A spatial decision support system for peatland fires prediction and prevention in Bengkalis Regency, Indonesia

S I Maulana1,2*, L Syaufina3, L B Prasetyo4, M N Aidi5

1 Study Program of Natural Resources and Environmental Management Science, IPB University, Bogor Indonesia
2 Research Development and Innovation Agency, The Ministry of Environment and Forestry-Republic of Indonesia
3 Department of Silviculture, Faculty of Forestry, IPB University, Bogor Indonesia
4 Department of Forest Resources Conservation and Ecotourism, Faculty of Forestry, IPB University, Bogor Indonesia
5 Department of Statistics, Faculty of Mathematics and Natural Sciences, IPB University, Bogor Indonesia

Corresponding author*: sandhimaulana2018@gmail.com

Abstract. A Spatial decision support system (SDSS) is an integrated computer-based system that can be used to support decision makers in addressing spatial problems through iterative approaches with functionality for handling both of spatial and non-spatial databases, analytical modelling capabilities, decision making support, as well as effective data and information presentation utilities. Previously, many studies have proven that this kind of decision support system is also useful in addressing wildfires problems effectively. Considering this technological advancement, this study is primarily aimed to develop a peatland fires management system by implementing the concept of SDSS. Developed system in this study is consisting of two separate sub-system, namely prediction and prevention sub-systems, which are then integrated into one whole working scheme using loose coupling method. Overall, it can be concluded that such integrated prediction and prevention system has various advantages. Firstly, it is useful to establish rapid coordination among involved stakeholders in deciding suitable approaches to prevent peatland fires. Secondly, promoting a more pro-active fire management system that is relied on predict-and-prevent approach. Thirdly, avoiding further delay on fires prevention while minimizing error in resources allocation. Lastly, this kind of decision support system can be rapidly updated following on-going technological and field situation developments.

1. Introduction
Over the last few decades there has been a significant increase in the use of geographical information. As reported by Sugumaran et al. [1], this may happen due to the widespread availability of navigation technology and internet-based spatial data processing services that can be accessed by the public. Along with the increasingly affordable technological evolution, the use of spatial data in supporting decision-making process in complex situations is also growing exponentially, particularly related to environmental management issues, land use planning, and cross-border disaster management. Taking into account of this notion, an approach that often be implemented is the development of a Spatial Decision Support System (SDSS) [1], [2].
Conceptually, SDSS is an integrated computer system that is able to assist decision makers in solving various spatial problems through an iterative approach that is equipped with the ability to handle both of spatial and non-spatial data, analytical modeling skills, ability to support decision selection, and the ability to present data and information effectively [1]. Based on this conceptual understanding, this approach may also be utilized to establish a decision support system in the field of forest and land fires control. For example, Lee et al. [3] have built The Spatial Fire Management System (SFMS) in Canada. Noonan-Wright et al. [4] have established the Wildland Fire Decision Support System (WFDSS) for the United States. Meanwhile, Kalabokidis et al. [5] have developed the Auto-Hazzard Pro Decision Support System (AHPDSS) to be implemented in Europe-Mediterranean region.

In general, those decision support systems were developed by utilizing an internet network in order to increase the effectiveness of forest and land fire control efforts given the short availability of preparation time. Considering those technological advancements in the area of forest and land fires control, this study is primarily aimed to develop a predictive-preventive control model for peatland fires in Bengkalis Regency by applying the concept of SDSS. This kind of control model may not only useful to support the establishment of rapid coordination among the local community, government, and concession holders, but also allows the authorities to be able to allocate their limited resources appropriately based on prediction of fire occurrences and their suitable prevention alternatives.

2. Method
2.1 Study location
This study was taken place in Bengkalis Regency that is located in the eastern coast of Sumatera Island. Geographically, as illustrated in Figure 1, this area is situated between 2°7′37.2″-0°55′33.6″ North and 100°57′57.6″-102°30′25.2″ East. The selection of this research locations is mainly based on the consideration that Bengkalis Regency is dominated by peatlands. In the meantime, this regency has also been regarded as one of recurring areas of peatland fires in Sumatera. In addition, due to its geographical position that is close to Malaysia and Singapore, Bengkalis Regency has continually received considerable attentions from various parties during the implementation of the ASEAN Agreement on Transboundary Haze Pollution (AATHP) which has been ratified by the Government of Indonesia through Law No. 26/2014.

