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Fluctuation of Soil Water Content in the Tropical Seasonal Forests of Cambodia Focusing on Soil Types and Properties

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Abstract

Forests with a tropical monsoon climate are often influenced by extreme climatic phenomena. We investigated the differences in actual water content of surface soils in a lowland evergreen forest (EF) and deciduous forest (DF) in Cambodia, yearly from 2014 to 2016. The average soil water content values were higher for lowland EF than for DF, showing a distinct difference in the dry seasons. A major reason for this were the differences in soil type and thickness: Acrisols have an average thickness of 7 m, whereas Plinthosols, Arenosols, and Leptosols have an average thickness of 1 m; thicker, fine-textured soils contain and supply substantial amounts of water even in dry seasons. In the lowland EF site, some ponds were near the stream water during an average year's dry seasons because the groundwater levels were close to the soil surface year-round. However, in extreme climate, such as "El Niño" in February 2016, all ponds in the EF dried up, and the surface soils contained no water at several points of higher elevation. At the lowland DF site, even during "El Niño," the surface soil water content did not reach zero; this could be due to their high water-holding capacity and low evapotranspiration, and the effect of no understory vegetation. On average, the lowland DF site showed lower values than the lowland EF site, especially in Leptosols, which are quite thin. Soil water content fluctuation is important for understanding Cambodia's unique forest landscape; specifically, lowland EF and DF form a mosaic in a similar monsoon climate. We presented the variations of soil water content spatially, seasonally, and interannually, which were mainly explained by soil thickness and partially by soil type and texture. The spatial variations in the 4-ha plot corresponded well with the tree species characteristics.

Discipline: Forestry
Additional key words: El Niño, lowland deciduous forest, lowland evergreen forest, soil thickness

Introduction

The two types of tropical seasonal forests in Cambodia, lowland evergreen forest (EF) and lowland deciduous forest (DF), are presumably formed under distinct soil moisture availability in the dry season (Ohnuki et al. 2008a). Lowland EF with *Diospyros* spp., *Sindora siamensis*, and *Syzygium* spp., among others, are formed on thick Acrisols and distributed in the west bank of Mekong in the Kampong Thom province (Iida et al. 2013, Ito unpublished data, Tani et al. 2007). The canopy of an EF is foliated throughout the year, and forest trees are assumed to be able to use soil moisture even during the dry season. Contrarily, lowland DF with deciduous dipterocarps and *Terminalia* spp. defoliate during the dry season (Ministry of Agriculture and Forestry 1968, Pin et al. 2013), as the forest trees hardly use soil moisture in dry seasons. Lowland DFs are predominant, and they cover 25% of the land area (Forestry Administration 2011) and widely extend over the east bank of Mekong in the Kratie province.

Soil types and thicknesses are the main distinctions

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in the belowground conditions of both sites. Lowland EF are formed on Acrisols (Ohnuki et al. 2007, 2008b, Toriyama et al. 2013), whereas lowland DF are formed on Plinthosols (Toriyama et al. 2010), Arenosols, and Leptosols, according to the Food and Agriculture Organization (FAO) classification (FAO 1998). The differences in soil type potentially affect the soil's physical property of retaining water through the differences in soil texture. Soil thickness has a direct impact on its possible water storage capacity. Measurements were taken at a very limited number of sites, but soil thicknesses of 13.2 m in EF and 2.6 m in DF have been reported (Ohnuki et al. 2008a). Although the growing environments of lowland EF and DF become clear at some level because of the small scales of measurements and analysis, they were lacking in the amount of scale for determining areas on a similar topography.

Additionally, El Niño–Southern Oscillation (ENSO) has much effect on the tropical seasonal forests because of the interannual change of precipitation (Kabeya et al. 2021, Malhi & Wright 2004, Räsänen & Kummu 2013, Rasmusson & Carpenter 1982, Webster & Yang 1992). The interannual and seasonal fluctuation of soil water content, comparing multiple years with and without ENSO influence, has not yet been investigated.

In this study, we focus our attention on the soil water content fluctuation of surface soils in lowland EF and DF in Cambodia. Firstly, we clarified the spatial distribution of soil thickness relating to topography and soil types in 4-ha plots of both forests. Secondly, we evaluated the spatial variation of surface soil water content in the 4-ha plots, as well as the seasonal and interannual fluctuation for 3 y, including the extra dry season affected by El Niño, from 2014 to 2016.

Furthermore, in relation to the spatial variation of soil water content, we referred to the extent of ponds at the lowland EF plot and leafing during the dry season at the lowland DF plot. Finally, we examine and analyze the relationship between the fluctuation of soil water content and several soil properties, including soil types and thicknesses.

