In Thailand, point source pollutants such as industrial wastewater are controlled by regulations (e.g., MNRE, 2016); however, the wastewater standard does not focus on total nitrogen pollution. On the other hand, non-point sources possibly caused by the leaching and runoff of nutrients from soil in agricultural area are more difficult to control. Several complaints indicated that water pollution in the NNR basin is from agricultural wastewater such as pig farming (TPBS, 2017), rice field (DOF, 2019), and duck farming (NPLO, 2020). Hence, the NNR water quality has been classified as deteriorated especially in the agricultural and municipal area (REO7, 2017; REO7, 2020).

Using MFA could help provide comprehensive information about sources, flows, and sinks of N (Brunner and Rechberger, 2004). Several studies agreed that MFA is a powerful tool for nutrient

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management in the watershed (Schaffner et al., 2011; Kupkanchanakul et al., 2015; Alvarez et al., 2018; Ta et al., 2018). MFA results can be used to support environmental protection (Wang et al., 2015), to recognize environmental problems early (Elshkaki and Graedel, 2013), and to establish priority for environmental measures (Kwonpongsagoon et al., 2007; Schaffner et al., 2009; Wongsoonthornchai et al., 2016). Thus, MFA was chosen to investigate the N flows in the NNR basin. The objectives of this study were to indicate the significant sources of N; to estimate the N loading to surface water; and to suggest the mitigation for N management.

2. METHODOLOGY

Material flow analysis (MFA), a systematic model based on the law of mass conservation, was applied in this study to estimate the flows and stocks of nitrogen through products and processes in the NNR basin. This study focuses on nitrogen emissions especially N loading to the surface water and recommendations to decrease the excess nitrogen loading.

2.1 System analysis

2.1.1 Study area

The NNR Basin, located in Nakhon Nayok Province, Central Thailand, covers 212,200 ha with hills in the north and flat toward the south. The land is mainly used for agriculture extending over 54% of the total area, with rice fields occupying 72% of the total agricultural area. The basin is also taken up by roughly 30% forest, 9% community and industrial area, and 7% other areas (water body, grass land, shrub land, and soil pit) (LDD, 2018) (Figure 1).

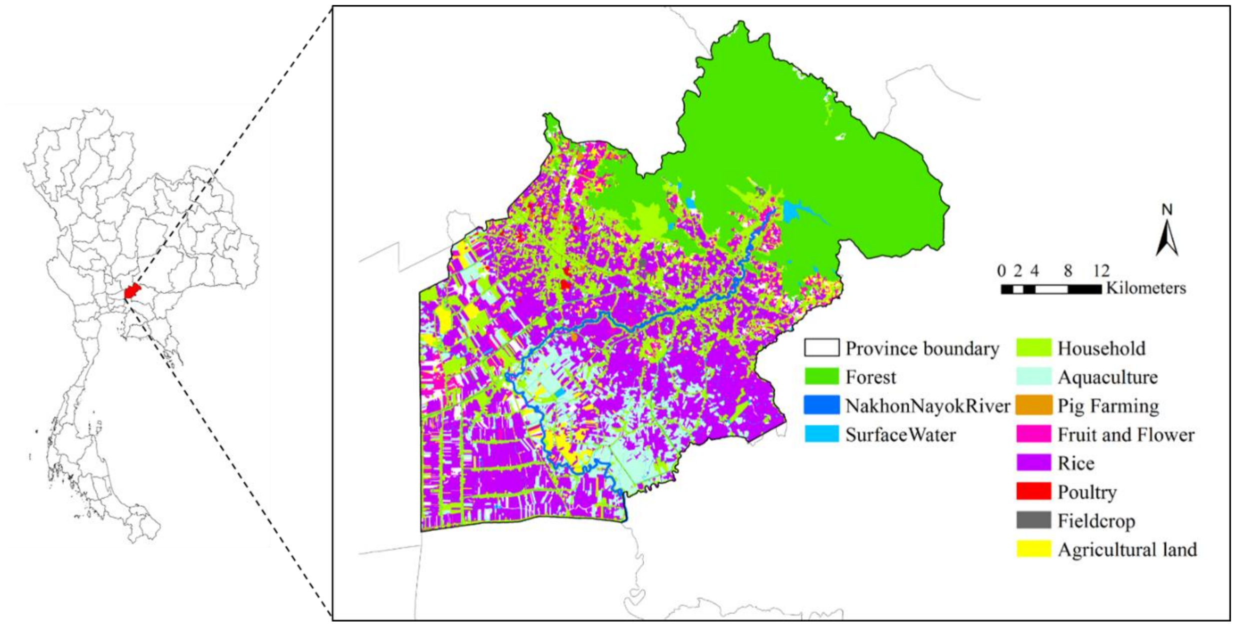

Figure 1. System boundary and land use of the Nakhon Nayok River Basin

The Nakhon Nayok River, the main river in this sub basin, is known as a tourist attraction. The NNR is also an important water source of local people for consumption and recreation. Nevertheless, it has been reported to have the high concentration of N compounds which can lead to eutrophication (Figure 2).

2.1.2 System boundary

The geographic area of this study is the NNR Basin and the data used for estimating N flows were collected in 2018. The seven subsystems were studied based on the MFA methods. The subsystems included (1) rice cultivation; (2) pig farming; (3) aquaculture; (4) poultry farming; (5) field crop cultivation; (6) fruit and flower farming; and (7) households (Figure 2). The N inputs flowing into the rice system included fertilizer ($I_{fert}^{(N)}$), rain ($I_{rain}^{(N)}$), fixation ($I_{fix}^{(N)}$), and water irrigation ($I_{irri}^{(N)}$). The outflows were emission ($O_{emiss}^{(N)}$), rice yield ($O_{yield}^{(N)}$), and drainage ($O_{drain}^{(N)}$) as shown in Figure 3.

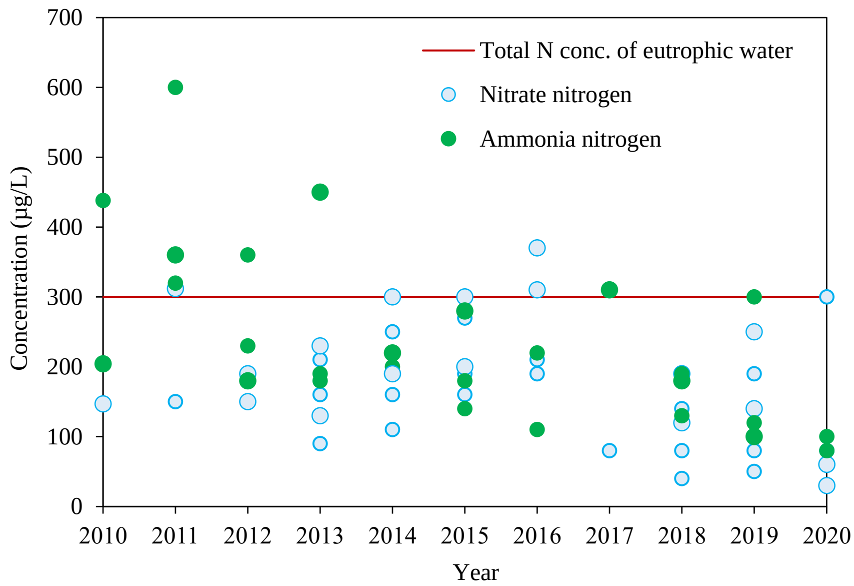

Figure 2. The temporal nitrate nitrogen and ammonia nitrogen in Nakhon Nayok River Basin during 2010-2020 (REO7, 2020).

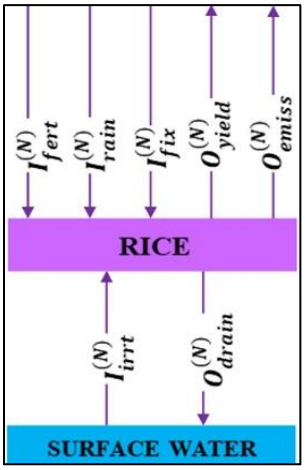

Figure 3. The system analysis of nitrogen flows through the rice system in the Nakhon Nayok River Basin

2.2 Model Approach

The Model approach of this study consists of a general model and specific models based on the mass balance principle. The general model of mass balance is in Equation (1):

$$\sum_{i=1}^{n} m_{input} = \sum_{i=1}^{n} m_{output} + m_{storage} \quad (1)$$

Where; $\sum_{i=1}^{n} m_{input}$ indicates the sum of all inputs for process i, and $\sum_{i=1}^{n} m_{output}$ is the sum of all outputs for process i. Parameter "m" is the mass flow in a system, and n is the number of processes.

Most specific models of N flows for each subsystem were adopted from Schaffner (2007). To calculate the inflows and outflows of N, the equations and the values of rice cultivation are shown as an example in Table 1 and Table 2, respectively. Scenario analysis was the final step to establish the recommendations based on the key flows of N loading and possibilities in the area.

Table 1. Equations for calculation of nitrogen input through rice cultivation

Variables	Definition	Value	Unit	Reference
Input	$\sum \text{input}_{\text{rice}}^{(N)} = I_{\text{fert}}^{(N)} + I_{\text{rain}}^{(N)} + I_{\text{irrg}}^{(N)} + I_{\text{fix}}^{(N)}$			
Fertilizer	$I_{\text{fert}}^{(N)} = P_{\text{freq}} \cdot P_{\text{area}} \cdot P_{\text{i\_fert}} \cdot C_{\text{i\_fert}}^{(N)}$			
P_{freq}	Frequency of rice cultivation	2	crop/year	This study
P_{area}	Rice area	81,854	ha	LDD (2018)
P_{i_fert}				
- 16-20-0	NPK fertilizer	187.29	kg/ha-crop	This study
- 46-0-0	Urea fertilizer	102.11	kg/ha-crop	This study

Table 1. Equations for calculation of nitrogen input through rice cultivation (cont.)

Variables	Definition	Value	Unit	Reference
$C^{(N)}_{i\_fert}$				
- 16-20-0	N concentration in NPK	160	mg/kg	Schaffner (2007)
- 46-0-0	N concentration in urea	460	mg/kg	
Rainfall	$I^{(N)}_{rain} = P_{rain} \cdot P_{area} \cdot C^{(N)}_{rain}$			
P_{rain}	Rainfall	1,692.9	mm/year	RIHC (2020)
$C^{(N)}_{rain}$	N concentration in rain	3	mg/L	Schaffner (2007)
Irrigation	$I^{(N)}_{irrg} = [M_{evp} + M_{drain} + M_{per} - M_{efr}] \cdot C^{(N)}_{NR}$			
M_{evp}	$M_{evp} = P_{freq} \cdot P_{area} \cdot P_{evap} \cdot 10000$			
M_{dra}	$M_{drain} = (P_{Land} + P_{depth}) \cdot P_{freq} \cdot P_{area} \cdot k_{drain}$			
M_{per}	$M_{per} = P_{perc} \cdot P_{area} \cdot 365$			
M_{efr}	$M_{efr} = (1 - k_{roff}) \cdot P_{area} \cdot P_{rain}$			
P_{evap}	Evapotranspiration	575	mm/crop	DOED (1992)
P_{Land}	Water for land preparation	275	mm/crop	RID (2016)
P_{depth}	Water depth rice	150	mm/crop	Schaffner (2007); DOED (1992)
P_{perc}	Percolation	1	mm/day	Schaffner (2007)
P_{water}	Total water requirement	1,000	mm	DOR (2020)
k_{drain}	TF drain with field water	0.5	-	Schaffner (2007)
k_{roff}	TF rainfall to runoff	0.43	-	
$C^{(N)}_{NR}$	N concentration in water	0.32	mg/L	This study
Fixation	$I^{(N)}_{fix} = P_{area} \cdot P_{freq} \cdot C^{(N)}_{fix}$			
$C^{(N)}_{fix}$	N fixation by rice	5	kg/ha-crop	Schaffner (2007)

Table 2. Equations for calculation of nitrogen output from rice cultivation

Variables	Definition	Value	Unit	Reference
Output	$\sum output = O^{(N)}_{yield} + O^{(N)}_{NR} + O^{(N)}_{emis}$			
Yield	$O^{(N)}_{yield} = P_{freq} \cdot P_{area} \cdot P_{yield} \cdot C^{(N)}_{yield}$			
P_{yield}	Grain yield	5,000	kg/ha-crop	This study
$C^{(N)}_{yield}$	N concentration in grain yield	12	g/kg	Schaffner (2007)
To River	$O^{(N)}_{NR} = O^{(N)}_{roff} + O^{(N)}_{drain}$			
$O^{(N)}_{roff}$	$O^{(N)}_{roff} = k^{(N)}_{roff} \cdot I^{(N)}_{fert}$			
$O^{(N)}_{drain}$	$O^{(N)}_{drain} = k_{drain} \cdot k^{(N)}_{drain} \cdot O^{(N)}_{surplus}$			
$O^{(N)}_{surplus}$	$O^{(N)}_{serplus} = \sum input^{(N)}_{rice} - O^{(N)}_{yield} - M^{(N)}_{residual} + M^{(N)}_{ash}$			
$M^{(N)}_{residual}$	$M^{(N)}_{residual} = M_{rice} \times P_{res} \times P^{(N)}_{res}$			
$M^{(N)}_{ash}$	$M^{(N)}_{ash} = \left(1 - k^{(N)}_{burn}\right) \times k_{burn} \times M^{(N)}_{residual}$			
k_{drain}	TF drain with field water	0.5	-	Schaffner (2007)
$k^{(N)}_{drain}$	TF N surplus drain	0.65	-	
P_{res}	Crop residual rice	4,062.5	kg/ha-crop	Lertkrai (n.d.)
$P^{(N)}_{res}$	N concentration in crop residual rice	5.38	g/kg	
$k^{(N)}_{runoff}$	TF N runoff	0.1	-	Schaffner (2007)
Emission	$O^{(N)}_{Emis} = I^{(N)}_{input} \cdot k^{(N)}_{emis}$			
$k^{(N)}_{emis}$	TF of N emission	0.0117	t N_2O-N/t N	USEPA (1995)

2.3 Data acquisition and calibration

There are two types of data in this study: primary and secondary. For the primary data, systematic random sampling was applied to collect water samples from 15 points with different land uses along the NNR. The water samples were obtained from mid-river, stored at 4°C, and returned to the laboratory immediately. Then, TKN, nitrite nitrogen, and nitrate nitrogen were analyzed using APHA section 4500-Ammonia, 4500-NO_2-B, and 4500-NO_3-B, respectively. Furthermore, the primary data also included interviews with 40 farmers on the patterns and frequency of cultivation, types, frequency, and fertilizer application. The data were analyzed by arithmetic mean ($\overline{X}$) as shown in Equation (2):

$$\overline{X} = \frac{\sum_{i=1}^{n} x_i}{n} \quad (2)$$

Where; n is the total number of observations in the data set and x_i represents the observation value.