![Figure 1. Study location](image)

Source: Maulana *et al* [6]

2.2 Model conceptualization
The development of a predictive-preventive control model for peatland fires in this study was conducted based on the concept of the Spatial Decision Support System (SDSS), in which that there were five main components covered, including the ability to manage and analyze both spatial and non-spatial data; ability to perform spatial and non-spatial modelling; ability to support decision making process; visualization through interactive user interfaces, as well as stakeholders management [1] [7].
Overall, established peatland fires control model in this study was composed of two sub-models, namely prediction sub-model and prevention sub-model.

2.2.1 Prediction sub-model

The prediction sub-model applied in this study was developed based on spatial logistic regression method and has been published in [6]. Performance of this prediction sub-model had also been verified and validated using an independent testing subset, and the results showed were consistently reliable (verification model: P-value < 0.001, Nagelkerke $R^2 = 0.314$, AUC = 0.8309; model validation: overall accuracy = 85.16%) [6]. This prediction sub-model may provide preparation time up to two months prior the beginning of peatland fire season. The independent variables used in the prediction sub-model include physiographic variables (density of artificial drainage networks / canals and density of natural drainage networks / river), peat’s physical characteristics variables (depth and type of peat), climate variables (monthly rainfall and moisture index), as well as human activity variables (road network density, as well as the type of peatland use and cover). Meanwhile, the dependent variable is the area of peatland affected by fire. This prediction sub-model can be written mathematically as shown in Equation 1 [6], whereas details of its explanatory variables are depicted in Table 1.

$$
P = \frac{e^{(\beta_0 + \beta_1 P_{	ext{t-LUC Bare Land}} + \beta_2 P_{	ext{t-LUC Farming Field}} + \beta_3 P_{	ext{t-LUC Forest}} + \beta_4 P_{	ext{t-LUC Plantation}} + \beta_5 P_{	ext{t-Luc Shrubs}} + \beta_6 P_{	ext{t-Luc Depth D2}} + \beta_7 P_{	ext{t-Luc Depth D3}} - 3.230E-01 + 1.733E-01 - 1.864E+00 + 8.133E-01 + 9.853E-01 - 9.532E-01 + 7.953E-01 + 1.677E+00 + 2.108E+00 + 1.258E+00)}{1 + e^{(\beta_0 + \beta_1 P_{	ext{t-LUC Bare Land}} + \beta_2 P_{	ext{t-LUC Farming Field}} + \beta_3 P_{	ext{t-LUC Forest}} + \beta_4 P_{	ext{t-LUC Plantation}} + \beta_5 P_{	ext{t-Luc Shrubs}} + \beta_6 P_{	ext{t-Luc Depth D2}} + \beta_7 P_{	ext{t-Luc Depth D3}} - 3.230E-01 + 1.733E-01 - 1.864E+00 + 8.133E-01 + 9.853E-01 - 9.532E-01 + 7.953E-01 + 1.677E+00 + 2.108E+00 + 1.258E+00)}}$$

(Eq. 1)