Study area

The survey sites for this study were in the provinces of Kampong Thom and Kratie (Fig. 1: top). In the Kampong Thom province, in an area of lowland EF (12.73°N, 105.47°E), the surface geology was Quaternary, forming river terraces overlying sedimentary rocks. According to the FAO classification, the main soil distributed in the area is Acrisols (Toriyama et al. 2007a), which contains much silt fraction near the surface. In the Kratie province, in an area of lowland DF (12.92°N, 106.20°E), the surface geology consisted of old sedimentary rocks and basalts. The main soils distributed in the area are Plinthosols, Arenosols, and Leptosols, according to the FAO classification (FAO 1987, Toriyama et al. 2007b). Plinthosols are clayey soils possessing a hard layer of plinthite in the shallow layer; Arenosols are thick, sandy soils; and Leptosols are shallow, debris soils. Meteorology observation towers were installed in both sites (Iida et al. 2013, 2016, 2020; Kenzo et al. 2012; Nobuhiro et al. 2007; Shimizu et al. 2018; Tamai et al. 2007). The average precipitation from 2013 to 2017 in Phnom Penh was 1,450 mm (Japan Meteorological Agency 2020); the values significantly changed from 1,066 (2015, El Niño) to 1,869 mm (2016, from El Niño to La Niña) (Ju & Slingo 1995, Zhang et al. 2002) (Table 1).

At each site, a 4-ha (200 m × 200 m) permanent vegetation census plot was established, with the meteorological tower placed at the center (Fig. 1: bottom). The vegetation of the lowland EF (plot EF: A) was dominated by *Myristica iners* (Myristicaceae), which had prop and buttress roots (Yamada 1984), contributing to 18% of the basal area. The other dominant species was *Lophopetalum duperreanum* (Celastraceae), contributing to 9.4% of the basal area, and *Tristaniopsis merguensis* (Myrtaceae), contributing to 8.8% of the basal area. The stand density was 1,485 ha^{-1}, and the maximum tree height was 43.9 m (Ito unpublished data). 11 wells were also installed to measure the groundwater levels (Kabeya et al. 2021). Conversely, in the lowland DF (plot DF: B), the vegetation was dominated by *Dipterocarpus tuberculatus* (Dipterocarpaceae), contributing to 31% of the basal area. The other dominant species was *Shorea siamensis* (Dipterocarpaceae), *S. obtusa* (Dipterocarpaceae), and *Terminalia alata* (Combretaceae), contributing to 19.1%, 18.5%, and 18.5% of the basal area, respectively. The stand density was 564 ha^{-1} (Ito et al. 2018), and the maximum tree height was 27.9 m (Monda et al. 2016). The trees of *T. alata* were divided into two phenotypes: the glabrous leaf type and hairy leaf type (Ito et al. 2018). The understory vegetation was dominated by *Vietnamosasa pusilla*, a perennial grass, which experiences the dieback of its aboveground portion before the middle of the dry season. The leaf flush of the understory vegetation occurs after the early leaf expansion of the overstory trees (Iida et al. 2020).

Methods

Soil thicknesses were measured using a dynamic cone penetrometer in and around both plots (Ohnuki et al.