The secondary data were divided into three groups: (1) the general data such as rainfall and land use were derived from national statistics; (2) the specific data for the subsystems (e.g., rice area, and rice yield) were collected from the government sector and literature; and (3) transfer coefficients (TF) were obtained from Schaffner (2007). The specific data collected in the study area by the local government sector were prioritized in this study.

For calibration, the quantitative data were crosschecked with other sources. For example, the rice area data from the Land Development Department (LDD, 2018) were identical to the data from the Nakhon Nayok Statistical Office (NNSO, 2019). In addition, the uncertainty intervals of the information sources were determined (Danius, 2002) for data quality. The uncertainty range of the data in this study was between 10% and 40% which presented moderately because the data can be variated up to 80% when determining by expert judgement (Zoboli et al., 2016).

3. RESULTS AND DISCUSSION

3.1 Nitrogen flow

The flows of nitrogen through the NNR basin in 2018 were illustrated in Figure 4. The total input and output of nitrogen were approximately 54,542 tons/year and 41,232 tons/year, respectively. The system storage calculated from the difference between the total input and output was 13,310 tons/year. Aquaculture (36%) and rice cultivation (33%) were the major sources of N inputs, followed by poultry farming (21%). The main sources of N outputs were also aquaculture (44%) and rice cultivation (32%).

Aquaculture was the predominant source of N flows despite not being the main type of land use in the NNR basin. About 99% of its N inputs were from the feeds containing N needed for fish and shrimp growth. The catfish feed was the largest N input with around 550 tons/ha, about 1.5 times higher than the snakehead fish feed. For the shrimp, the main N input was the water due to the large farming area. Moreover, catfish farming was also the main source of N outputs (68%), with 90% of its N inputs discharged to the river. The low level of N recovered in catfish (approximately 14%) could be the reason (Worsham, 1975).

Rice cultivation was the second-largest source of N inputs and outputs in the basin. Although the fertilizer application was lower than the average at 209-350 kgN/ha/crop in China (Sui et al., 2013; Chen et al., 2014; Ding et al., 2020), the fertilizer was still the largest N input responsible for nearly 70% of the total N input of the subsystem. Additionally, The N input from the rain was 12 times higher than the irrigation ascribable to the higher nitrogen concentration in the rain than in the river; both sources contributed around 23% of the total N input. Regarding N outputs, about 74% of N was discharged from the system with yield while roughly 24% to the NNR.

Pig and poultry farming were the third and the fourth largest sources of N inputs in the basin. Almost 100% of N flowed into both systems via the feeds. Pig farming is a minor contributor of N loading to the surface water due to Thailand's regulation for wastewater from pig farming. However, pig farming played an important role in N emission as N_2O was present during the composition, aerobic and anaerobic treatments of pig slurry and dung.

The NNR basin is also famous for flower planting. For the fruit and flower subsystems, fertilizer was the main N input, contributing to 98% of the total N input. While 68% of N flowed out the subsystems with yield, about 5% went to the river through runoff and leaching processes.

Nitrogen flowing into household subsystem was 98.7% via food and 1.3% via water. In terms of on-site wastewater treatment plants, most households in the NNR basin had either a septic tank or cesspool. Nevertheless, some households directly discharged the greywater into the river; consequently, nitrogen flowed out with the wastewater and solid waste was around 727 tons/year and 237 tons/year, respectively.

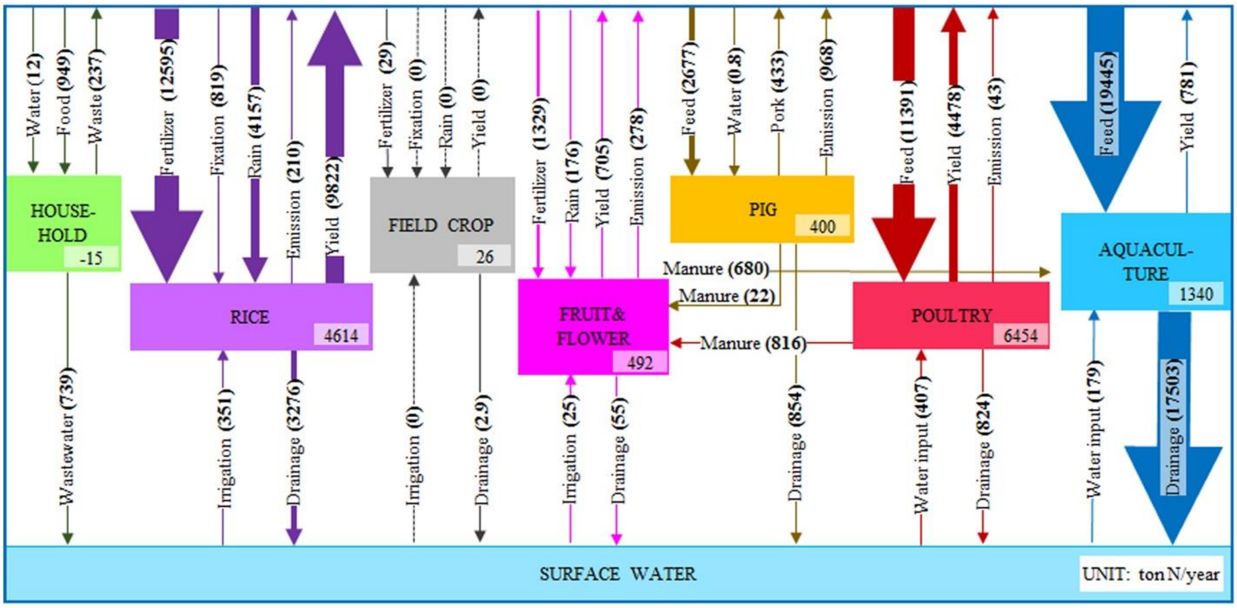

Figure 4. Nitrogen flows through the rice system in Nakhon Nayok River Basin, 2018

3.2 Nitrogen loading to the surface water

Around 23,254 tons/year of N or 42% of N inputs reached the surface water. Aquaculture was responsible for 17,503 tons/year of N discharge, which was five times higher than that of the rice system. The ratio of N loading to the NNR to the N input of aquaculture was about 0.89 being in the same range of 0.73 to 0.86 reported by Lazzari and Baldisserotto (2008). The poultry subsystem had the highest storage (48%); consequently, its ratio of N loading to N input (0.07) was lower than that of the rice system (0.18) (Figure 5).

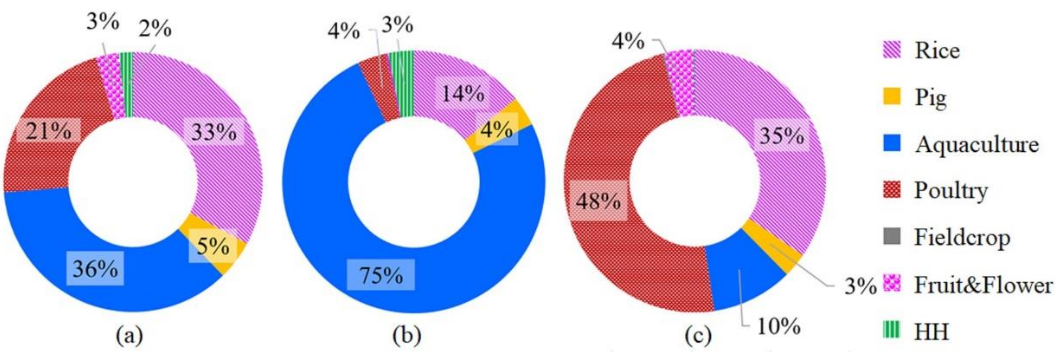

Figure 5. Proportion of nitrogen flows from each subsystem in Nakhon Nayok River Basin (a) nitrogen input; (b) nitrogen loading to NNR; and (c) nitrogen storage

As presented in Table 3, aquaculture and rice cultivation were the key flows of N discharged to the NNR, Thachin, and Lower Bang Pakong, except for the Maeklong River Basin (Schaffner, 2007; Tipsaeng, 2014; Pharino et al., 2016). The nitrogen flux of the NNR basin was roughly 2-3 times higher than other areas; however, it was comparable to the non-forest area of the Meklong River Basin. The possibility was that despite being the smallest area among the others, as discussed in section 3.1, the NNR Basin received N mostly from three times more catfish farms existing in the area than in the Thachin River Basin.

3.3 Scenario analysis

There were five recommendations for reducing N loading from aquaculture, rice cultivation, and households. The details for each scenario were described below.

Scenario 1: Implementation of wastewater treatment for aquaculture

The wetland system was recommended for aquaculture due to the high removal efficiency of nitrogen. As pond systems are the most common aquacultural systems in Nakhon Nayok Province, accounting for approximately 99.89% (NNPFO, 2018), the wetland is an alternative system that can be applied for wastewater management. Lin et al. (2002) reported the average nitrogen removal efficiencies of 86% to 98% for ammonia, >99% for nitrite nitrogen, 82% to 99% for nitrate nitrogen, and 95% to 98% for the total inorganic nitrogen. Considering aquaculture wastewater law (MNRE, 2008), big farms (larger than 1.6 ha) are obliged to control N concentration. Although aquacultural farms in Nakhon Nayok are small with the average area of 1.34 ha (NNPFO, 2018), wastewater treatment should be implemented for at least 5% in each district to control N pollution. This scenario also suggested that 20% of the recent aquacultural farming area should have been wetland for aquaculture wastewater treatment.

Table 3. The key flows of nitrogen input through the river basins in Thailand

River Basin	Nitrogen loading to surface water (ton/year)	Nitrogen flux		Key flow of N discharge	Reference
		(ton/ha)	(ton/cap)		
Nakhon Nayok	23,254	0.11	0.09	Aquaculture Rice	This study
Thachin	45,036	0.05	0.02	Aquaculture Rice	Schaffner et al. (2007)
Lower Bangpakong	15,001	0.03	0.02	Aquaculture Rice	Tipsaeng (2014)
Meklong	25,911	0.04	0.03	Household Industry	Pharino et al. (2016)

Scenario 2: Reduction of 10% of catfish culture

Schaffner (2007) suggested that reduction of catfish culture could decrease the largest amount of N discharge; however, it can be difficult to implement since catfish is the economic fish in the area. Therefore, reducing only 10% of the catfish farming was instead recommended.

Scenario 3: Reduction of fertilizer use in rice cultivation during the rainy season

The results from MFA showed that fertilizer was the main cause of the excessive N discharged from rice cultivation. The survey results also revealed that the fertilizer application in the rice system were higher than the recommended rates by the Thai Department of Rice at 125-156 kg/ha/crop for NPK fertilizer and 31-63 kg/ha/crop for urea fertilizer (DOR, 2020). Therefore, reducing fertilizer application in the rainy season was encouraged.

Scenario 4: Reduction of fertilizer application in rice cultivation during both rainy and dry seasons

Even though the NPK fertilizer application in dry season was in between the recommended range at 156-219 kg/ha/crop, the urea fertilizer application was higher than recommended at 63-94 kg/ha/crop (DOR, 2020). Thus, this scenario suggested reducing the fertilizer application in rice system during both rainy and dry seasons.

Scenario 5: Construction of a centralized municipal wastewater treatment plant

The construction of a centralized municipal wastewater treatment plant was recommended for Nakhon Nayok Province. The activated sludge (AS) wastewater treatment plant could remove about 67% of the nitrogen from wastewater (Hsu, 1998).

Table 4 displays the scenario analysis from the assumptions in MFA. The five scenarios showed that construction of wetland on 20% of the recent aquacultural area could successfully remove 2,800 tons/year of the N loading. The reduction of only 10% of catfish farming can also lower the amount of N released to the river by 1,754 tons/year. The reduction of fertilizer application during rainy and dry seasons also cuts N loading to the surface water by approximately 753-2,285 tons/year. Lastly, the construction of a centralized wastewater treatment plant in the area helps decrease the N discharge around 500 tons/year. To further reduce N loading, Nakhon Nayok province should promote the wetland for aquaculture and suggest the farmers to reduce their fertilizer application in rainy and dry seasons.

Table 4. The scenario analysis and the potential reduction

No.	Scenario	N (ton/year)	Potential reduction
0	Current situation	23,254	-
1	Implementation of wastewater treatment from aquaculture	20,454	12.0%
2	Reduction of 10% of catfish farming	21,500	7.5%
3	Reduction of fertilizer use in rainy season	22,578-21,606	3.0-7.0%
4	Reduction of fertilizer use in rainy season and dry season	20,969-22,501	3.2-10%
5	Construction of the central municipal wastewater treatment plant	22,754	2.2%

4. CONCLUSION

This research estimated the overall N flows and indicated the key flows of N loading causing the risk of euthrophication in the NNR Basin. Despite the limited data on the study area, MFA was able to provide the comprehensive flows of N loading to the NNR and to establish priorities for environmental measures. The total input and output of nitrogen in 2018 were approximately 54,542 tons/year and 41,232 tons/year, respectively. The NNR received around 23,254 tons/year of N from anthropogenic activities and aquaculture was identified as the main source and key flows of N pollution. Thus, the reduction of 10% of catfish farming was prioritized to decrease the risk of eutrophication in the NNR Basin.

