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Modification of a fire drought index for tropical wetland ecosystems by including water table depth

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ABSTRACT

In this paper, we discuss how an existing empirical drought index, i.e. the Keetch–Byram Drought Index (*KBDI*) that is commonly used for assessing forest fire danger, has been adjusted and modified for improved use in tropical wetland ecosystems. The improvement included: (i) adjustment of the drought factor to the local climate, and (ii) addition of the water table depth as a dynamic factor to control the drought index. We distinguished three different indices, the original Keetch–Byram Drought Index, the adjusted *KBDI* ($KBDI_{adj}$) that represents the original drought index, but including local climate information, and the modified *KBDI* (*mKBDI*) that considers both local climate information, and soil and hydrological characteristics. The *mKBDI* was developed and tested in a wetland forest of South Sumatra (Indonesia) from April 2009 to March 2011. During this period, hydrometeorological data were monitored and used to calculate the *KBDI*, $KBDI_{adj}$, and *mKBDI*. First, *mKBDI* was calibrated using observed soil moisture that was converted to an observed drought index (DI_{obs}). The results indicate that performance of the *mKBDI* is encouraging based on the following: (i) its pattern followed the dynamics of DI_{obs}, (ii) prediction of frequency of fire danger classes, and (iii) statistically criteria. The *mKBDI* clearly outperformed *KBDI* and $KBDI_{adj}$. Furthermore, we found a critical water table depth when it reaches maximum fire danger (0.85 m for the wetland forest of South Sumatra) below which danger does not increase anymore. The *mKBDI* could be more widely applied, if pedotransfer functions are developed that link easily obtainable soil properties to the parameters of the water table factor. Our findings encourage land use planners, water managers and stakeholders (e.g. forest estate owners) to integrate local climate information, and soil and hydrological characteristics into the Keetch–Byram Drought Index to better predict fire danger, particularly in tropical wetland ecosystems.

1. Introduction

Forest fire is a common phenomenon during dry seasons in equatorial rain forest regions, particularly in Sumatra and the Borneo in Indonesia (e.g. Goldammer, 2007; Miettinen et al., 2013). Land clearing activities meant to grow crops and to plant trees triggered fire during the dry season. It has become a critical problem in Southeast Asia, and previous studies report that it has a significant impact on socio-economic activities in the region (e.g. Salafsky, 1994; Chokkalingam et al., 2005); Dennis et al., 2005). Additionally, it also influences human health (Dennekamp and Abramson, 2011), particularly through increasing air pollution (Kunii et al., 2002; Frankenberg et al., 2005; Marlier et al., 2013). In some circumstances fire has positive impacts; because it may help to maintain habitat types used by specific taxa (e.g. Cleary et al., 2004). However, it mainly leads to ecological and environmental degradation, such as biodiversity loss (Ager et al., 2007), and to significant change in the floristic and structure of natural forest ecosystems (Xaud et al., 2013; Wallenius et al., 2007). As fire has a significant impact on human activities and environment, it challenges scientists to understand fire behaviour (e.g. occurrence, ignition, intensity, potential spread) particularly related to weather (e.g. Wibowo et al., 1997; Arpaci et al., 2013; Petros et al., 2011), and to develop tools for management (e.g. Adams et al., 2013).

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Society and environment are anticipated to benefit from the increased knowledge and improved management tools.

Forest fire danger often rises during dry seasons, which is associated with a rainfall deficit. As rainfall reduces, soil moisture depletes to compensate for evapotranspiration. Fuels become drier making these vulnerable to ignite and burn. Previous studies demonstrate that soil moisture deficits influence moisture content in dead fuels (necromass and surface litter, e.g. Pook and Gill, 1993; Pellizzaro et al., 2007). Soil moisture deficit is therefore a good proxy for the fuel moisture content and hence to assess fire danger potential (Cooke et al., 2012). One of the drought indices specifically developed to assess fire danger is the Keetch–Byram Drought Index (Keetch and Byram, 1968). Other drought indices can be found in Petros et al. (2011) and Arpaci et al. (2013). Several efforts have been carried out to show that the Keetch–Byram Drought Index (*KBDI*) is related to fuel moisture content in several ecosystems particularly for shrubs (Pellizzaro et al., 2007) and savannah (Verbesselt et al., 2006).

The *KBDI* was developed for forest control management and fire danger assessment in the USA, in particular Florida State (Keetch and Byram, 1968). The index is a cumulative estimate of moisture deficiency based on meteorological variables and an empirical approximation for moisture depletion in the upper soil and litter layer. It uses mean annual rainfall measured in Florida as a climate indicator (Keetch and Byram, 1968). The *KBDI* has been widely used for assessing fire danger because it is easy to calculate (Dimitrakopoulos and Bemmerzouk, 2003) and it does not require a lot of data (i.e. daily maximum air temperature and rainfall at a nearby standard meteorological station). Several studies have applied the *KBDI* in other areas than Florida State, such as Northern Eurasia (Groisman et al., 2007), Hawaii (Dolling et al., 2005), Australia (Boer et al., 2009; Finkele et al., 2006; Caccamo et al., 2012), Russia (Malevsky-Malevich et al., 2008), Mediterranean regions (Petros et al., 2011), in Southeast Asia, such as Indonesia (Murdiyarso et al., 2002; Buchholz and Weidemann, 2000) and Malaysia (Ainuddin and Ampun, 2008). Heim (2002) and Petros et al. (2011) indicate that the *KBDI* is the most widely used and accepted index for forest fire monitoring and prediction.