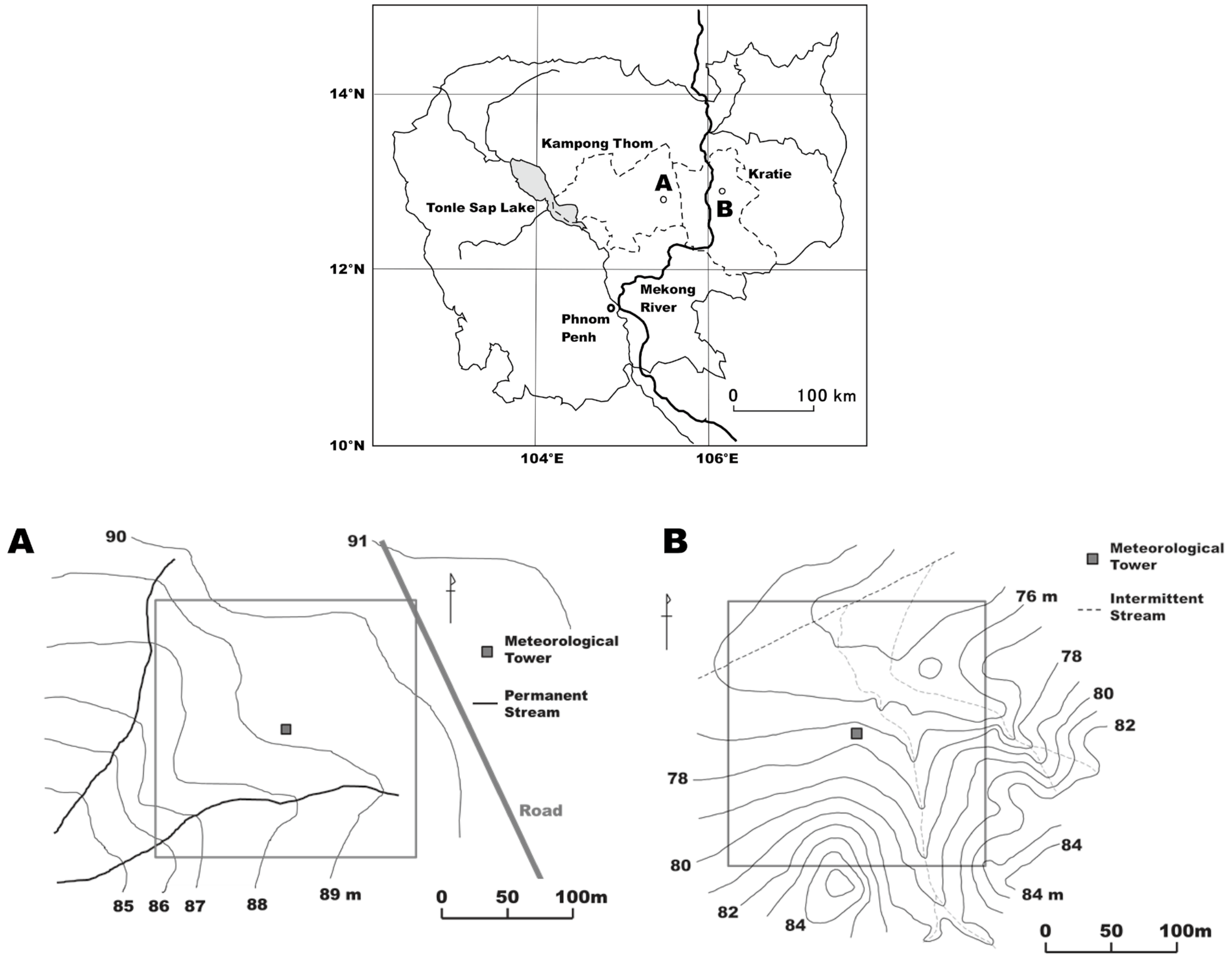

Fig. 1. Topographic map of plots evergreen forest (EF) and deciduous forest (DF) with a location map of Cambodia
A: plot EF, B: plot DF, Kampong Thom: area of Kampong Thom province, Kratie: area of Kratie province

Table 1. Precipitation data of Phnom Penh from 2013 to 2017

Year	2013	2014	2015	2016	2017
Jan.	0.0	0.0	3.0	0.0	16.0
Feb.	0.0	6.0	0.0	0.0	7.0
Mar.	2.0	14.0	3.0	0.0	15.0
Apr.	134.0	147.0	125.0	3.0	250.0
May	100.0	45.0	34.0	36.0	230.0
Jun.	209.0	199.0	100.0	243.0	95.0
Jul.	146.0	191.0	74.0	285.0	159.0
Aug.	146.0	194.0	191.0	105.0	273.0
Sep.	124.0	231.0	246.0	357.0	326.0
Oct.	299.0	250.0	185.0	465.0	139.0
Nov.	213.0	158.0	92.0	201.0	143.0
Dec.	51.0	33.0	13.0	174.0	18.0
AVE	118.7	122.3	88.8	155.8	139.3

Revised from the Japan Meteorological Agency (http://www.data.jma.go.jp/)

2007, 2008b). The apparatus consisted of four parts: a top cone with a sharp (60°) angle and diameter of 25 mm, guide rod, knocking head, and 5-kg weight. The soil thicknesses were expressed in Nc values obtained from the penetrometer test. The values were determined by counting the number of times the weight had to be dropped from a height of 50 cm to drive the cone 10 cm into the soil. The threshold of soil layer and saprolite (weathered rock) was 5 of Nc value, and the saprolite zone was from 6 to 50 of Nc value. The measurements were continued until the Nc value exceeded 50 until fresh bedrocks.

Soil profiles were dug near the measuring points of soil thickness. At plot EF, distributing only one soil type (Acrisols), we dug two profiles at the northern and southern points of the plots for confirming the less of the difference of soil properties. Meanwhile, at plot DF, we dug small soil profiles at all measuring points for confirming soil types and soil texture in situ.

Soil water content, which is the main target of this paper, was measured five times from 2014 to 2016 using time-domain reflectometry (TDR) (FIELD SCOUT TDR100; Spectrum Technologies, Inc., Aurora, USA); calibration-free in two measuring modes of volumetric soil water content) on 39 points (plot EF) and 40 points (plot DF). The measurements of dry seasons included the month of February in 2014, 2015, and 2016, and those of the rainy seasons included September 2014 and November 2016. For the measurement, two probes (length: 12 cm) were placed vertically into the soil surface, and the collected data are shown as the average value from the surface to −12-cm depth (Ohnuki et al. 2020). Here, we measured in high clay mode the areas of Plinthosols and in standard mode the other soil types.

Furthermore, only in plot EF, we checked visually the existence of ponds and prop and buttress roots near the measuring points of soil water content. Moreover, only in plot DF, we verified the leafing during a dry season in January 2020. The verification was conducted by counting whether the trunks of 10 trees near the measurement points of soil water content leaved or not. Additionally, leafing was divided into "green leafing," "reddish leafing," and "none leafing."

Results and discussion

1. Relationship between soil thickness, topography, and soil types

In plot EF, soil thickness ranged from 2 m to over 10 m (Fig. 2-A). Soils thinner than 6 m were distributed along the two headwater streams, in the south and west areas of the plot; thicker soils over 6 m were located on the slightly mounded northeast area among the two streams. Although only Acrisols are found in the plot, iron-rich, reddish surface soils were found near the streams in the south and west areas, and iron-poor, whitish surface soils extend in the northeast area of the plot.

Contrastingly, in plot DF (Fig.2-B), soil thickness ranged from less than 0.5 to 2.5 m. Different from another plot, thicker soils were located along and around the intermittent streams, except for the uppermost reach of them. The hilly area in the south and east sides of the plot had quite shallow soils. With respect to the soil types (Fig. 3), the distributed areas of Leptosols and thin soil thickness areas (median value: 0.4 m) overlapped each other less than 1 m. Moreover, Plinthosols and Arenosols had similar soil thicknesses; the median values were 1.7 m and 1.4 m, respectively. These two groups were significantly different at $P < 0.05$ (following the Tukey–Kramer honestly significant difference test) (Ito et al. 2017).