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REFERENCES

Alvarez J, Roca M, Valderrama C, Cortina JL. A phosphorous analysis in Spain. Science of the Total Environment 2018; 612:995-1006.

Brunner PH, Rechberger H. Practical Handbook of Material Flow Analysis. Florida, USA: Lewis Publisher; 2004.

Chen X, Cui Z, Fan M, Vitousek P, Zhao M, Ma W, et al. Producing more grain with lower environmental costs. Nature 2014;514:486-9.

Chislock MF, Doster E, Zitomer RA, Wilson AE. Eutrophication: Causes, consequences, and controls in aquatic ecosystems. Nature Education Knowledge 2013;4(4):1-8.

Danius L. Data Uncertainties in Material Flow Analysis: Local Case Study and Literature Survey. Stockholm, Sweden: Royal Institute of Technology; 2002.

Department of Groundwater Resources (DGR). Water Analysis: The Study of Impact and Monitoring from Agricultural Waste that Effect to Groundwater and Mitigation Methods in Bang Pakong River Basin. Bangkok, Thailand: Ministry of Natural Resources and Environment; 2006 (in Thai).

Department of Energy Development (DOED). The Study of Energy Use Behavior and Pattern for Plant Cultivation. Bangkok, Thailand: Ministry of Science, Technology and Environment; 1992 (in Thai).

Department of Fishery (DOF). Investigation of water pollution complaint in Nakhon Nayok [Internet]. 2019 [cited 2021 Jan 15]. Available from: https://www4.fisheries.go.th/local/index.php/main/view_activities/16/64557 (in Thai).

Department of Rice (DOR). Rice knowledge bank: The use of fertilizer [Internet]. 2020 [cited 2020 Aug 25]. Available from: http://www.ricethailand.go.th (in Thai).

Ding W, He P, Zhang J, Liu Y, Xu X, Ullah S, et al. Optimizing rates and sources of nutrient input to mitigate nitrogen, phosphorus, and carbon losses from rice paddies. Journal of Cleaner Production 2020;256:1-13.

Elshkaki A, Graedel TE. Dynamic analysis of the global metals flows and stocks in electricity generation technologies. Journal of Cleaner Production 2013,59:260-73.

Food and Agriculture Organization of the United Nations (FAO) and International Water Management Institute (IWMI). Water Pollution from Agriculture: A Global Review. Rome, Italy: FAO; 2017.

Hsu T. Nutrient removal from municipal wastewater by activated sludge process. Journal of Environmental Science and Health 1998;33(6):1205-7.

Kammuang A. Methodological Approach Development of a Test Kit for Freshwater Eutrophication Monitoring: A Case Study of Pathumthani and Nakhonnayok Provinces [dissertation]. Thailand: Nida University; 2010.

Knobeloch L, Anderson H. Blue babies and nitrate-contaminated well water. Environmental Health Perspectives 2000; 108(7):675-8.

Kupkanchanakul W, Kwonpongsagoon S, Bader HP, Scheidegger R. Integrating spatial land use analysis and mathematical material flow analysis for nutrients management: A case study of the Bang Pakong River basin in Thailand. Environmental Management 2015;55:1022-35.

Kwonpongsagoon S, Bader HP, Scheidegger R. Modelling cadmium flows in Australia on the basis of a substance flow analysis. Clean Technologies and Environmental Policy 2007;9(4):313-23.

Land Development Department (LDD). GIS Database of Nakhon Nayok Province. Bangkok, Thailand: Ministry of Agriculture and Cooperatives; 2018.

Lazzari R, Baldisserotto B. Nitrogen and phosphorus waste in fish farming. Boletim do Instituto de Pesca Sao Paulo 2008; 34(4):591-600.

Lertkrai W. Nutrient Cycling and Increasing of Organic Matter from Crop Residual in Agricultural Land by Tillage. Bangkok, Thailand: Land Reform Area Development Bureau; n.d.

Lin YF, Jing SR, Lee DY, Wang TW. Nutrient removal from aquaculture wastewater using a constructed wetland system. Aquaculture 2002;209(1-4):169-84.

Marine and Coastal Resources Research and Development Center (MCRC). Salt-freshwater mixing zone in the Upper Gulf of Thailand [Internet]. 2020 [cited 2020 Oct 15]. Available from: https://dmcrth.dmcr.go.th/umcr/detail/1027/ (in Thai).

Marine Knowledge Hub. Red tide in Thailand [Internet]. 2020 [cited 2020 Aug 21]. Available from: http://www.mkh.in.th/index.php?option=com_content&view=article&id=321&Itemid=366&lang=en.

Ministry of Natural Resources and Environment (MNRE). Effluent Standard for Freshwater Aquaculture: Volume 125, Part 30. Thailand: Royal Government Gazette; 2008 (in Thai).

Ministry of Natural Resources and Environment (MNRE). Effluent Standard for Industry, Industrial Estate and Industrial Park: Volume 133, part 129. Thailand: Royal Government Gazette; 2016 (in Thai).

Nakhon Nayok Province Livestock Office (NPLO). Investigation of water pollution complaint in Nakhon Nayok [Internet]. 2020 [cited 2021 Jan 15]. Available from: http://pvlo-nky.dld.go.th/webnew/index.php/th/news-menu/livestock-news-menu/995-2020-01-31-02-33-17 (in Thai).

Nakhon Nayok Provincial Fishery Office (NNPFO). Freshwater Culture Household by Type of Culture, Production of Freshwater Aquaculture and District: 2018. Nakhon Nayok, Thailand: Ministry of Agriculture and Cooperatives; 2018.

Nakhon Nayok Statistical Office (NNSO). Rice Statistical Information. Nakhon Nayok, Thailand: Ministry of Digital Economy and Society; 2019 (in Thai).

Pharino C, Sailamai N, Kamphaengthong PL. Material flow analysis of nitrogen in Maeklong River Basin in Ratchaburi and Samut Songkhram Province, Thailand. Water Conservation Science and Engineering 2016;1:167-75.

Region Irrigation Hydrology Center (RIHC). Annual Rainfall in Nakhon Nayok. Bangkok, Thailand: Royal Irrigation Department; 2020 (in Thai).

Regional Environmental Office 7 (REO7) (Saraburi Province). Report of Surface Water Quality. Nonthaburi, Thailand: Permanent Secretary Natural Resources and Environment, Ministry of Natural Resources and Environment; 2017 (in Thai).

Regional Environmental Office 7 (REO7) (Saraburi Province). Water Quality Database. Nonthaburi, Thailand: Permanent Secretary Natural Resources and Environment, Ministry of Natural Resources and Environment; 2020 (in Thai).

Royal Irrigation Department (RID). The Estimation of Water for Rice Field Preparation in Irrigation Area. Bangkok, Thailand: Ministry of Agriculture and Cooperatives; 2016 (in Thai).

Schaffner M, Bader HP, Scheidegger R. Modeling non-point source pollution from rice farming in the Thachin River Basin. Environment Development and Sustainability 2011;13:403-22.

Schaffner M, Bader HP, Scheidegger R. Modeling the contribution of point sources and non-point sources to Thachin River water pollution. Science of the Total Environment 2009; 407(17):4902-15.

Schaffner M. Applying a Material Flow Analysis Model to Assess River Water Pollution and Mitigation Potentials: A Case-study in the Thachin River Basin, Central Thailand [dissertation]. Switzerland: Swiss Federal Institute of Aquatic Science and Technology; 2007.

Smith VH, Schindler DW. Eutrophication science: Where do we go from here? Trends in Ecology and Evolution 2009;24: 201-7.

Sui B, Feng X, Tiam G, Hu X, Shen Q, Guo S. Optimizing nitrogen supply increases rice yield and nitrogen use efficiency by regulating yield formation factors. Field Crops Research 2013;150:99-107.

Ta TT, Trinh DA, DO NT. Nitrogen flow assessment in rapidly urbanizing Hai Duong Province downstream of Cau River Basin, Vietnam. Journal of Material Cycles and Waste Management 2018;20:533-42.

Thai PBS (TPBS). Complaining of the wastewater from pig farming which has been occurred for 20 years [Internet]. 2017 [cited 2021 Jan 15]. Available from: https://news.thaipbs.or.th/content/263574 (in Thai).

Tipsaeng P. Mass Flow Analysis for Nitrogen in Lower Bangpakong River of Chachoengsao Province [dissertation]. Thailand: Chulalongkorn University; 2014.

United States Environmental Protection Agency (USEPA). AP 42: Fifth Edition, Volume I Chapter 14: Greenhouse Gas Biogenic Sources. USEPA; 1995.

Vitousek PM, Aber JD, Howarth RW, Likens GE, Matson PA, Schindler DW, et al. Human alteration of the global nitrogen cycle: Sources and consequences. Ecological Applications 1997;7:737-50.

Wang YS, Chen PC, Ma HW. Material flow analysis of phosphorus in Taiwan. Global Environmental Research 2015;19:27-33.

Wongsoonthornchai M, Kwonpongsagoon S, Scheidegger R. Modeling mercury flows in Thailand on the basis of mathematical material flow analysis. CLEAN - Soil, Air, Water 2016;44(1):16-24.

World Health Organization (WHO) and European Commission (EC). Eutrophication and Health. Luxembourg: Office for Official Publications of the European Communities; 2002.

Worsham RL. Nitrogen and phosphorus levels in water associated with a channel catfish (*Ictalurus punctatus*) feeding operation. Transactions of the American Fisheries Society 1975;104: 811-5.

Yang X, Wu X, Hao HL, He ZL. Mechanisms and assessment of water eutrophication. Journal of Zhejiang University SCIENCE B 2008;9(3):197-209.

Zoboli O, Laner D, Zessner M, Rechberger H. Added values of time series in material flow analysis: The Austrian phosphorus budget from 1990 to 2011. Journal of Industrial Ecology 2016;20(6):1334-48.

Factors Affecting the Prevalence of Fecal Pathogen Infections: Approaches for Health Risk Protection

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ABSTRACT

Septic tank sludge or fecal sludge (FS) is often discharged on public areas without any treatment, causing environmental and adverse public health effects. Millennium Development Goal 7c (MDG 7c) targets improved access to water and sanitation because 85% of the world's total FS is often discharged on public areas. Like other countries, Thailand faces fecal slugde management (FSM) problems leading to significant fecal pathogen infections, especially in the north and northeastern regions. This study assessed the effects of unsafely-managed FS on human health risks in two cities, Natan City and Tham Lod City in Thailand, that have relatively high liver fluke and diarrhea infections, and identified the factors relating to FSM practices that affect the prevalence of liver fluke and diarrhea infections due to FS. Specific measures were proposed in delivering integrated FSM solutions and health risk protection toward the Sustainable Development Goal No. 6 (SDG6) targets of safely managed sanitation and hygiene services. Based on data collected from these cities from February to May 2019, factors relating to FSM practices that affect the prevalence of liver fluke and diarrhea infections were identified and analysed using multiple regression analysis. Based on the findings, specific measures in delivering integrated FSM solutions and health risk protection toward the Sustainable Development Goals 6 (SDG 6) are proposed. Because no FS treatment facilities operate in Natan City and Tham Lod City, almost 100% of FS is discharged directly into open drains, resulting in diarrhea and liver fluke infections among local people. The findings identified the factors relating to FSM practices that affect the prevalence of liver fluke and diarrhea infections and proposed specific measures in delivering integrated FSM solutions and health risk protection, such as promoting education programmes, avoiding direct FS discharges into open drains and nearby streams, and providing innovative FSM technologies to eradicate fecal pathogen infections.

1. INTRODUCTION

Most cities in low and middle income countries face adverse public health effects due to inadequate fecal sludge management (FSM) practices. Despite the target of the Millennium Development Goals 7c (MDG 7c), which aims to improve access to water and sanitation by 2015, 85% of the world's total FS is directly discharged onto public areas without any treatment, causing environmental pollution and public health problems (Al-Mohammed et al., 2010; Yoshida et al., 2019). Unsafely-managed FS contains pathogens leading to significant fecal pathogen infections worldwide, especially among Southeast Asian nations such as Thailand, Myanmar and Cambodia. Previous studies by Taweesan et al. (2015) and Bisung et al. (2015) emphasized the inadequate FS collection and FS treatment facilities leading to the contamination of water resources and groundwater. A similar finding was confirmed by the World Health Organization and the United Nations International Children's Emergency Fund (2017) which stated that the prevalence of fecal pathogen infections by food- and water-borne transmitted helminths in Southeast Asian Nations has been found in areas of these

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countries characterized by poor sanitation and hygiene. Among food- and water-borne transmitted helminth infections, 127 million people in Asian Countries are infected with *Ascaris lumbricoides* of which 115 million are infected with *Trichuris trichiura* and more than 70 million have hookworm infections (Torgerson and Macpherson, 2011).

In Thailand, for example, statistics released in 2017 by the the Department of Disease Control revealed that almost 30,000 people die from liver fluke infections yearly, an average of 76 deaths daily. Although the Royal Thai Government has implemented various national health campaigns and improved public access to medical services which aim to reduce liver flukes, the decrease in the infection rate of helminth-led liver disease remains a huge challenge countrywide. One of the most common causes of helminth-led liver disease is a lack of safely-managed sanitation, particularly inadequate FS treatment and improper FSM, despite the fact that about 99% of the Thai population have been able to access improved drinking water and sanitation facilities in the last decade (World Health Organization and United Nations International Children's Emergency Fund, 2017).

Several studies have attempted to determine the factors which influence the prevalence of fecal pathogen infections, but the effects of unsafely-managed FS on human health risks such as liver fluke and diarrhea infections are commonly ignored (Bdir et al., 2010; Sripa et al., 2010; Dufour et al., 2012; Sithithaworn et al., 2012; Prasongwatana et al., 2013; Aggarwal et al., 2017; Freeman et al., 2017; Penakalapati et al., 2017; Wolf et al., 2019). Understanding the factors relating to FSM practices that affect fecal pathogen infections due to unsafely-managed FS is needed to improve the efficiency of the entire management system. These factors are further exacerbated by financial constraints and the limited awareness of the central government in spite of their declaration to comply with the Sustainable Development Goals (SDG) by 2030, including SDG 6, “Clean Water and Sanitation”. For example, urban and peri-urban areas of Cambodia employ on-site sanitation systems, i.e., cesspools or septic tanks, to treat toilet wastewater, but the FSM practices are poorly managed, causing fecal pathogen infections, e.g., diarrhea (Ferrer et al., 2012; United Nations World Water Assessment Programme, 2015).