Table 1. Explanatory variables and significance levels for prediction sub-model

| Variable                  | Estimate | Std. Error | z value | Pr(>|z|) |
|---------------------------|----------|------------|---------|----------|
| (Intercept)               | -1.211E+01 | 2.296E-01 | -5.272E+01 | < 2e-16 **|
| Cnl_Den                   | -7.066E-04 | 8.375E-05 | -8.437E+00 | < 2e-16 **|
| Rvr_Den                   | -1.318E-02 | 2.453E-04 | -5.371E+01 | < 2e-16 **|
| Rd_Den                    | 4.747E-03  | 6.029E-05 | 7.875E+01  | < 2e-16 **|
| Pt_LUC Bare Land          | 5.352E+00  | 1.935E-01 | 2.766E+01  | < 2e-16 **|
| Pt_LUC Farming Field      | 3.586E+00  | 1.830E-01 | 1.959E+01  | < 2e-16 **|
| Pt_LUC Forest             | 2.832E+00  | 1.765E-01 | 1.605E+01  | < 2e-16 **|
| Pt_LUC Plantation         | 3.274E+00  | 1.760E-01 | 1.860E+01  | < 2e-16 **|
| Pt_LUC Shrubs             | 3.743E+00  | 1.762E-01 | 2.124E+01  | < 2e-16 **|
| Pt_Depth_D2               | 1.263E+01  | 1.428E-01 | 8.505E-01  | 3.76E-01 **|
| Pt_Depth_D3               | 6.566E+01  | 1.607E-01 | 4.086E+00  | 4.38E-05 **|
| Pt_Depth_D4               | -3.230E-01 | 1.733E-01 | -1.864E+00 | 6.23E-02 **|
| Pt_Type_H2a               | 8.133E-01  | 1.440E-01 | 5.648E+00  | 1.62E-08 **|
| Pt_Type_H3a               | -9.853E-01 | 1.621E-01 | -6.078E+00 | 1.22E-09 **|
| Pt_Type_H4a               | 7.953E-01  | 1.740E-01 | 4.570E+00  | 4.89E-06 **|
| Pt_Type_S1a               | 1.677E+00  | 3.739E-02 | 4.485E+01  | < 2e-16 **|
| Pt_Type_S2a               | 2.108E+00  | 1.445E-01 | 1.458E+01  | < 2e-16 **|
| Pt_Type_S2c               | 1.258E+00  | 1.493E-01 | 8.429E+00  | < 2e-16 **|
| Pt_Type_S3a               | 2.174E+00  | 1.619E-01 | 1.342E+01  | < 2e-16 **|
| NDMI_October (t-3)        | -6.658E+00 | 8.193E-02 | -8.126E+01 | < 2e-16 **|
| Precip_October (t-3)      | 3.533E+02  | 6.382E-04 | 5.536E+01  | < 2e-16 **|

Source: Maulana et al.[6]

2.2.2 Prevention sub-model

The prevention sub-model applied in this study refers to the decision support system (DSS) scheme in formulating peatland fire prevention strategies in Bengkalis Regency taken from [8]. This hierarchical sub-model was established based on analytical hierarchy process (AHP) method with consistency ratio (CR) of about 0.02 [8]. Overall, in this hierarchical scheme, there were four levels covered, namely...
target area, institutional criteria, institution in charge and prevention alternatives, as illustrated in Figure 2.

**Figure 2.** Weighted hierarchical scheme of peatland fire prevention sub model
Source: Maulana et al. [8]

2.3 Integration between peatland fire prediction and its prevention directives
This study applies a loose coupling mechanism as an integration approach between peatland fire prediction sub-model and peatland fire prevention sub-model [1], [9], [10]. Loose coupling integration approach is one of the most widely implemented in the development of SDSS-based models because it has several advantages, such as being able to facilitate interaction between different tools, where each of those tools may have a unique data format; does not require large scale investment; does not require intensive work processes for building common user interfaces for each software used; this mechanism is modular so that it may be upgraded rapidly without requiring software development from the beginning (major software rebuilding) when a system update occurs [9, 11, 12]. Referring to this intermediation concept, the calculation results between the prediction sub-model (spatial) and the sub-model of prevention strategies determination (non-spatial) are integrated by utilizing the attribute table function available in ArcGIS 10.5 software.

3. Result and discussion
3.1 Predictive-preventive scheme for peatland fire control in Bengkalis Regency
Based on the stages that have been implemented, the predictive-preventive control model in this study can be illustrated schematically as presented in Figure 3. In this scheme, there is a continuity between five basic components of SDSS, as explained by [1], including database management, model management, knowledge management, dialogue management, up to stakeholder management. The database components that are managed in this control model are divided into two parts, namely a spatial database which contains a series of data with geographical references needed as the input in calculating the likely time, location, and extent of peatland fire that will occur; and a strategic database that contains data on preference for prevention target areas, institutional capabilities, responsible parties for activities and alternative actions needed as input in determining the direction of strategies that can be applied. Spatial database management in this control model is carried out with the help of...
the ArcCatalog module in ArcGIS 10.5 software. Meanwhile, the strategic preference database is managed using Expert Choice 11 software. Technically, different with the spatial database in the model developed by Lee et al. [3], Noonan-Weight [4], Kalabodikis [5] which only covers climate and physiographic variables, the spatial database in this study also includes peat physical characteristics variables, as well as human activity variables. The addition of these variables needs to be implemented because basically for tropical area like Bengkalis Regency, climate and physiographic variables only act as supporting factors, not the triggers of peatland fire occurrences [13, 14, 15].