2. Fluctuation of soil water content in each plot

The soil water content was measured five times: thrice during the dry seasons and twice during the rainy seasons. As mentioned earlier, El Niño had affected the February 2016 data, and La Niña had affected the November 2016 data.

In the first measurement during the dry seasons in February 2014 (Fig. 4), the soil water content ranged from 30 to 40% along and near the two headwater streams in plot EF (a). The higher the elevation from the streams, the lower the soil water content. The minimum value was 2% in the northeast part of the plot. In plot DF (b), along and near the intermittent streams, several points showed rather high values of over 30%. However, the median values were not significantly different among the three soil types, ranging from 6 to 8%. During this period, there was no significant difference among the three soil types.

In the first measurement during the rainy season in September 2014 (Fig. 5), in plot EF (a), except for the northeast part, the values were over 20%. Especially on concave-shaped gentle slopes near the headwater streams, the values often showed over 40%, and some ponds appeared. In plot DF (b), the highest values ranging 30%-40% appeared only in the distributed areas of Arenosols. In contrast, the areas of Leptosols showed distinctly low values, i.e., 5.1%-10%. The values of both soil types were significantly different at $P < 0.01$ (following the Steel–Dwass test, a nonparametric multiple comparison test).

Next, in the second measurement during the dry

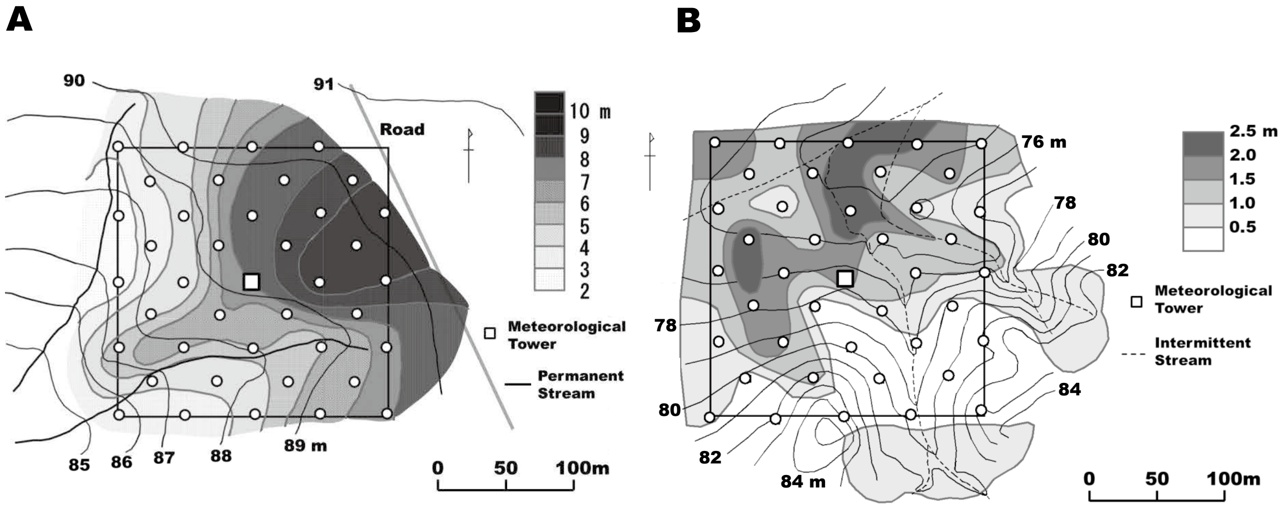

Fig. 2. Distribution of soil thickness in both plots
A: plot evergreen forest (EF), B: plot deciduous forest (DF)

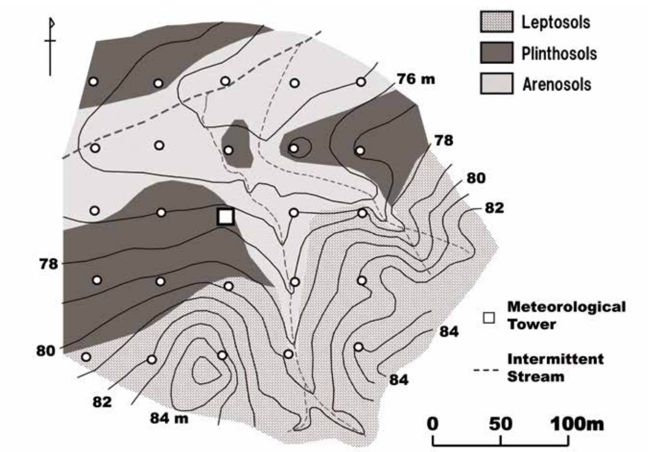

Fig. 3. Soil map in plot deciduous forest (DF)
Revised from Ohnuki et al. (2014)