Furthermore, due to inadequate FS collection and treatment, and lack of FS treatment facilities, most FS collected by unlicensed FS collection operators, is directly discharged in unsanitary ways leading to contaminated water resources and groundwater (Frenoux and Tsitsikalis, 2014). These findings were confirmed by Brown et al. (2013), who stated that one of the most common causes of diarrhea infections is a lack of safe sanitation and clean water. The aims of this study were: (i) to assess the effects of unsafely-managed FS on human health risks of two cities in Thailand that have relatively high liver fluke and diarrhea infections; (ii) to identify the factors relating to FSM practices that affect the prevalence of liver fluke and diarrhea infections due to unsafely-managed FS; and (iii) to propose specific measures in delivering integrated FSM solutions and health risk protection toward Sustainable Development Goal no. 6 (SDG6) targets for safely managed sanitation and hygiene services.

2. METHODOLOGY

2.1 Study areas

This study was conducted from February to May 2019 in two cities: Natan City in Sakon Nakhon Province, Northeastern Thailand, and Tham Lod City in Mae Hong Son Province, Northern Thailand, as shown in Figure 1. These cities had a high prevalence of liver fluke and diarrhea infections (>20%) during the period of 2013 to 2017, respectively (Department of Disease Control, 2017). These two study areas were selected using the Getis-Ord Gi* technique by considering the high prevalence rates of liver fluke and diarrhea infections. The Getis-Ord Gi* technique is a statistical technique used to identify hot spot areas by considering incident data, i.e., the number of liver fluke and diarrhea infections, while including selected impact attributes in the analysis. FSM data were collected from 300 households per city by field visits, questionnaire surveys and face-to-face interviews with key informants (such as vacuum truck staff, FS plant operators, local leaders, farmers and concerned households). The key informants who contributed to this study varied considerably: vacuum truck staff (3%); FS plant operators (3%); local leaders (10%); village health volunteer (8%); households (58%); and others (18%).

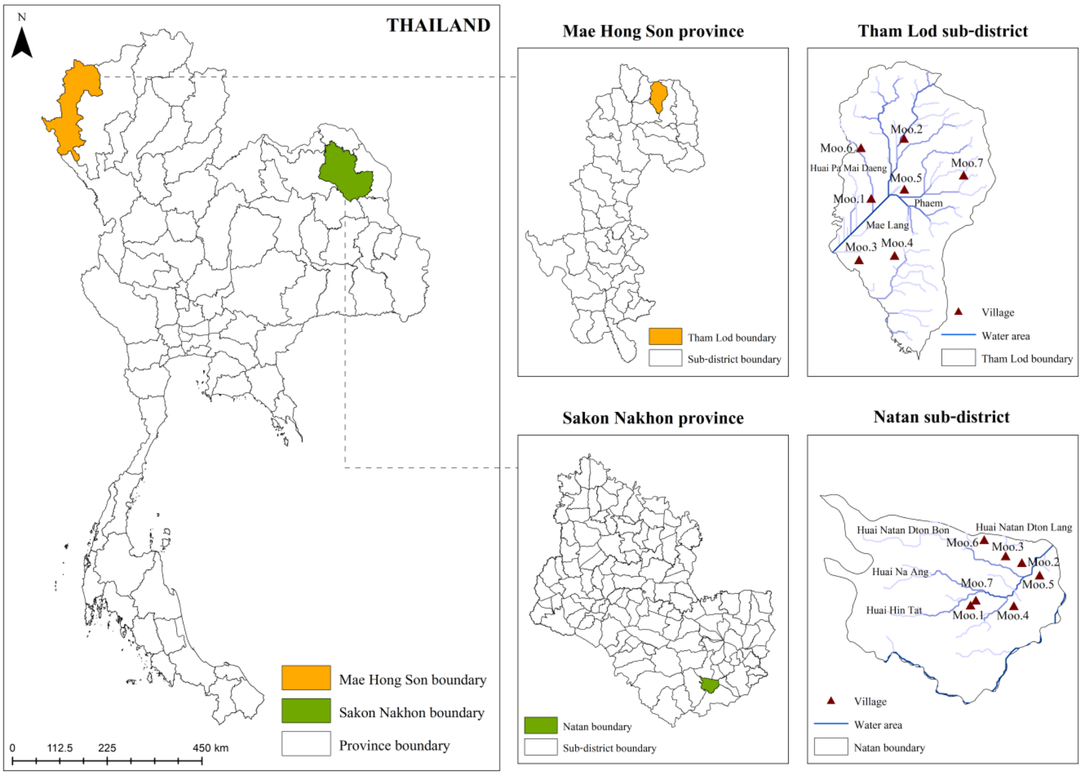

Figure 1. Study areas

2.2 Factor identification for data collection

At present, several factors affect the prevalence of liver fluke and diarrhea infections. Reviews of the relevant literature from various countries were conducted (Pham-Duc et al., 2011; Ferrer et al., 2012; Huong et al., 2014; Molla et al., 2014; Jeff et al., 2017). It was found that the significant factors included: (1) socio-demographic variables (sex, age, education level, income and occupation) of those who regularly have contact with FS (vacuum truck staff, FS plant operators and farmers); (2) personal hygiene (drinking water from natural resources, water supply from natural resources, consumption of treated water, raw or undercooked fish and washing hands before meals); (3) FSM practices (type of on-site sanitation systems, direct FS discharges into open drains, frequency of FS emptying and open defecation); and (4) knowledge of liver fluke and diarrhea infections and their relationships with FSM. The percentage of liver fluke and diarrhea infections were obtained from the official records of each village in these cities during the period of 2013 to 2017 (Department of Disease Control, 2017). In addition, the presence of liver fluke eggs in septic tanks, vacuum trucks, and FS treatment plants in Natan City was assessed in order to correlate the data on FSM practices in response to liver fluke infections.

2.3 Data analysis

Descriptive statistics, particularly percentage distribution, was applied for preliminary analyses and to present the effects of unsafely-managed FS on the prevalence of liver fluke infections in this study. For the cities considered to have unsafely-managed FS, the FS collected from households was directly discharged into open drains or nearby water resources. Cities were considered to have a “high” prevalence of infection rates when the prevalence of liver fluke and diarrhea infections was more than 20%, “moderate” when the prevalence infection rates were from 10 to 20% and “low” when the prevalence infection rates were less than 10% (Huong et al., 2014). Factors relating to FSM practices that affect the prevalence of liver fluke and diarrhea infections were identified using multiple regression analysis. Regression models were developed to describe the relationship between fecal pathogen infections and other important factors. Cronbach’s alpha was adopted to measure how the combined factors related to the extent of fecal pathogen infections in the range 0.80 to 0.85 which indicated a good correlation.

3. RESULTS AND DISCUSSION

3.1 Effects of unsafely-managed FS on human health risks

The effects of unsafely-managed FS on the prevalence of liver fluke infections are shown in Figure 2. It can be seen that all villages in Natan City were found to have a "high" prevalence of liver fluke infections (more than 20%). The results presented in Figure 2 indicate that unsafely-managed FS had significant direct effects on the prevalence of liver fluke infections (r=0.72). One of the most common causes of liver fluke infection was a lack of safely-managed FS, particularly inadequate FS treatment and improper FSM. A similar study was documented by the Department of Disease Control (2017), showing that although 99% of the Thai population have access to improved sanitation facilities, i.e., latrines, the decrease in the rate of liver fluke infections remains a huge challenge countrywide. Previous studies by Aggarwal et al. (2017) and Chudthaisong et al. (2015) reported that food-borne parasitic infections were correlated with a lack of FSM facilities and personal hygiene factors. Similar studies were documented by Lindahl et al. (2015), Grundy-Warr et al. (2012), and Yoshida et al. (2019) showing that the significance of direct contact with FS was found to be an influential factor on the prevalence of liver fluke infections.

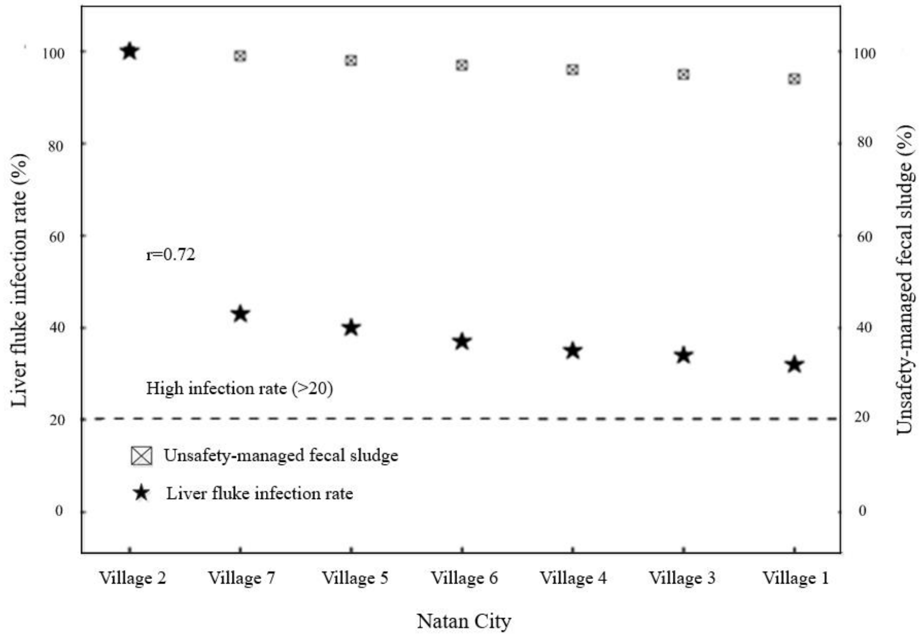

Figure 2. Effects of unsafely-managed FS on the prevalence of liver fluke infections in Natan City, Sakon Nakhon Province, Thailand

The effects of unsafely-managed FS on the prevalence of diarrhea infections are presented in Figure 3. It can be seen that 5 of the 7 villages surveyed were found to have a "high" prevalence of diarrhea infections; only two of the villages surveyed reported less than 20%. The results of Figure 3 show the significance of unsafely-managed FS directly affects the prevalence of diarrhea infections (r=0.80). From the survey results, it was found that the major reason for FSM complaints was improper FS handling and disposal practices. Most community members in Tham Lod City could be at risk from adverse health impacts through consuming contaminated fish, fruit or vegetables. Related studies by Bisung et al. (2015) emphasized that one of the most common factors of diarrhea infections is inadequate FSM services affecting unsafe drinking water. Improper FSM often leads to contamination of water resources and groundwater, and subsequent diarrhea infections among the people concerned, especially in the absence of water resources. To address these problems, personal hygiene programs should be introduced to raise public awareness of unsafely-managed FS and to better understand the importance of safe water and FSM practices. Similar findings were obtained by Jung et al. (2017), showing the effects of neighbourhood and household sanitation conditions on diarrhea morbidity.

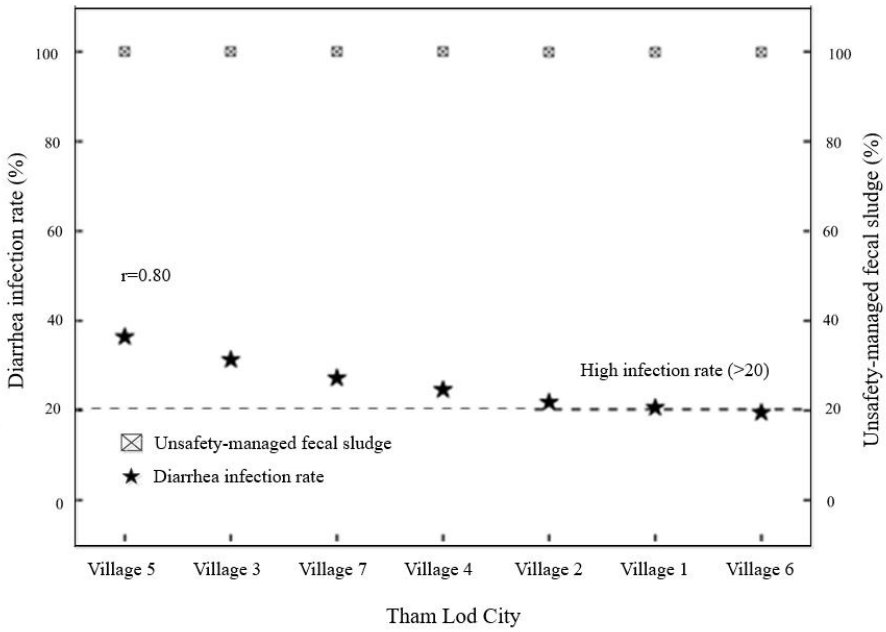

Figure 3. Effects of unsafely-managed FS on the prevalence of diarrhea infections in Tham Lod City, Mae Hong Son Province, Thailand

3.2 Factors affecting the prevalence of liver fluke and diarrhea infections due to unsafely-managed FS

The relationship between FSM practices and liver fluke infections are shown in Figure 4. Model HLF shows a strong relationship (adjusted R^2=0.80) between a set of selected factors and rates of liver fluke infection indicators (Equation (1)) in Natan City, Sakon Nakhon Province. Four significant factors included drinking water from natural resources, direct FS discharges into open drains, consuming raw or undercooked fish and knowledge of liver fluke infections indicated strong and fair significant effects on the prevalence of liver fluke infections (Figure 4). From the survey results, most households surveyed in Natan City lacked adequate sanitation and FSM facilities, especially farmers using temporary huts with no latrines leading to the possibility of FS pollution of water resources, including liver fluke eggs. The presence of liver fluke eggs were found in 60% of the FS samples collected in septic tanks. This result implies that inadequate FSM facilities are directly associated with liver fluke infections. From the survey results, more than 50% of the households interviewed in Natan City stated that defecation behaviors were common practice for farmers, as well as consumption of raw or undercooked fish. A related study by Sithithaworn et al. (2012) documented that people in Natan City normally consume raw or semi-cooked food regularly. A study by Ziegler et al. (2011) showed that the prevalence of liver fluke infections depended not only on inadequate FSM practices, but also personal hygiene and knowledge of liver fluke infections. At present, although the Thai government is implementing health campaigns on liver flukes in Thailand, the lack of sustained funding and continuous campaigns are the main reasons for the poor awareness of the local people toward fecal pathogen infections.