Although the *KBDI* has broadly been used, improvement of the *KBDI* model structure or its application is still necessary, especially for regions with climates, soils and hydrology distinct from those of Florida, such as tropical wetland ecosystems in Southeast Asia. Without any adjustment to the model structure, the application of the *KBDI* in other climates still may be problematic (Liu et al., 2010), as the drying rate in the index depends on the mean annual precipitation representative for Florida State (Keetch and Byram, 1968). These issues suggest that the wider applicability of the *KBDI* could be improved when the model would be adapted to accommodate other climate, soil and hydrological conditions than those in Florida.

The development of the *KBDI* for wetland ecosystems in Indonesia is a challenge because the tropical climate has an annual rainfall that is nearly twice that of Florida. These large differences in annual precipitation imply affect drying rates. In addition, locations in Indonesia (particularly in Sumatra and the Borneo Islands) that experience forest fires are predominantly wetlands. This is where fire has the most severe impacts on air pollution and *GHG* emissions. They also represent a 'last frontier' where non-wetland forests have already been destroyed and converted. The shallow water table that occurs there, supplies water into the surface layer through capillary rise (upward flow in unsaturated soil). In dry seasons, water tables tend to decrease, causing the upper layer to dry. Hence the fuel becomes much more vulnerable to fire than in non-wetland conditions. However, currently no model structure is available that integrates the higher annual rainfall and the water table into the drought index for use in tropical wetland ecosystem. We anticipate that integrating these aspects in the *KBDI* will improve applicability in Southeast Asia and progress on the studies by Murdiyarso et al. (2002), Buchholz and Weidemann (2000) and Ainuddin and Ampun (2008). Therefore, the objective of this paper is: (i) to modify the fire drought index *KBDI* for climate, soil, and hydrological conditions representative for wetland areas in humid tropical climates, and (ii) to analyze the influence of the water table depth on the dynamics of the *KBDI*.

2. The Keetch–Byram Drought Index

2.1. Original model

The Keetch–Byram Drought Index (*KBDI*) uses a mathematical function to correlate weather conditions to potential fire danger, which can be applied both to accidental and deliberate fire initiation. The index is a number that represents the net effect of evapotranspiration and precipitation, which might lead to a soil moisture deficit in the duff and upper soil layers. Actually, it is a hydrological approach of fire danger and its application is only limited to forests. It is based upon a rather simple representation of a forest where the forest vegetation density is controlled by the mean annual rainfall, which controls the rate of soil moisture loss. The loss rate will decrease with lower forest vegetation density, hence with lower annual rainfall. The *KBDI* is based on 8 in. (203 mm) of soil water available for evapotranspiration (Keetch and Byram, 1968). It is expressed in hundredths of an inch on a scale from 0 to 800 × 10^{-2} in.). In the metric system, the index is on scale from 0 to 203. Zero indicates no moisture depletion and 203 reflect the highest depletion, i.e. the maximum drought severity level. Hence it represents the highest fire danger.

Mathematically, the *KBDI* is formulated as follows:

$$KBDI^t = KBDI^{t-1} + DF^t - RF^t \quad (1)$$

The variables and units are describes in Table 1.

In general, the drought factor (DF^t, Crane, 1982) on a given day in the metric system is:

$$DF^t = \frac{(203 - KBDI^{t-1})(0.968e^{(0.0875\times T_m+1.552)} - 8.3)\times 10^{-3}}{1 + 10.88e^{(-0.001736\times R_0)}} \quad (2)$$

Rainfall is considered to reduce the drought index, if it is more than 5.1 mm/day (Eq. (3)):

$$RF^t = \begin{cases} (R^t - 5.1), & R^t \geq 5.1\ \text{mm/day, 1st rainy day} \\ R^t, & R^{t-1} \geq 5.1\ \text{mm/day, 2nd and the next rainy day} \\ 0, & R^t < 5.1\ \text{mm/day} \end{cases} \quad (3)$$

2.2. Model improvement

Previous research already has indicated that the *KBDI* even in the USA is not everywhere a good indicator of the fire danger, such as in Mississippi region (Cooke et al., 2007; Choi et al., 2009) and Georgia region (Chan et al., 2004). Thus, an improvement is necessary to account for other climatic conditions. Furthermore, capillary rise from the water table to the topsoil in wetlands also needs to be included. A modified *KBDI* is proposed that takes into account local climate information, and soil and hydrological characteristics.

2.2.1. Improvement using local climate conditions

Climate variables influence the development of the drought index *KBDI* over time. Keetch and Byram (1968) assumed that climate variables (particularly annual rainfall and evapotranspiration) determine how much water will be lost from the soil-duff