Figure 3. Schematic illustration of predictive-preventive model for peatland fire control in Bengkalis Regency

Meanwhile, in the model management component, as previously mentioned, the spatial model applied is a prediction model that can provide preparation time of up to 2 months prior the beginning of initial burning month. The availability of such preparation time is a crucial element considering that peatland fire has been widely acknowledged to be so hard to suppress when it was already occurred [16], [17], [18]. This prediction sub-model was built using R Studio software and can be managed with the help of ArcGIS 10.5 software. Meanwhile, the prevention sub-model that is utilized in determining the direction of prevention strategies was established based on a decision support system (DSS) scheme that was prepared through the analytical hierarchy process (AHP) approach. The AHP-based prevention sub-model can be used in the process of formulating a complex and unstructured
situation into a certain hierarchical structure, by giving a subjective value of the relative importance of each variable, and determining which variable has the highest priority in influencing outcomes in the situation faced, as stated by Marimin et al. [19]. This non-spatial sub-model is managed using Expert Choice 11 software.

Afterwards, the intermediation process between the results of peatland fire prediction with the direction of the necessary preventive strategies is carried out in the knowledge management section. In this section, prevention strategy placement is carried out with due regard to the results of the prevention sub-model and also considering the knowledge base owned by the analyst/operator regarding actions that can be applied according to the defined peatland ecosystem status (e.g. cultivation function / protected function), peatland management status (e.g. concession / non-concession), as well as the type of land use that exists. This intermediation step is carried out with the help of attribute table function in ArcGIS 10.5 software. Due to the need for involvement of the operator’s knowledge base in the intermediation process, the predictive-preventive control model structure in this study still requires the support of well-trained and experienced human resources to act as an analyst and operator of the developed system, as also described by [20].

Subsequently, the process of presenting outputs from the predictive-preventive model is carried out in the dialogue management section. In this section, the output is presented in the form of an interactive web-based interface based on a geographic coordinate system (world geodetic datum system/WGS-84) that can be accessed quickly through the internet either through a web-desktop browser (e.g. Safari on MacOS Chrome and Firefox on Windows) and web-mobile browsers (Figure 4). In addition, visualization with the concept of interactive web-based interface also allows decision makers/end users to interact with the results presented. The interactive functions that can be implemented include adding new layers, measurement of distance between points and area in metric units (e.g. m², km², hectare), geoprocessing analysis operations, features drawing, up to print formatting if visualization of print output is needed. All of those interactive functions can be directly accessed by the decision maker/end user through an online network connection. Internet-based application management in this study was established using ArcGIS Online-IPB University.

The last part of the predictive-preventive model scheme developed in this study is stakeholder management. Basically, in this section there are four main components involved, namely developer, analyst/operator, expert and decision maker/end user, as suggested by [1]. Ideally, analyst/operator is an officer who has expertise in the field of geographic information system and is familiar with peatland fire control policies, so that they may work separately from the developer. However, in this study the analyst/operator function is still held by developers who are in charge of collecting data, designing system architecture, programming system functionality, preparing required sub-models, analysing data, conducting intermediation process between sub-models, up to interpretation and visualization of produced output. Duality in function between developer and analyst according to [1], is a common thing to be implemented in the development of SDSS-based models. At the time of implementation, analysts/operators can be stationed in a collaboration office established at the Local Disaster and Fire Fighting Agency (BPBD-Damkar), as stipulated in Bengkalis Regency Regulation 23/2015. In order to be able to conduct their assignments, the analyst/operator requires a Windows 10-based computer operating system with a minimum 2.2 GHz Central Processing Unit (CPU) equipped with hyper-threading or multi-core capabilities, Random Access Memory (RAM) 16 GB, 256MB minimum Graphics Processing Unit (GPU) and 2 TB internal data storage.