$$H_{LF} = 30.457 - 1.993(\text{DRINKING}^{***}) + 2.282(\text{DIRECT FS}^{***}) + 0.546(\text{FISH}^{***}) + 0.716(\text{LV KNOWLEDGE}^{***}) + 0.027(\text{OCCUPA}^{*}) \quad (1)$$

Model HDA provides a set of significant factors correlating to the prevalence of diarrhea infections (adjusted R^2=0.85) (Equation (2)), namely, income and drinking water from natural resources in Tham Lod City, Mae Hong Son Province (Figure 4). This finding implies that people with low incomes can not afford the FS treatment facilities. A similar finding was confirmed by Bisung et al. (2015) which showed that low income and unemployment were barriers to achieving “safe water and sanitation”. Most of the surveyed households in Tham Lod City consume drinking water and use a water supply from natural resources without any treatment, causing more diarrhea infections as documented by Jung et al. (2017) and Ferrer et al. (2012). In this respect, data on risk assessment concerning fecal pathogen infections should be provided for FSM. In addition, available innovative FSM technologies such as solar septic tanks are strongly recommended to reduce fecal pathogen infections before discharge into water resources as documented by Koottatep et al. (2014).

$$H_{DA} = 1892.542 - 1.651(INCOME^{**}) + 0.688(DRINKING^{**}) + 1.344(OCCUPA^{*}) + 2.182(AGE^{*}) + 1.688(TREATED^{*}) \quad (2)$$

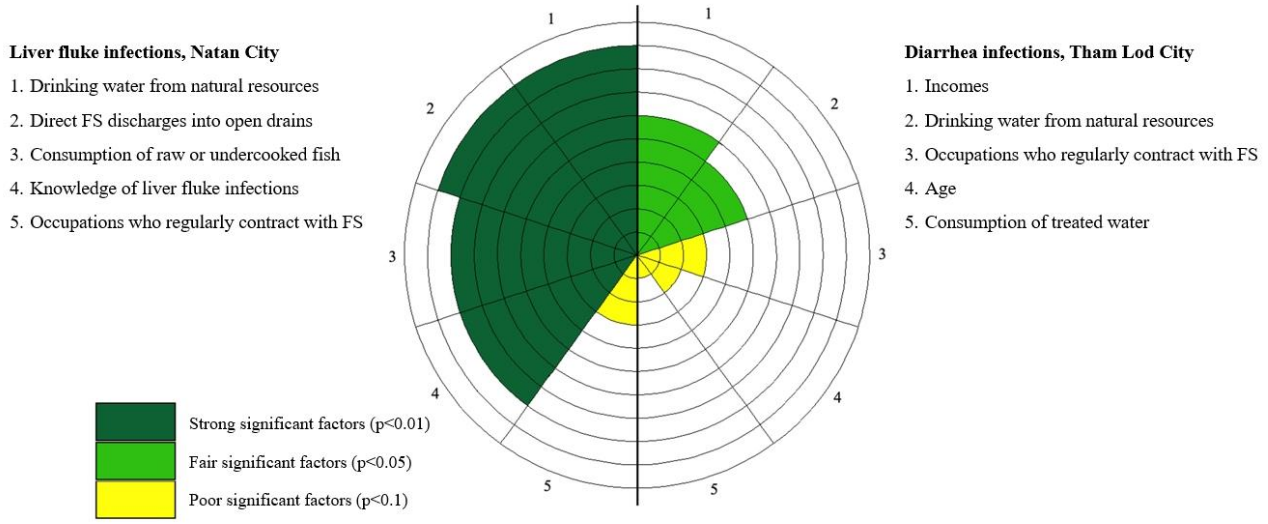

Figure 4. Factors affecting the prevalence of liver fluke and diarrhea infections

4. CONCLUSION

In this study, the effects of unsafely-managed FS on human health risks, as well as the factors relating to FSM practices that affect the prevalence of liver fluke and diarrhea infections were identified and analysed using multiple regression analysis. Results of the assessment and their significant factors analysed in this study could be used to propose specific measures in delivering integrated FSM solutions and health risk protection to comply with the Sustainable Development Goal (SDG) in 2030 including SDG 6 “Clean Water and Sanitation”. Although about 99% of the Thai population have access to safe latrines, most of the surveyed households were found to have unsafely-managed FS leading to liver fluke and diarrhea infections. In this respect, FS problems need to be properly managed to eradicate liver fluke and diarrhea infections. The findings identified the significance of unsafely-managed FS which had direct effects on the prevalence of liver fluke and diarrhea infections in these cities. Four significant factors strongly affected the prevalence of liver fluke infections in Natan City, Sakon Nakhon Province which included: drinking water from natural resources, direct FS discharges into open drains, consuming raw or undercooked fish and lack of knowledge of liver fluke infections. Specific measures to reduce liver fluke infections were proposed such as promoting education programmes relating to FSM practices and fecal pathogen infections and avoiding direct FS discharges into open drains and nearby streams.

With regard to Tham Lod City, Mae Hong Son Province, there are several significant factors that correlated with the prevalence of diarrhea infections which included income and drinking water from natural resources. In this respect, innovative FSM technologies such as solar septic tanks and promoting health education campaigns are strongly recommended to reduce fecal pathogen infections.

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REFERENCES

Aggarwal D, McGregor A. Protozoal gastrointestinal infections. Medicine 2017;45:695-98.

Al-Mohammed HI, Amin TT, Aboulmagd E, Hablus HR, Zaza BO. Prevalence of intestinal parasitic infections and its relationship with socio-demographics and hygienic habits among male primary schoolchildren in Al-Ahsa, Saudi Arabia. Asian Pacific Journal of Tropical Medicine 2010;3:906-12.

Bdir S, Adwan G. Prevalence of intestinal parasitic infections in Jenin Governorate, Palestine: A 10-year retrospective study. Asian Pacific Journal of Tropical Medicine 2010;3:745-7.

Bisung E, Elliott SJ, Schuster-Wallace CJ, Karanja DM, Bernard A. Dreaming of toilets: Using photo voice to explore knowledge, attitudes and practices around water-health linkages in rural Kenya. Health and Place 2015;31:208-15.

Brown J, Cairncross S, Ensink JH. Water, sanitation, hygiene and enteric infections in children. Archives of Disease in Childhood 2013;8:629-34.

Chudthaisong N, Promthet S, Bradshaw P. Risk factors for *Opisthorchis viverrini* infection in Nong Khai Province, Thailand. Asian Pacific Journal of Cancer Prevention 2015;16:4593-6.

Department of Disease Control. Parasitic and Diarrhea Infection in Thailand During Period 2013-2017. Thailand: Ministry of Public Health in Thailand; 2017.

Dufour A, Bartram J, Gannon V. Animal Waste, Water Quality and Human Health. Geneva, Switzerland: World Health Organization; 2012.

Ferrer A, Nguyen-Viet H, Zinsstag J. Quantification of diarrhea risk related to wastewater contact in Thailand. Ecohealth 2012;9:49-59.

Freeman MC, Garn JV, Sclar GD, Boisson S, Medlicott K, Alexander KT, et al. The impact of sanitation on infectious disease and nutritional status: a systematic review and meta-analysis. International Journal of Hygiene and Environmental Health 2017;220:928-49.

Frenoux C, Tsitsikalis A. Domestic private fecal sludge emptying services in Cambodia: Between market efficiency and regulation needs for sustainable management. Journal of Water, Sanitation and Hygiene for Development 2014;5:143-55.

Grundy-Warr C, Andrews RH, Sithithaworn P, Petney TN, Sripa B, Laithavewat L, et al. Raw attitudes, wetland cultures, life-cycles: Socio-cultural dynamics relating to *Opisthorchis viverrini* in the Mekong Basin. Parasitology International 2012;61:65-70.

Huong LQ, Forslund A, Madsen H, Dalsgaard A. Survival of *Salmonella* spp. and fecal indicator bacteria in Vietnamese biogas digesters receiving pig slurry. International Journal of Hygiene and Environmental Health 2014;217:785-95.

Jeff S, Prasad M, Agamuthu P. Asia Waste Management Outlook. UNEP Asian Waste Management Outlook. Nairobi, Kenya: United Nations Environment Programme; 2017.

Jung YT, Hum RJ, Lou W, Cheng Y-L. Effects of neighbourhood and household sanitation conditions on diarrhea morbidity: Systematic review and meta-analysis. PLoS ONE 2017; 12:e0173808.

Koottatep T, Phuphisith S, Pussayanavin T, Panuvatvanich A, Polprasert C. Modeling of pathogen inactivation in thermal septic tanks. Journal of Water, Sanitation and Hygiene for Development 2014;4:81-8.

Lindahl JF, Grace D. The consequences of human actions on risks for infectious diseases: A review. Infection Ecology and Epidemiology 2015;5:e300485.

Molla NA, Mollah KA, Fungladda W, Ramasoota P. Multidisciplinary household environmental factors: Influence on DALYs lost in climate refugees community. Environmental Development 2014;9:1-11.

Penakalapati G, Anderson D, Mahtani AG, Grimes JET, Rehfuess EA, ClasenTF. The impact of sanitation on infectious disease and nutritional status: A systematic review and meta-analysis. International Journal of Hygiene and Environmental Health 2017;220:928-49.

Pham-Duc P, Nguyen-Viet H, Hattendorf J, Zinsstag J, Cam PD, Odermatt P. Risk factors for Entamoeba histolytica infection in an agricultural community in Hanam Province, Vietnam. Parasites and Vectors 2011;4:102.

Prasongwatana J, Laummaunwai P, Boonmars T, Pinlaor S. Viable metacercariae of *Opisthorchis viverrini* in northeastern Thai cyprinid fish dishes-as part of a rational program for control of *O. viverrini*-associated cholangiocarcinoma. Parasitology Research 2013;112:1323-7.

Sithithaworn P, Andrews RH, Nguyen VD, Wongsaroj T, Sinuon M, Odermatt P, et al. The status of opisthorchiasis and clonorchiasis in the Mekong Basin. Parasitology International 2012;61:10-6.

Sripa B, Kaewkes S, Intapan PM, Maleewong W, Brindley PJ. Food-borne trematodiases in Southeast Asia epidemiology, pathology, clinical manifestation and control. Advance in Parasitology 2010;72:305-50.

Taweesan A, Koottatep T, Polprasert C. Effective faecal sludge management measures for on-site sanitation systems. Journal of Water, Sanitation and Hygiene for Development 2015; 5:483-92.

Torgerson PR, Macpherson CN. The Socioeconomic burden of parasitic zoonoses: Global trends. Veterinary Parasitology 2011;182:79-95.

United Nations World Water Assessment Programme. The United Nations World Water Development Report 2015: Water for a Sustainable World. Paris, France: United Nations Educational, Scientific and Cultural Organization; 2015.

Wolf J, Johnston R, Hunter PR, Gordon B, Medlicott K, Prüss-Ustün A. A fecal contamination index for interpreting heterogeneous diarrhea impacts of water, sanitation, and hygiene interventions and overall, regional and country estimates of community sanitation coverage with a focus on low- and middle-income countries. International Journal of Hygiene and Environmental Health 2019;222:270-82.

World Health Organization and United Nations International Children's Emergency Fund. Progress on Drinking Water, Sanitation and Hygiene: 2017 Update and SDG Baselines. Geneva, Switzerland: World Health Organization; 2017.

Yoshida I, Horie O, Akkhavong K. Predictors of hookworm and *Opisthorchis viverrini* infection among adolescents in urban Laos: A cross-sectional study. Research and Report in Tropical Medicine 2019;10:31-41.

Ziegler AD, Andrews RH, Grundy-Warr C, Sithithaworn P, Petney TN. Fighting liver-flukes with food safety education. Science 2011;331:2823.

Characterization of Polycyclic Aromatic Hydrocarbons and Bioaugmentation Potential of Locally Isolated Beneficial Microorganisms Consortium for Treatment of Tar-Balls

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ABSTRACT

Oil spills are one of the environmental pollutions that commonly occur along coastal areas. Tar-balls are one of the products that come from the oil spill pollution. In this study, tar-ball pollution was monitored at 10 points along the coastline of Marintaman Beach in Sipitang, Sabah, Malaysia. This research determined the physical characteristics, composition, and concentration of Polycyclic Aromatic Hydrocarbons (PAHs) in tar-balls. The total number of tar-balls collected was 227 (n=227). The tar-balls were observed in various shapes and the sizes were recorded in the range of 0.1 cm to 6.9 cm. The composition and concentration of Polycyclic Aromatic Hydrocarbons (PAHs) in the outer and inner layer of tar-balls were determined. The results showed that the main Polycyclic Aromatic Hydrocarbons (PAHs) compounds were found in inner layers of the tar-balls with benzo (g,h,i) perylene (72.26 mg/kg), flourene (59.87 mg/kg), dibenzo (a,h) anthracene (44.48 mg/kg), indeno (1,2,3-c,d) pyrene (78.18 mg/kg), and benzo (e) fluoranthene (45.70 mg/kg), respectively. Further research was done with the bioaugmentation study of locally isolated beneficial microorganisms (LIBeM) consortium for treatment of tar-balls in an Aerated Static Pile (ASP) bioreactor system. The results showed that, after 84 days of treatment, this consortium, consisting of *C. tropicalis*-RETL-Cr1, *C. violaceum*-MAB-Cr1, and *P. aeruginosa*-BAS-Cr1, was able to degrade total petroleum hydrocarbon (TPH) by 84% as compared to natural attenuation (19%). The microbial population of this consortium during the biodegradation study is also discussed in this paper.