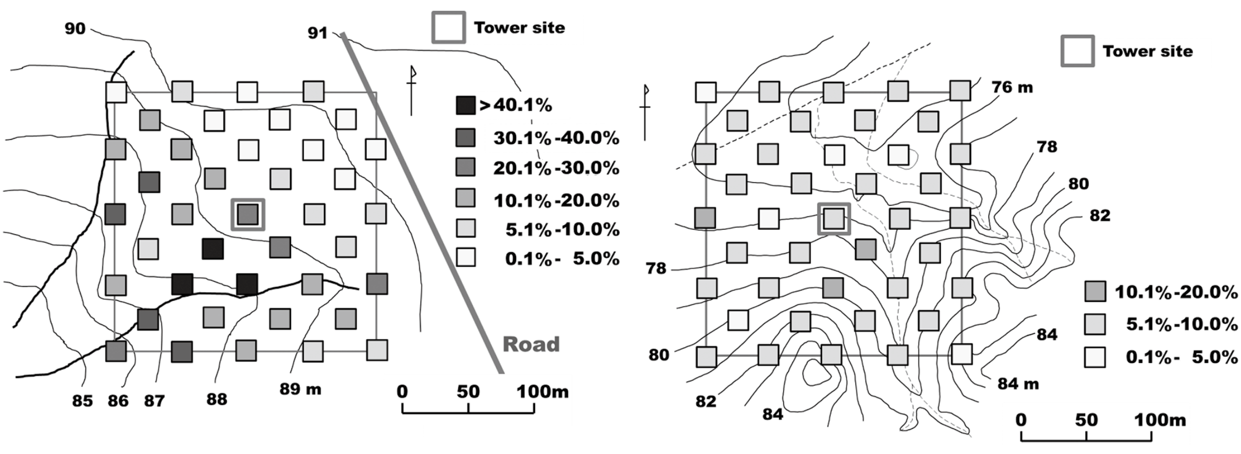

Fig. 4. Soil water content in February 2014
a: plot evergreen forest (EF), b: plot deciduous forest (DF), %: % in volume

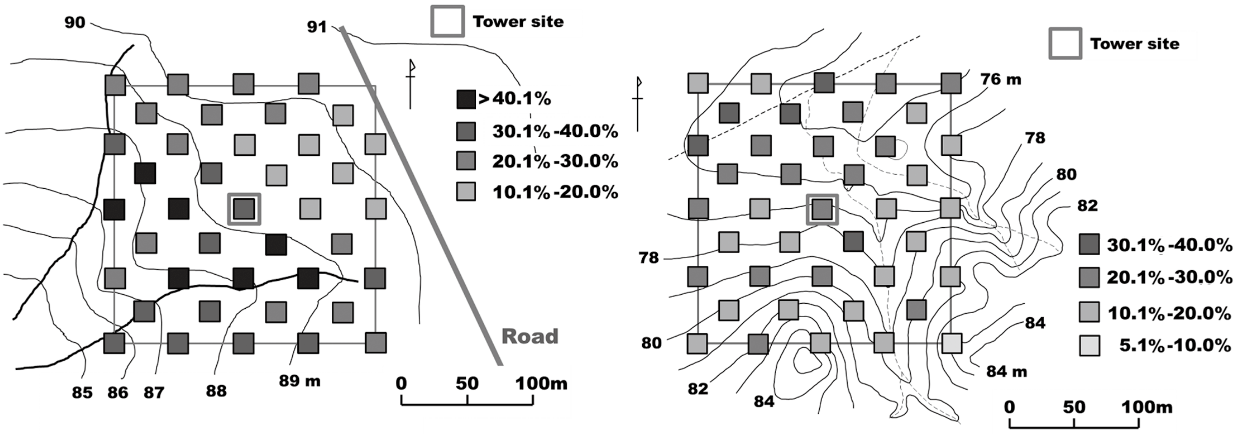

Fig. 5. Soil water content in September 2014
a: plot evergreen forest (EF), b: plot deciduous forest (DF), %: % in volume

seasons in February 2015 (Fig. 6), owing to the smaller precipitation in the former several months of 2014, the soil water content of both plots was less than that in February 2014. In plot EF (a), the values ranged less than 10% at 21 points, of which there were values less than 5% at 8 points. In plot DF (b), the effect of smaller precipitation was larger than that in the EF plot; over 90% of the points showed values less than 10%. During this period, there was no significant difference in each soil type.

In the third and last measurement during the dry seasons in February 2016 (Fig. 7), the El Niño from 2015 to 2016 severely affected the soil water content of plot EF (a). Due to the extreme desiccation of the surface soils, five points indicated 0% soil water content. Moreover, no point showed a value over 30%, and there were no ponds, even along and near the headwater streams. However, there was no severe effect in plot DF (b). Similar to the values of February 2015, 95% of the points showed values less than 10%; however, all points had significant values of soil water content. As with the former measurements, there was no significant difference in each soil type.

Finally, the second and last measurement during the rainy seasons was conducted in November 2016 (Fig. 8), with much precipitation from June to October owing to La Niña. In both plots, the soil water content was similar to that of September 2014. Giving a detailed description, wet points with over 40% of soil water content decreased from 7 to 2 points in plot EF (a), although all points showed the same range of values in plot DF (b) (see Fig. 5). The values of Arenosols and Leptosols were significantly different at $P < 0.05$ (following the Steel–Dwass test).