Meanwhile, experts are people who have expertise and knowledge specifically on the topic of peatland fire in Bengkalis Regency. According to [20], the team of experts involved may originated from either the local area (local expert) or from outside the area (outside expert). In line with this perspective, the expert team in the predictive-preventive model in this study came from the Laboratory of Forest and Land Fire-IPB University, the Faculty of Engineering-Pasir Pangaraian University, and the Bengkalis Regency Government. The experts involved play a role in providing strategic advice and considerations to analysts/operators regarding alternative options available in the formulation process of appropriate peatland fire prevention measures based on their experience, expertise, and
review of data and information received from the decision maker/end user. Strategic considerations from the experts are given in the form of paired comparison questionnaires, where the results can be entered by analysts/operators in the strategic preferences database.

![Image of Bengkalis Peatland Prediction and Prevention Web Application](image)

**Figure 4.** Visualization of interactive web-based interface

In the meantime, decision makers/end users are stakeholders who will utilize the output of information generated as a basis for decision making. In this study, the parties that become decision makers/end users are concession holders, and the Local Disaster and Fire Fighting Agency (BPBD-Damkar) who act as the main coordinator in preventing peatland fire outside concession area. During the implementation of this system, this coordinating institution may also coordinate with other relevant institutions that are directly domiciled in Bengkalis Regency (e.g. the Agricultural Service, the Environmental Service, the Public Works Service, the Military and Police unit, the Civil Service Police Unit, the Community Fire Care Group, and Fire Care Farmers Group); as well as institutions in the nearest area, namely Manggala Agni Dumai and Siak Operational Areas. Technically, the online system that is built has two kinds of access options, namely public and limited access. Therefore, during its implementation the operator may restrict access to the system to be available only for parties related to peatland fire control in Bengkalis Regency by applying a username and password mechanism.

### 3.2 Implementation cycle

Proposed cycle of implementation of the predictive-preventive control model in this study is presented in Figure 5. The division of work phases is carried out based on consideration of the results of research on the trends of forest and land fires in Bengkalis Regency, as reported in [6], in which shows that the peak of peatland fire season in this regency tends to occur in January-August, with the highest incidence in February and March. The results are also in line with the findings reported by Syaufina et al. [21]. Considering those findings, in order to increase the effectiveness of peatland fire control, especially to avoid further delay during fire suppression, the work phase should begin by focusing on the warning stage and the implementation of preventive actions in November to December. The updating pattern in the predictive-preventive model in this study can be carried out in a modular manner, where calculations on the prediction sub-model can be carried out every November 1.
Meanwhile, the prevention sub-model can be renewed at any time if there is a change in strategic considerations, both related to the applicable laws and regulations, as well as related institutional aspects (e.g. budget availability, work authority, coordination capacity, completeness of the national education plan, as well as the human resources number and level of education) among local governmental agencies in Bengkalis Regency.

Figure 5. Proposed cycle of implementation

Overall, the implementation of such a predictive-preventive scheme may improve the effectiveness and efficiency of peatland fire control in Bengkalis Regency, due to its various advantages. First, it presents a decision support system that allows stakeholders to rapidly coordinate with each other in determining actions that need to be taken to prevent peatland fire. Secondly, the implementation of this model may encourage the adoption of a more pro-active approach through a predict and prevent mechanism, so that it may reduce and/or replace current fire control approach that still relied on detect and suppress strategy that is evidently ineffective in controlling peatland fire. Third, this predictive-preventive control model may also avoid delay in handling and misallocation of limited resources (e.g. budget, human resources, tools and facilities) in inappropriate locations. Lastly, it may also be rapidly upgraded to adapt to technological progress (e.g. software, hardware) and situation development in the field, without requiring high costs because of its modularity nature.

4. Conclusion
This study has presented the entire process in developing a predictive-preventive control model for peatland fire in Bengkalis Regency. Based on the spatial decision support system (SDSS) concept, the predictive-preventive control model in this study has covered five main components that divided into three levels, namely database management in the level of input, model management and knowledge management in the level of process, and dialogue management and stakeholder management in the level of output. Overall, the predictive-preventive model in this study consists of two sub-models, namely the prediction sub-model and the sub-model in determining appropriate prevention strategy. Those sub-models were integrated based on a loose coupling approach. Considering its accuracy and flexibility, the implementation of such a predictive-preventive system may increase the effectiveness and efficiency of peatland fire control in Bengkalis Regency.