1. INTRODUCTION

Oil pollution is considered to be one of the major contributors to marine environment pollution. This organic contaminant comes from uncontrolled oil spillage during transportation, manufacturing, and run-off from terrestrial sources. As a result of oil spilled in the marine environment, many implications occur. One of them is the formation of tar-balls. Tar-balls are the product of weathered marine oils, regardless of source. Tar-balls come from many sources of petroleum and they are mostly derived from different activities such as tanker washing and routine shipping operations (Chandru et al., 2008). In Malaysia, a few studies on tar-balls have been conducted, notably by Zakaria et al. (2002), Yong (2003), Johnson (2004), and Chandru (2005). Despite the ever-growing cases of accidental and non-accidental oil pollution in the sea, limited study has been done to understand the effects inflicted on the marine environment. This study contributes to providing information regarding the effect of oil pollution on the onshore environment, specifically in terms of the PAH levels. PAH is chosen among other compounds due to the carcinogenic and toxic properties. PAH negatively impacts the marine habitat, mainly affecting the filter and bottom-feeders as they lack PAH-metabolizing enzymes (Adzigbli and Yuewen, 2018). Analyzing the chemical makeup

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of tar-balls gives a further understanding on beach oil pollution. The Sipitang beach is also of concern as it serves as a developing recreational spot. Hence, this study describes the distribution and abundance of stranded tar-balls at the coastline of Marintaman Beach, Sepitang, Sabah. The analysis allows a better understanding on the precautions to the oil spill in the marine environment and the cause of variability in tar-ball accumulation nearby the coastal water. In addition, we introduce one practical and environmentally friendly method to treat tar-balls by using locally isolated microorganisms (LIBeM) which has the potential to degrade hydrocarbons as well as phenol (Piakong, 2006; Nurulhuda and Piakong, 2007).

2. METHODOLOGY

2.1 Study area

The Marintaman Beach (5°04′45.30″N, 115°33′02.95″N), a beach in Sipitang, is located in the southwestern town of Sabah. The beach is a part of an extended bay that stretches for about 92.79 km. The beach consists of unique rock formations and boulders strewn on the right flank of its beach.

2.2 Sampling location

Tar-ball samples were collected from the coastline of the Marintaman Beach Sipitang based on the transect line area from the high tide to the low tide of the beach. Figure 1 shows the coastline area at Marintaman Beach Sipitang that is located 39.93 km from the federal territory of Labuan. It was found that there were many oil production activities such as shipping, petroleum processing and excavation of crude oil carried out on and off the shore.

2.3 Sample collection

A total of 227 tar-balls along the Marintaman Beach was collected in February 2016. Samples were collected from a one-meter strip running across the beach from high tide line to the present water level. The samples were collected in 10 stations assigned along the 1.63 km of the coastline of Marintaman Beach. The tar-balls were wrapped with aluminum foil and put inside a glass jar and ziploc bag to avoid contamination. Collected samples were kept in a cold box at 4°C prior to the bioaugmentation study.

2.4 Bioreactor design

Figure 2 shows a bioreactor designed with a size of 30 cm × 20 cm × 25 cm. The bioreactor made of acrylic material was supplied with three tubes at the side of the reactor connected to the air pump (Model RESUN LP100 Low Noise Air Pump) and was used for bioaugmentation study (Piakong and Nur Zaida, 2018). There are three parts of the reactor which consists of gravel-sized (1-1.5 cm), sand, and soil on the surface. The soil that had been used in this study was mixed well meanwhile the effluent at the bottom of the reactor was collected in the universal bottle.

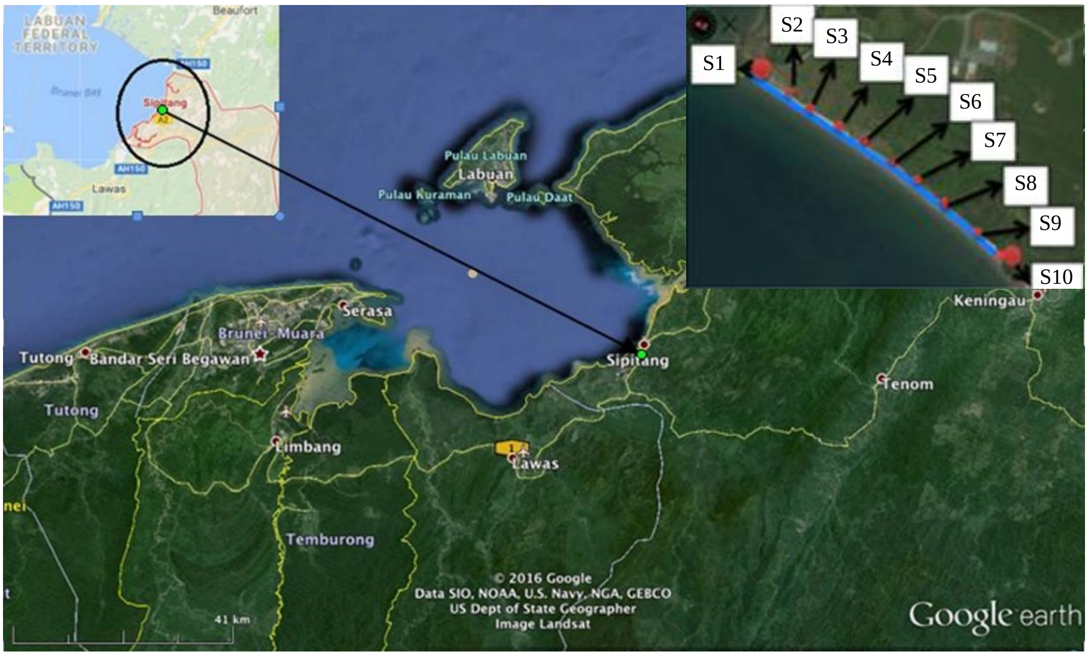


Figure 1. Sampling location of tar-balls in the coastal area of Sipitang, Sabah, Malaysia

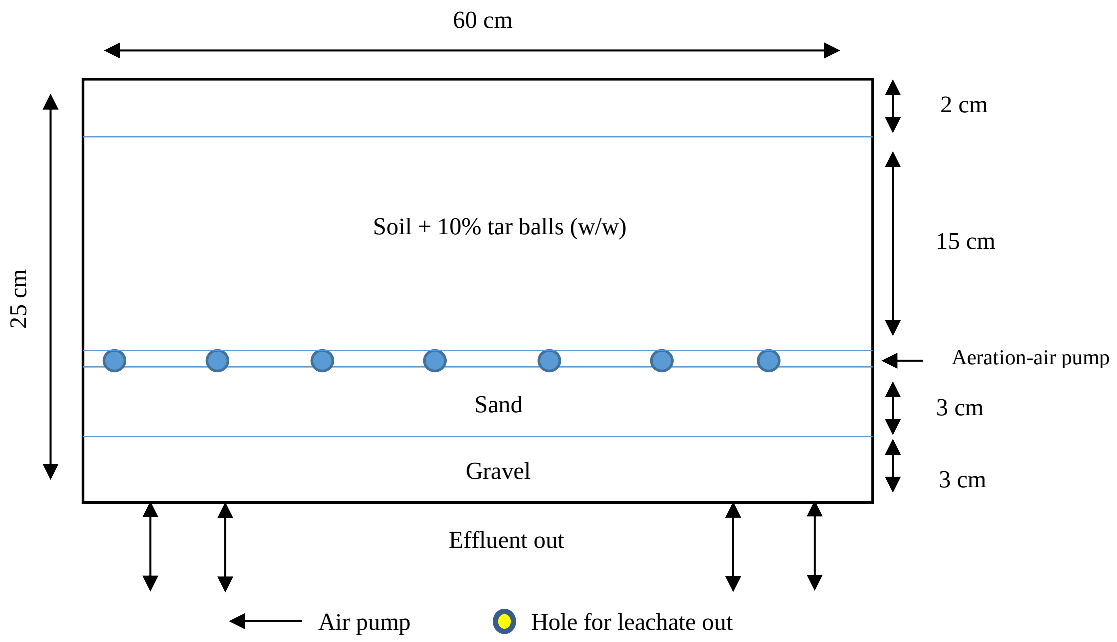
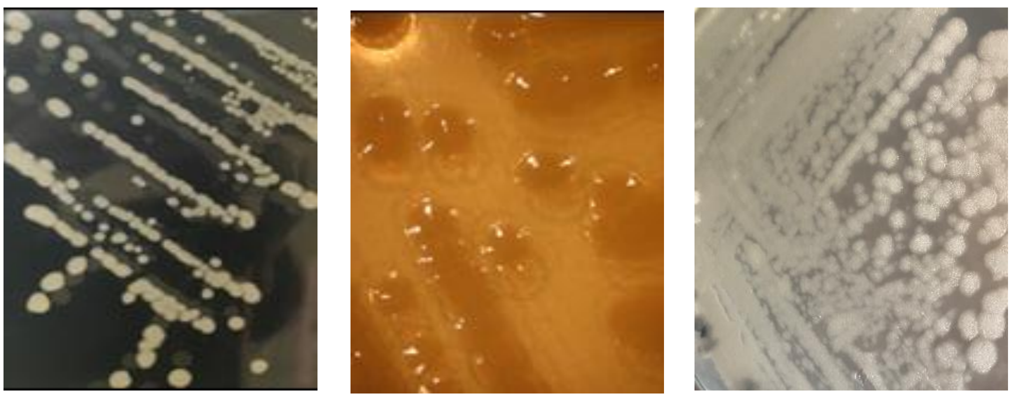


Figure 2. The layout of bioreactor used to treat tar-balls (Piakong and Nur Zaida, 2018)

2.5 Sources of microorganisms

The microorganisms were obtained from Environmental Microbiology Laboratory, Faculty of Science and Natural Resources, Universiti Malaysia Sabah. There are three species used, *Candida tropicalis*-RETL-Cr1, *Chromobacterium violaceum*-MAB-Cr1, and *Pseudomonas aeruginosa*-BAS-Cr1. These cultures were proved to degrade oil sludge efficiently based on previous study by Piakong and Nur Zaida, (2018). The colony of these micro-organisms is shown in Figure 3.



(a) (b) (c)

Figure 3. Colony morphology of LIBeM (a) *C. tropicalis*-RETL-Cr1, (b) *C. violaceum*-MAB-Cr1, and (c) *P. aeruginosa*-BAS-Cr1 used in this study.

2.6 Culture medium

The media used for inoculation of LIBeM consortium was Ramsay broth as mentioned by Frank et al. (2020). All of the ingredients were suspended in a Schott bottle with 1,000 mL of deionized distilled water. After that, the mixture was autoclaved at 121°C for 15 min. The Ramsay broth was cooled to room temperature and stored in a sanitized cabinet.

2.7 Inoculum preparation

The inoculation of LIBeM consortium into the tar-balls treatment reactor was conducted in liquid form. A single colony of bacteria isolate was inoculated into Ramsay broth at 30°C for 24 h in an orbital shaker at 200 rpm. A total of 10% of the cultured bacteria (1×10^7 CFU/mL) with OD 0.5 and above at 600 nm was used as inoculum. Then 10%

(v/v) inoculants of consortium cultures were added into the treatment reactor that contains 100 g of tar-balls that are crushed mixed with soil for bioaugmentation studies. The inoculation of LIBeM consortium into the treatment plot was done every 2 weeks.

2.8 Experimental set-up

A portion of 1,000 g of soil was sieved through a 0.20 mm sieve size to remove the remaining debris in the soil. A total of 100 g of tar-balls was mixed over the soil for further bioaugmentation studies. The following treatment in duplicate was performed for 84 days in ambient temperature as shown in Table 1.

Table 1. Bioaugmentation of tar-balls by LIBeM consortium in liquid formulation

Treatment	Content
Treatment 1	Non inoculation of microorganism in the soil (Natural attenuation - NA)
Treatment 2	The tar-balls were treated with consortium (RETL-Cr1 + MAB-Cr1 + BAS-Cr1) (LIBeM-LIQ)

2.9 Determination of total petroleum hydrocarbon (TPH) in tar-balls

Total petroleum hydrocarbon was carried out based on the gravimetric method (Soxhlet extraction) (USEPA 3540C) (Adeniji et al., 2017). A 20 g soil sample was grained and placed in a thimble and extracted with dichloromethane (DCM). Then the thimble was placed in a Soxhlet extractor. 250 mL of dichloromethane was added into the round bottomed flask (RBF). The extraction process took place for 11 h. The total solvent was cleared completely with the vacuum evaporator at 40-50°C. The RBF together with the extract was cooled in a desiccator after being dried in an oven at 40°C. The percentage of total petroleum hydrocarbon (TPH) was calculated using the formula below:

$$\%\ \mathrm{TPH} = \frac{\text{Min extract weight in RBC}}{\text{Weight of sample}} \times 100$$

3. RESULTS AND DISCUSSION

3.1 Composition and concentration of PAH in tar-balls

The major PAH composition of outer and inner layered of tar-balls samples are presented in Figure 4 and 5. The total cumulative concentrations of PAH levels are significantly higher in the inner layer (469.79 mg/kg), whereas the outer layer was lower with 172.64 mg/kg. In the sample 2-outer, the PAH compound fluorene was the highest at 59.87 mg/kg, followed by benzo (b) fluoranthene at 45.70 mg/kg and benzo (g,h,i) perylene at 31.61 mg/kg. The lowest concentration for sample 2-outer was acenapthylene, 5.22 mg/kg, benzo (a) pyrene, 9.75 mg/kg, and dibenzo (a,h) anthracene, 10.98 mg/kg, respectively. In sample 1-outer, the highest PAH concentration found was in benzo (e) pyrene, benzo (g,h,i) perylene, and benzo (b) fluoranthene with concentrations of 28.52 mg/kg, 24.58 mg/kg, and 23.65 mg/kg, respectively. In sample 2-outer, the distribution of PAH composition was spread out more evenly than sample 1-outer. Various concentrations of these elements may be caused by several weathering processes, such as evaporation, dissolution, photochemical oxidation, dispersion, emulsification, adsorption onto suspended particulate material, and sedimentation (Leili et al., 2020).