3. Distribution of trees with prop and buttress roots and soil water content at plot EF

As noted above, plot EF was located at the uppermost reach of the two headwater streams. Except for an extraordinary dry period influenced by the El Niño from 2015 to 2016, several ponds and marshes spread along a stream and near the tower site (Fig. 9-X). According to Kabeya et al. (2021), the groundwater levels near the headwater stream during dry seasons showed at most −50 cm in normal years; however, from 2015 to 2016 (El Niño), it showed −180 cm. Meanwhile, *M. iners* (Myristicaceae), which is the most dominant species in plot EF and has prop and buttress root, were distributed around the same place (Fig. 9-Y). Notably, ponds and *M. iners* widely extended over 100 m of length and 10 m-25 m of width in the southeast area of the plot.

On a global scale, the main habitat of *M. iners* was the lower reach of great rivers, for instance, Mekong, Menam Chao Phraya, and Irrawaddy (Yamada 1984). There were mildly-sloped freshwater marsh forests in large areas. The location of this plot was apart from the large freshwater marsh forests; however, owing to the constant excessive moisture condition along and near the headwater streams, the habitat of *M. iners* could have been maintained.

4. Distribution of leafing in the dry season at plot DF

In addition to the main measurements, we verified the leafing during the dry season at plot DF on January 31, 2020. The leafing was confirmed by counting the green, reddish, and none leafing of 10 trees around the measuring points of soil water content. Figure 10 shows the result of 40-point measurements using the soil map. Although the measurements were conducted during the middle of the dry season, we could verify the

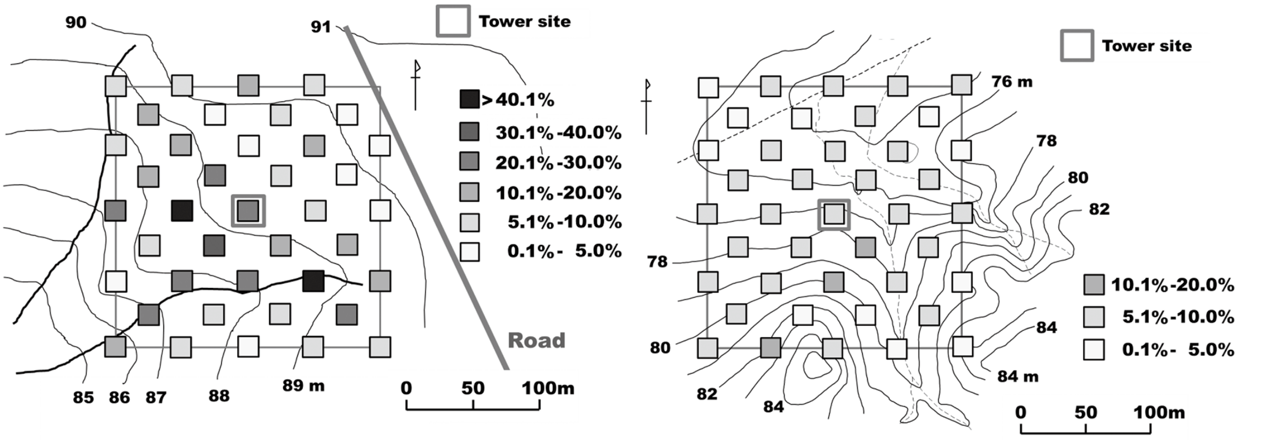

Fig. 6. Soil water content in February 2015
a: plot evergreen forest (EF), b: plot deciduous forest (DF), %: % in volume

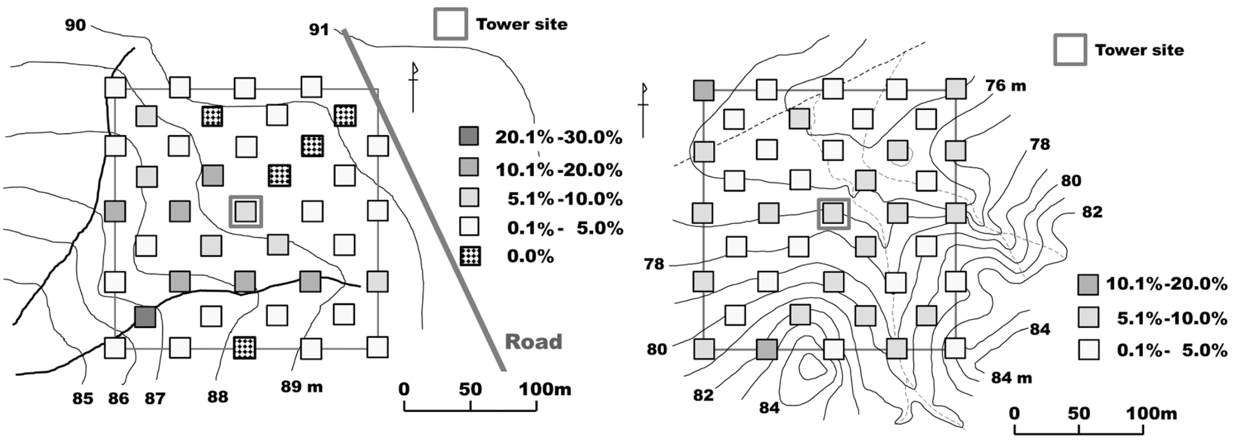

Fig. 7. Soil water content in February 2016
a: plot evergreen forest (EF), b: plot deciduous forest (DF), %: % in volume