References
[1] Sugumaran R and Degroote J 2011 Spatial Decision Support Systems: Principles and Practices (New York, US: CRC Press-Taylor & Francis Group)
[2] Guarnieri F, Jaber A and Wybo J-L 2008 Spatial decision support and multi-agent systems: Application to forest fire prevention and control In Brugnot G (editor) Spatial Management
of Risks (London, UK: ISTE Ltd)

[3] Lee B S, Alexander M E, Hawkes B C, Lynham T J, Stocls B J and Englefield 2002 Information in support of wildland fire management decisions making in Canada Computers and Electronics in Agriculture 37 185-198

[4] Noonan-Wright E K, Opperman T S, Finney M A, Zimmerman G T, Seli R C, Elenz L M, Calkin D E and Fiedler J R 2011 Developing of US Wildland Fire Decision Support System Journal of Combustion doi: 10.1155/2011/168473

[5] Kalabokidis K, Xanthopoulos G, Moore P, Caballero D, Kallos G, Llorens J, Roussou O and Vasilakos C 2011 Decision support system for forest fire protection in the Euro-Mediterranean Region European Journal of Forest Resources doi: 10.1007/s10342-011-0534-0

[6] Maulana S I, Syaufina L, Prasetyo L B and Aidi M N 2019 Formulating peatland fire prevention strategy in Bengkalis Regency: An Application of analytical hierarchy process Journal of Sustainability Science and Management 14(3) 55-66

[7] Kemp K K 2008 Encyclopedia of Geographic Information Science (California, US: SAGE Publications Inc)

[8] Maulana S I, Syaufina L, Prasetyo L B and Aidi M N 2019 Formulating peatland fires prevention strategy in Bengkalis Regency: An application of analytical hierarchy process Paper presented at the 1st International Seminar on Natural Resources and Environmental Management Bogor 15 August 2019

[9] Giacomelli A 2005 Integration of GIS and simulation models In Campagna M (editor) GIS for Sustainable Development (Boca Raton, US: CRC Press)

[10] Chakhar S and Mousseau V 2008 Multicriteria spatial decision support systems In Shekhar S and Xiong H (editor) Encyclopedia of GIS (New York, US: Springer)

[11] Malezewski J 2006 GIS-based multicriteria decision analysis: a survey of literature International Journal of Geographical Information Science 20(7) 703–726

[12] Carrick N A and Ostendorf B 2007 Development of a spatial Decision Support System (DSS) for the Spencer Gulf penaeid prawn fishery South Australia Environmental Modelling & Software 22(2) 137–148

[13] Tacconi L, Moore P F and Kaimowitz D 2007 Fire in tropical forest – what is the really problem? Lessons from Indonesia Mitigations and Adaptation Strategies for Global Change 12 55-66

[14] Murdiyarso D and Adiningsih E S 2007 Climate anomalies, Indonesian vegetation fires and terrestrial carbon emission Mitigations and Adaptation Strategies for Global Change 12 101-112

[15] Hooijer A, Page S, Jauhiainen J, Lee W A, Lu X X, Idris A and Anshari G 2012 Subsidence carbon loss in drained tropical peatlands Biogeosciences 9 1053–1071

[16] Rein G, Cleaver N, Ashton C, Pironi P and Torero J L 2008 The severity of smouldering peat fires and damage to the forest soil Catena 74(3) 304-309

[17] Syaufina L 2008 Kebakaran Hutan dan Lahan di Indonesia (Malang, ID: Bayumedia)

[18] Budiningsih K 2017 Implementasi kebijakan pengendalian kebakaran hutan dan lahan di Provinsi Sumatera Selatan Jurnal Analisis Kebijakan Kehtatanan 14(2) 165–186

[19] Marimin and Maghfiroh N 2010 Aplikasi Teknik Pengambilan Keputusan Dalam Manajemen Rantai Pasok (Bogor, ID: IPB Press)

[20] Strager M P and Rosenberger R S 2006 Addressing the wicked problem of water resource management: An ecosystem services approach Ecological Economics 58(1) 79–92

[21] Syaufina L and Hafni D A F 2018 Variability of climate and forest and peat fires occurrences in Bengkalis Regency, Riau Jurnal Silvikultur Tropika 9(1) 60–68