For the inner-layered samples, a different trend can be seen as in Figure 5. The PAH concentrations for the inner layers of both samples were relatively higher than the outer-layered samples. The highest concentration was found in sample 2-inner and is followed by 1-inner. The highest PAH concentration in sample 2-inner was found in the compound indeno (1,2,3-c,d) pyrene, 78.18 mg/kg. Following that is benzo (g,h,i) perylene, 72.26 mg/kg, dibenzo (a,h) anthracene, 44.48 mg/kg, and 1-Methyl penanthrene, 33.59 mg/kg. The lowest PAH compounds found were benzo (a) pyrene (3.70 mg/kg), acenaphthene (3.71 mg/kg), and acenaphthylene (3.93 mg/kg). Outer-layered samples were seen to be dominated by PAH compounds of benzo (b) fluoranthene, benzo (k) fluoranthene, and benzo (g,h,i) perylene, respectively.

It shows that the concentration of PAH was higher in 2-inner than in 1-inner sample. The value of the total PAH concentration in inner layer was 61% more than the outer-layered samples. In the inner layers, benzo (g,h,i) perylene, dibenzo (a,h) anthracene, and indeno (1,2,3-c,d) pyrene had the highest concentration values with 72.26 mg/kg, 44.80 mg/kg, and 78.18 mg/kg, respectively. Napthalene and its derivatives seem to come in second for high concentrations. As seen in both the inner and outer samples, naphthalene, acenaphthylene, and ace-naphthrene have relatively the same concentrations. Fluorene has nearly similar concentrations in the inner samples of 1-inner and 2-inner, 32.54 mg/kg and 25.79 mg/kg, respectively. In both the inner and outer layers, it can be seen that PAH compounds methyl-anthracene

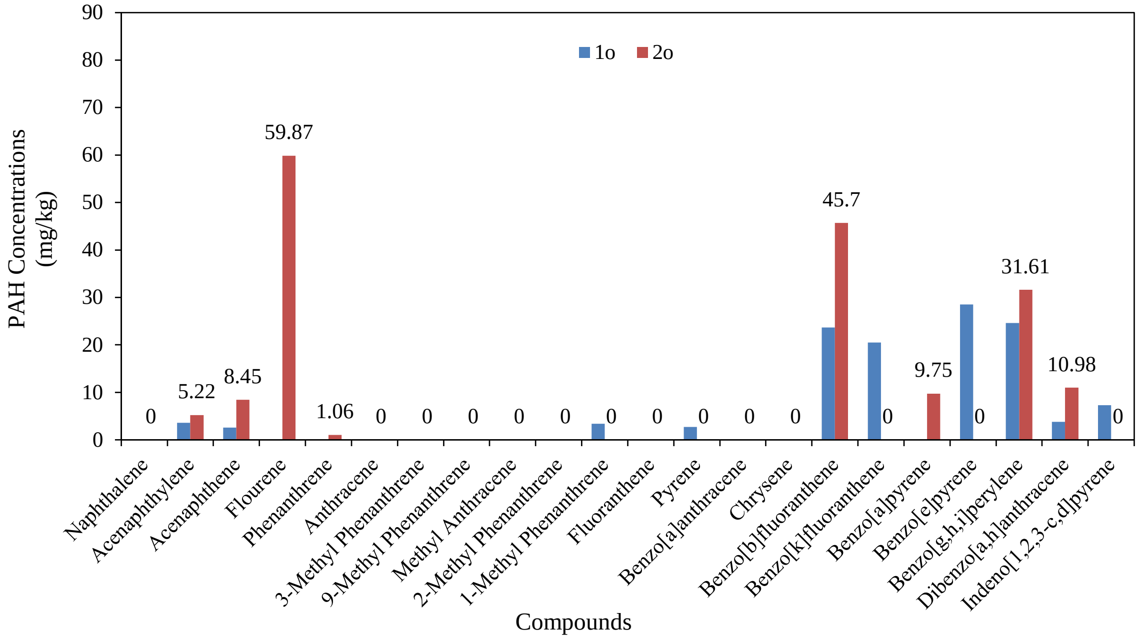


Figure 4. Characterization of PAHs compound in outer-layered samples of 1-outer (1o) and 2-outer (2o) (in mg/kg)

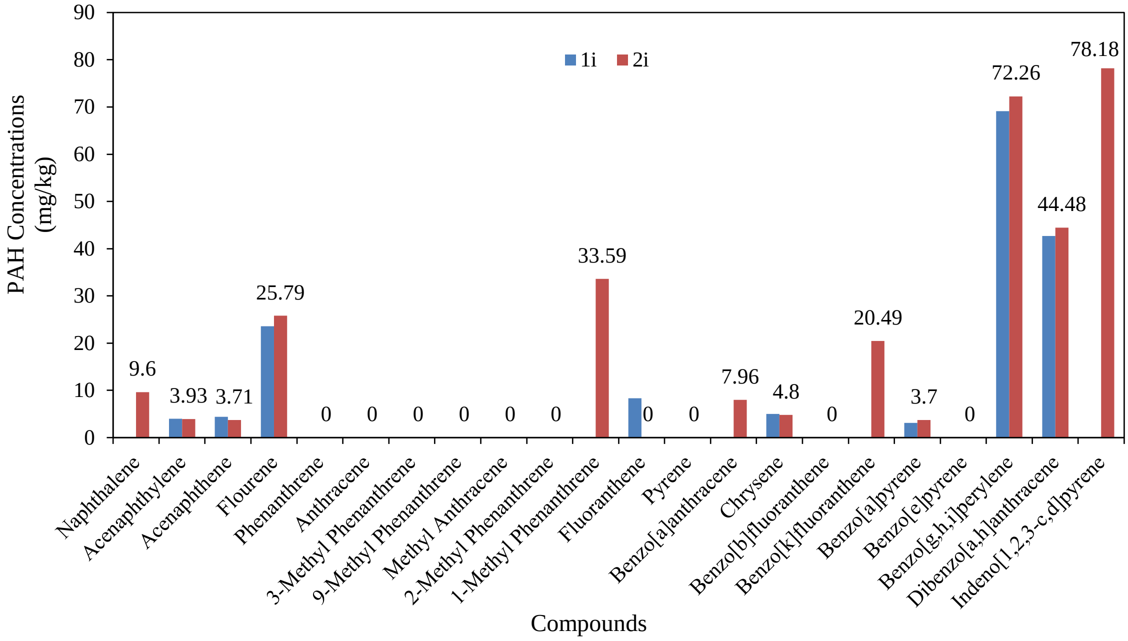


Figure 5. Characterization of PAHs compound in inner-layered samples of 1-inner (1i) and 2-inner (2i) (in mg/kg)

and the ones belonging to methyl-phenanthrene family were exceptionally absent in most of the samples. The compounds were either undetected by the GC/MS, the SIM method or had a negative value after the sample recovery.

The PAH found in outer-layered samples were lower than the inner-layered samples. The main reason for this is that the outer part is exposed, and hence easier for degradation processes to occur. PAH compounds are exceptionally sensitive to ultraviolet light (Abdel-Shafy and Mansour, 2016) and degrade easily. Jennifer et al. (2019) have also stated the significant linear correlation between PAH half-lives and solar radiation intensity. Thus, it can be inferred that exposure of tar-balls to sunlight will affect the concentration in the outer-layered samples.

3.2 Biodegradation of polycyclic aromatic hydrocarbons (PAHs) compounds by LIBeM consortium

Figure 6 shows the percent degradation of PAHs compound in tar-balls treated with LIBeM consortium (*C. tropicalis*-RETL-Cr1, *C. violaceum*-MAB-Cr1, and *P. aeruginosa*-BAS-Cr1). The results explain that the LIBeM consortium are able to degrade PAHs compound as compared to natural attenuation (control). It was found that LIBeM consortium were efficient in degrading the naphthalene, acenaphthalene, flourene, and benzo (b) fluoranthene at 84.62%, 80.37%, 83.87%, and 80.04%, respectively.

This finding agrees with Ana et al. (2020) who reported that most of hydrocarbon clastic bacterium were able to degrade n-alkanes and PAHs with four-rings PAH. It is interesting to note that in this present work, LIBeM consortium was found to degrade most of PAHs compound, especially pyrene. The result also showed that LIBeM consortium was able to degrade high molecular weight (pyrene) known to be recalcitrant to microbial attack (Gabriela et al., 2018).

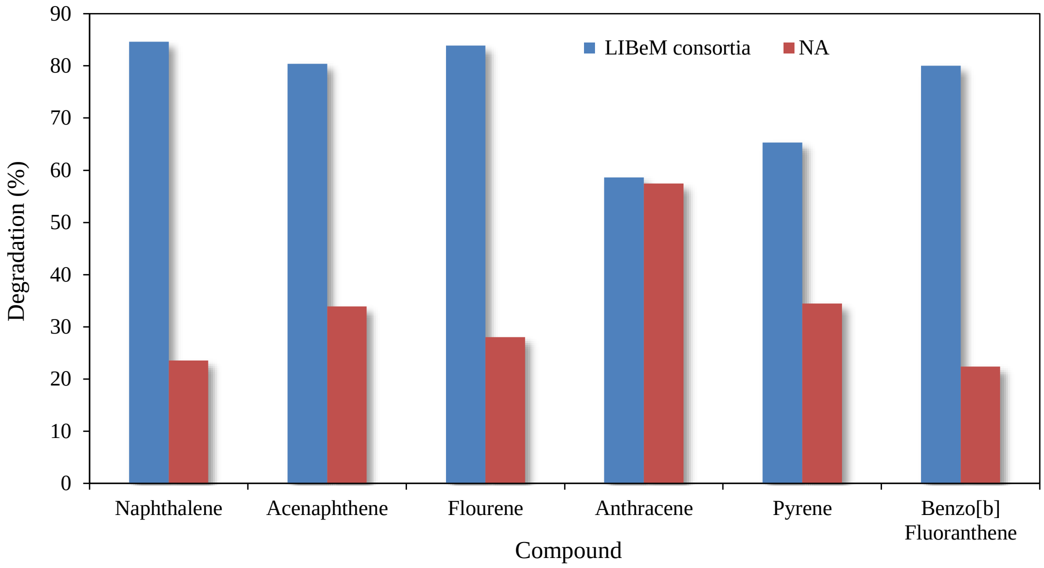


Figure 6. Biodegradation of polycyclic aromatic hydrocarbon (PAHs) of tar-balls by consortium LIBeM and Natural Attenuation (NA) after 84-days treatment.

Bioaugmentation with inoculation of LIBeM consortium appeared to be the most appropriate way to degrade PAHs compound while natural attenuation was capable to degrade a maximum of 57% of these elements. An increased in number of molecular weights will increase the hydrophobicity and decreased the solubility for indigenous microorganisms to degrade the compound (Ana et al., 2020). However, for LIBeM consortium the production of biosurfactant produced by *P. auruginosa* promoted the high degradation of PAHs compound. Thus, it can be concluded that the performance of LIBeM consortium to treat tar-balls achieved more than 80% as compared to natural attenuation in the control plot. It is noteworthy that the physical and chemical properties of PAHs compounds as well as their molecular weight have a considerable effect on microbial assimilation and biodegradation rate of the soil study (Sakshi and Haritash, 2020).

3.3 Biodegradation ratio of n-C_{17}:pristane, n-C_{18}: phytane, and pristane:phytane

The results of isoprenoids n-C_{17} and n-C_{18} for consortium LIBeM from initial week and after biodegradation study are shown in Table 2. These isoprenoids are highlighted due to the biodegradation and microbial activity that occur during the treatment of tar-balls. It is worth to note that the reduction of n-C_{17} and n-C_{18} in this study indicates the microbial degradation of tar-balls to less degradable compounds (Ruben et al., 2020). The results demonstrated that n-C_{17}:Pr and n-C_{18}:Ph ratios for LIBeM consortium sample compared to the control decrease with increasing the incubation time and reached its maximum after 12 weeks of incubation. The n-C_{17}:Pr and n-C_{18}:Ph ratio ranged from 0.1 to 3.8 and 0.5 to 3.2 while the Pr/Ph ratios range from 1.2 to 9.9 respectively. By comparing the results, it was found that n-C_{18}:Ph ratio was lower than n-C_{17}:Pr ratio.

Table 2. Comparison of biodegradation ratios of LIBeM consortium and natural attenuation.

Treatment	Week	C_{17}:pristane	C_{18}:phytane	pristane:phytane
LIBeM consortium	0	3.8	1.0	1.4
	12	0.4	0.8	1.2
Natural attenuation (Control)	0	1.2	3.2	9.9
	12	0.1	0.5	2.0

The results indicate that microbial degradation was actively involved during the treatment. This can be explained with the presence of biosurfactant by LIBeM consortium, thus make it easier to degrade both C_{17} and C_{18} as compared to pristine and phytane (Nasser et al., 2020).

It is important to note that n-alkanes have been degraded faster than isoprenoids, thus lead to decrease in ratio values of n-C_{17}:Pr and n-C_{18}:Ph. Dashtbozorg et al. (2019) stated that by considering the thermal maturity of the tar-balls, the biodegradation of n-alkanes is faster than isoprenoids. However, according to Lijmbach (1975), the value of Pr/Ph mainly comes from the different sources of the samples. He stated that different samples of tar-balls may come from different origin places, such as aquatic depositional environments (marine and brackish water) with value Pr/Ph (<2.0). Meanwhile, for Pr/Ph (2-4) these samples may come from fluviomarine and coastal swamp environments while high values of Pr/Ph (>10) are related to oxidizing conditions such as peat swamp.