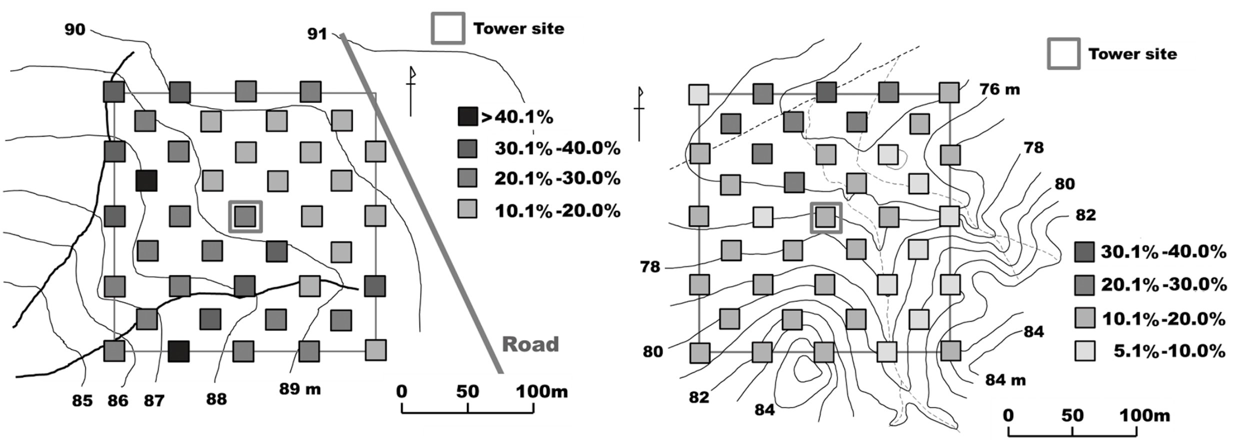

Fig. 8. Soil water content in November 2016
a: plot evergreen forest (EF), b: plot deciduous forest (DF), %: % in volume

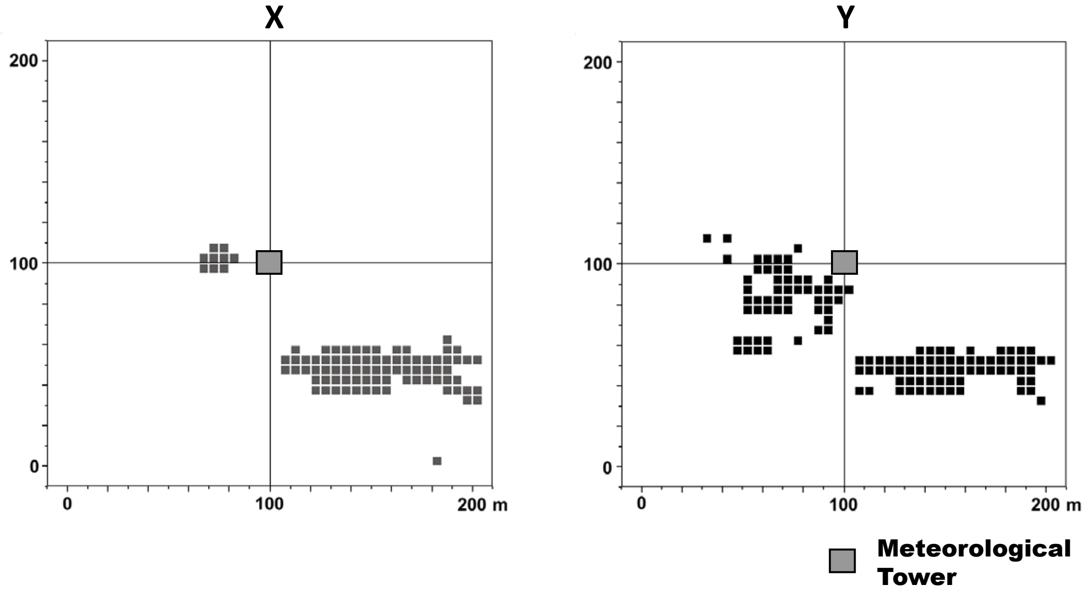

Fig. 9. Distribution of ponds and *Myristica iners* in plot evergreen forest (EF)
X: location of the ponds, Y: location of *M. iners*

predominance of leafing on 80% of the whole points. Comparing each soil type, Plinthosols and Arenosols had evidently high leafing ratio, and Leptosols showed a low leafing ratio. The values of both groups were significantly different at $P < 0.01$ (following the Steel–Dwass test).

One of the reasons for this could be the distinct difference of soil water content in the rainy seasons (see Figs. 5 & 8). Although the difference during the dry seasons was not very clear owing to the effect of constant evaporation from the soil surface, deeper soils where roots could reach and suction water could contain the difference of soil water volume affected by rainy season precipitation. Moreover, soil thickness also affects the difference in the water-holding capacity used for leaf flushing.

Another reason could be the distribution of the tree species, which can leave during the dry seasons and halts leaving at the beginning of the rainy seasons (Iida et al. 2016, Ito et al. 2018). The two types of *T. alata*, hairy type and glabrous type, had clear spatial separation. The former leaved during the dry seasons, whereas the latter leaved around June during the rainy season. The hairy type was limited to the flat areas along and near the intermittent streams, i.e., the areas of Arenosols and Plinthosols. Contrastingly, the glabrous type mainly extended over the hilly areas of Leptosols. The other main tree species, *D. tuberculatus*, *S. siamensis*, and *S. obtusa*, could leaf in dry seasons. As stated above, Figure 10 shows the effects of soil type, soil thickness, and the distribution of tree species.

5. Relationship between the fluctuation of soil water content and soil properties

Based on the measurement results, soil water content was linked to vegetation, soil type, soil thickness, and topography. In the two research plots, EF and DF, the most different factor concerning the soil water content was soil thickness (Fig. 2). Even in similar topographies of headstreams and back gentle hills, both research plots had different thicknesses of soil layer from 3 to over 10 m and from less than 0.5 to 2.5 m.

With respect to plot EF, the difference in the soil types could result in the distinction of growing environments, i.e., the difference in soil thickness led to the integral effective water storage capacity of soils. Toriyama et al. (2011) measured the effective water-holding capacity (ranges from −10 to −1,500 kPa) of DF soils, including the thin soil types, Plinthosols, Arenosols, and Leptosols. They demonstrated that the average effective water-holding capacity is 0.146 m^3m^{-3} and their porosity composition was also not so different. Furthermore, they concluded that the integral effective water-holding capacity is determined not by soil porosity composition but by soil thickness. Assuming that the effective water-holding capacity of the three soil types in plot DF is 0.146 m^3m^{-3}, the integral effective water storage capacity of each soil type are 248 mm for Plinthosols, 204 mm for Arenosols, and 58 mm for Leptosols. Thus, among the three soil types, Plinthosols could store more water, which could be available for deciduous trees. Moreover, considering that the distributional area of the Plinthosols is located at the foot of the hill, soil water and

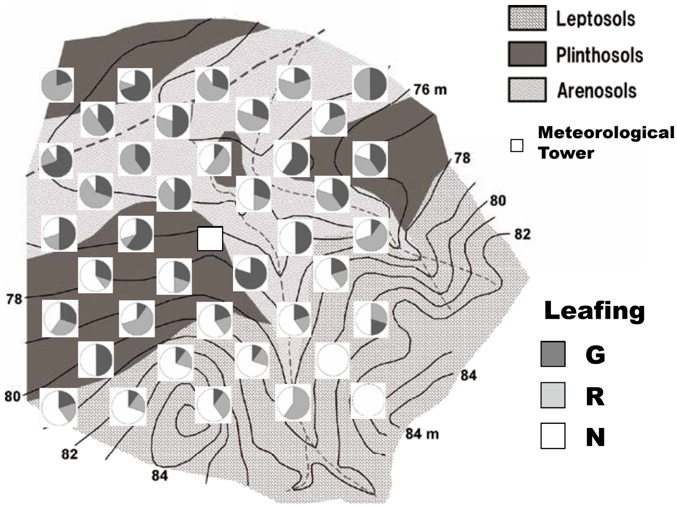

Fig. 10. Distribution of the leafing type in February 2020 in plot deciduous forest (DF) with the soil map
G: green leafing, R: reddish leafing, N: non leafing

groundwater could be supplied from the upper slope.

Comparing plots EF and DF based on the groundwater level during the dry season of a normal year, the former was found to be just below the surface besides and near the headwater streams (Kabeya et al. 2021); in contrast, the latter was in the weathered rocks deep under the ground (Kabeya et al. 2010). The reason for this difference of groundwater levels is that soil thickness plays a role in retaining and supplying water to headwater streams. At plot EF, from the actual measurements of groundwater levels and a water transfer model, the soil water would slowly move from the thicker soils in the northern area at a higher elevation to the lower headwater streams (Araki et al. 2007, 2008).

Soil texture, which is closely related to soil type in our study sites, affects the soil's physical properties of retaining water, resulting in different surface soil moisture under extremely dry conditions. Under the ultimate drying of surface soils owing to El Niño, most of the ponds disappeared in plot EF on February 2016 (Fig. 7), whereas the surface soils in plot DF were not severely affected compared to during the normal years. One of the reasons for the higher surface soil moisture in DF could be the distinction of surface soil texture that affects its water-holding capacity. Silty soils have lesser porosity than sandy and clayey soils (Ohnuki et al. 2008a, Toriyama et al. 2007a) and are very hard, with less than 10% soil water content (Ohnuki et al. 2008b). In addition to the small amount of water storage capacity in drier conditions, they showed a low water content of 0% (Fig. 7), partially caused by the effect of soil evaporation, the main source of water vapor released by the forest floor because of the dieback of understory vegetation during the middle dry season (Iida et al. 2020).

Altogether, the fluctuation of soil water content is a decisive factor in understanding Cambodia's unique forest landscape; particularly, the lowland EF and DF that form a mosaic in a similar monsoon climate. We presented the variations of soil water content spatially, seasonally, and interannually. These variations were mainly explained by soil thickness and partially by soil type and texture. The spatial variations in the 4-ha plot corresponded well with the tree species characteristics in both EF and DF plots.

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