3.4 Microbial population during biodegradation of tar-balls

Figure 7 shows the microbial population of LIBeM consortium and indigenous microorganisms in the control plot. The results showed that the highest microbial population was found in week 2 (LIBeM consortium), 8.8×10^8 CFU/mL. The results indicated that the inoculation of LIBeM consortium in treatment plot increased the microbial population due to the carbon consumption in the tar-balls. This leads to the significant TPH reduction respectively.

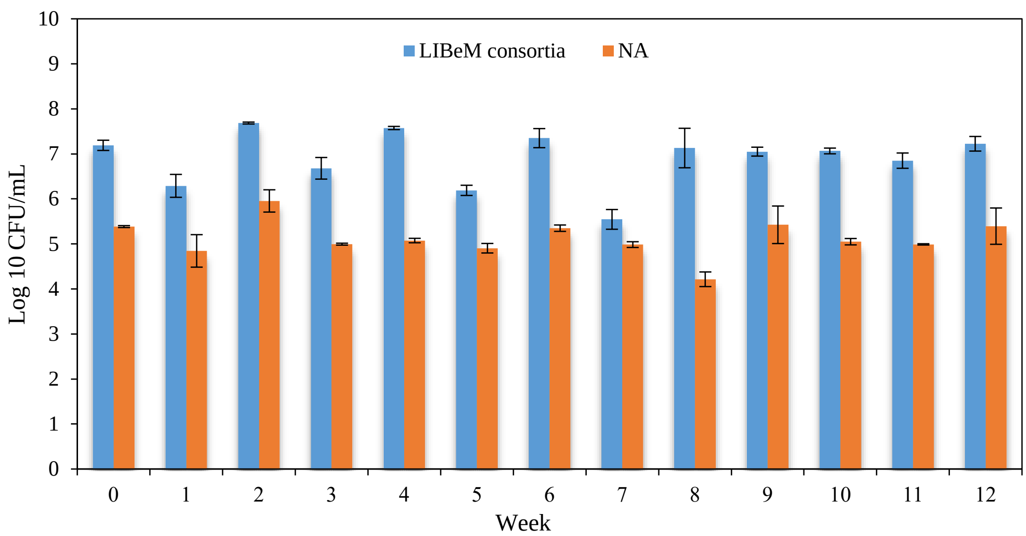


Figure 7. Microbial population of LIBeM consortium and natural attenuation during 12 weeks of tar-balls treatment.

On the other hand, the control plot which consists of indigenous microorganisms in the soil recorded the lowest microbial population in range of 6.2×10^7-7.7×10^8 CFU/mL through the treatment period. The depletion of microbial population in the control plot might be due to the toxic effect of the tar-balls towards the indigenous population. This explained the inability of these microorganisms to tolerate with tar-balls, and thus cause insignificant removal of TPH in the control plot. The biodegradation of tar-balls by LIBeM consortium was proven with scanning electron microscopy (SEM) image captured during the treatment study.

Figure 8 shows the SEM image of LIBeM consortium with 10^7 cells/g detected in the treated soil. The existence of microbial density of LIBeM consortium is dependent on the availability of gas exchange, nutrients content, and the physiochemical properties of the tar-balls treatment. There are pores on the surface filled with a number of small grains and holding a lot of floc, forming irregular structure of the shape of tar-balls in soil. The distribution of LIBeM consortium shows a heterogenous morphology as shown with enclosed dotted line area. The attachment of LIBeM consortium to the soil confirms that the formation of biofilm is an initial step in the biodegradation process of tar-balls. However due to homogeneously distributed and incubated period, the images were found non-uniform to cause the strain multiply.

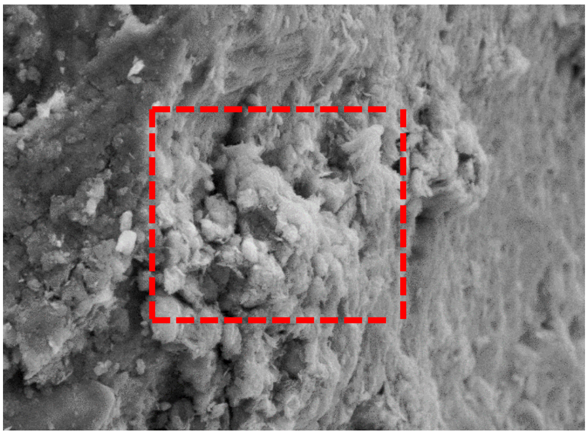


Figure 8. Scanning electron micrographs (SEM) images of LIBeM consortium with tar-balls contaminated soil under 1,000 x magnification.

4. CONCLUSION

This study concluded that the highest PAH concentration found in the tar-ball samples consisted of benzo (g,h,i) perylene, flourene, dibenzo (a,h) anthracene, and indeno (1,2,3-c,d) pyrene. Among these compounds, two of those are listed as Group B carcinogens. The top three compounds are benzo (g,h,i) perylene (72.26 mg/kg), flourene (59.87 mg/kg), dibenzo (a,h) anthracene (44.48 mg/kg), and indeno (1,2,3-c,d) pyrene (78.18 mg/kg). They are mostly found in the inner layers of the sample. Biodegradation of tar-balls by LIBeM consortium represents TPH biodegradation efficiency of 84% within 84-days period. The ASP-biodegradation has showed a great potential and integrated approach for treatment of tar-balls after oil-spill in marine ecosystem. Therefore, further research is recommended to carry out the ASP-enhanced bioaugmentation of tar-balls using other LIBeM products formulation, such as in powder and capsule form (LIBeM-POW and LIBeM-CAP).

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REFERENCES

Abdel-Shafy HI, Mansour MS. A review on polycyclic aromatic hydrocarbons: Source, environmental impact, effect on human health and remediation. Egyptian Journal of Petroleum 2016;25(1):107-23.

Adeniji AO, Okoh OO, Okoh AI. Analytical methods for the determination of the distribution of total petroleum hydrocarbons in the water and sediment of aquatic systems: A review. Journal of Chemistry 2017:1-13.

Adzigbli L, Yuewen D. Assessing the impact of oil spills on marine organisms. Journal of Oceanography and Marine Research 2018;6(1):2-7.

Ana M, Marija L, Hideyuku I, Vladimir B, Ivan K, Ksenija S, et al. Efficient biodegradation of petroleum n-alkanes and polycyclic aromatic hydrocarbons by polyextremophilic *Pseudomonas aeruginosa* san ai with multidegradative capacity. Journal Royal Society of Chemistry 2020;10(24):14060-70.

Chandru K. Temporal Distribution of Tar-Balls Stranded on The Beaches of Terengganu [dissertation]. Universiti Malaysia Terengganu, Malaysia; 2005.

Chandru K, Zakaria MP, Anita S, Shahbazi A, Sakari M, Bahry PS. Characterization of alkanes, hopanes and polycyclic aromatic hydrocarbons (PAH) in tar-balls collected from the East Coast of Peninsular Malaysia. Marine Pollution Bulletin 2008;56:950-62.

Dashtbozorg M, Riyahi B, Shushizadeh MR, Taghavi L. Quantitative evaluation of n-alkanes, PAHs, and petroleum biomarker accumulation in beach-stranded tar balls and coastal surface sediments in the Bushehr Province, Persian Gulf (Iran). Marine Pollution Bulletin 2019;146:801-5.

Frank AK, Phi R, Renija G, Jobin J, Shikha S, Mian H, et al. Upstream development of escherichia coli process with PhoA promoter using design of experiments (DoE). Journal of Industrial Microbiology and Biotechnology 2020;47:789-99.

Gabriela AL, Mariana J, Rafaella C, Marili VN, Lara DS. Polycylic aromatic hydrocarbons degradation by marine-derived basidiomycetes: Optimization of the degradation process. Brazilian Journal of Microbiology 2018;49:749-56.

Jennifer EB, Hayley H, Yong Y, Robert JL, Derek CG, Muir. Sources and environmental fate of pyrogenic polycyclic romatic hydrocarbons (PAHs) in the Arctic. Emerging Contaminants 2019;5:128-42.

Johnson KCC. The Tar-balls Pollution along the Coast of Kuala Terengganu [dissertation]. Universiti Malaysia Terengganu, Malaysia; 2004.

Leili M, Abbas R, Edris B, Hamid D, Abu HS, George ZK. Petroleum hydrocarbon removal from wastewater: A review. Processes 2020;8(4):447.

Lijmbach GWM. On The Origin of Petroleum. London, UK: Applied Science Publishers; 1975.

Nasser A, Al-Ghouti MA, Samir J, Nabil Z. Potential for native hydrocarbon-degrading bacteria to remediatehighly weathered oil-polluted soils in Qatar through self-purificationand bioaugmentation in biopiles. Biotechnology Reports 2020;28:e00543.

Nurulhuda Z, Piakong MT. Pertumbuhan *Candida tropicalis* RETL-Cr1 Dalam Medium Mengandungi Minyak Mentah. Proceedings of the 3rd Postgraduates Seminar; 2007 Oct 8-10; Palace Hotel, Kota Kinabalu: Malaysia; 2007.

Piakong MT. The Performance of Phenol Biodegradation by *Candida tropicalis* RETL-Cr1 Using Batch and Fed-batch Fermentation Techniques [dissertation]. Universiti Teknologi Malaysia, Johor Malaysia; 2006.

Piakong MT, Nur Zaida Z. Effectiveness of single and microbial consortium of locally isolated beneficial microorganisms (LIBeM) in bioaugmentation of oil sludge contaminated soil at different concentration levels: A laboratory scale. Journal of Bioremediation and Biodegradation 2018;9:2.

Ruben F, Ivan L, Carlos S, Diego B, Jose LRG, Ana IP. Bioaugmentation treatment of a PAH-polluted soil in a slurry bioreactor. Applied Science 2020;10:2837.

Sakshi, Haritash AK. A comprehensive review of metabolic and genomic aspects of PAH-degradation. Archives of Microbiology 2020;202:2033-58.

Yong JC. Chemical Composition of Distribution of Tar-balls along Terengganu Beach [dissertation]. Universiti Malaysia Terengganu, Malaysia; 2003.

Zakaria M, Takada H, Tsutsumi S, Ohno K, Yamada J, Kouno E. Distribution of polycyclic aromatic hydrocarbons (PAHs) in rivers and estuaries in Malaysia: A widespread input of petrogenic PAHs. Environmental Science and Technology 2002;39(9)1907-18.

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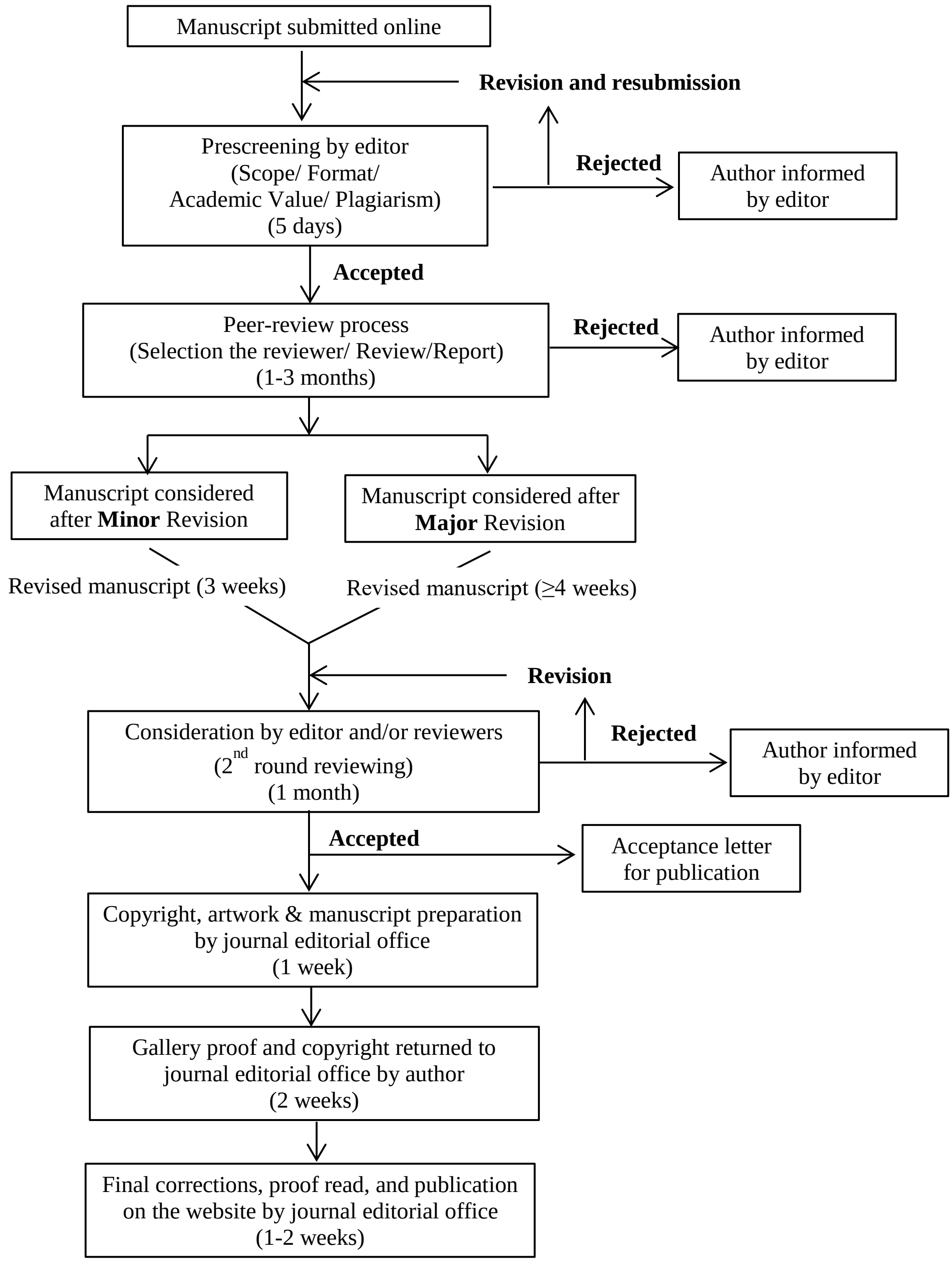

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