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Distribution, Growth and Site Requirements of Teak

Nobuyuki TANAKA*1, Tadao HAMAZAKI*2 and Tosporn VACHARANGKURA*3

*1 Department of Forestry Technology, Forestry and Forest Products Research Institute (FFPRI)
(Tsukuba, Ibaraki, 305 Japan)
*2 Department of Natural Resources, National Institute of Agro-Environmental Sciences(NIAES)
(Tsukuba, Ibaraki, 305 Japan)
*3 Forest Research Office, Royal Forest Department (Chatuchak, Bangkok, 10900 Thailand)

Abstract

The natural distribution of teak covers discontinuous regions in South and Southeast Asia. These regions are located within the total area of tropical summer-rain climate characterized by distinct rainy and dry seasons. The successful teak plantations are found in discontinuous areas with fertile soils, which are intrazonal and azonal soils derived from limestones, base-rich igneous rocks and alluvial materials. The discontinuous distribution of natural forests and plantations of teak is attributed to the discontinuous occurrence of suitable intrazonal and azonal soils. The dominant trees of natural forests in zonal soil areas under the same climate are deciduous dipterocarp species. The optimum soil conditions for teak growth include good drainage, deep subsoil, slightly acid to alkaline pH and abundance of bases, especially Ca. Emphasis is placed on yield tables and site quality maps for the efficient management of plantations, and on plant indicator methods such as trial planting and plant indicators for site selection.

Discipline: Forestry and forest products
Additional key words: *Tectona grandis*, deciduous dipterocarp species, plantation silviculture, site selection, climate, geology, soil, drainage, Ca, pH, plant indicator

Introduction

Teak (*Tectona grandis* Linn. f.) is one of the most valuable timber resources in the tropics. It is also one of the most widely studied tropical trees in terms of ecology and silviculture[13,21,23,26]. This species has been planted in various areas outside of its natural distribution areas since the 14th-16th century[1]. However, successful teak plantations are limited to discontinuous regions within the tropical climate belt. This fact suggests the importance of site selection for teak plantations.

In order to clarify the site conditions suitable for teak plantations, it is important to determine the main factors controlling the growth of teak. Kaosa-ard[8] considered that rainfall/soil moisture, temperature, light, geological formation and soil conditions were important factors controlling the natural distribution of teak. It is necessary to analyze the interrelationships between the distribution, growth and site conditions to determine the controlling factors. Using information from the literature and our studies, we will examine the site conditions of teak forests to define suitable and limiting conditions of climate and soil as site requirements of teak.

This paper is a revision of a preceding paper presented at the First National Seminar on Teak Planting in Vietnam (1995)[20]. The classification of soils in this paper is based on the legend of FAO-UNESCO soil map of the world[5].

Natural distribution of teak and climate

Teak is a tropical tree naturally distributed in limited regions of South and Southeast Asia. Its distribution is discontinuous, covering the Indian Peninsula, Myanmar, northern and western Thailand and

Present address:
*2 Environmental Resources Division, Japan International Research Center for Agricultural Sciences (Tsukuba, Ibaraki, 305 Japan)

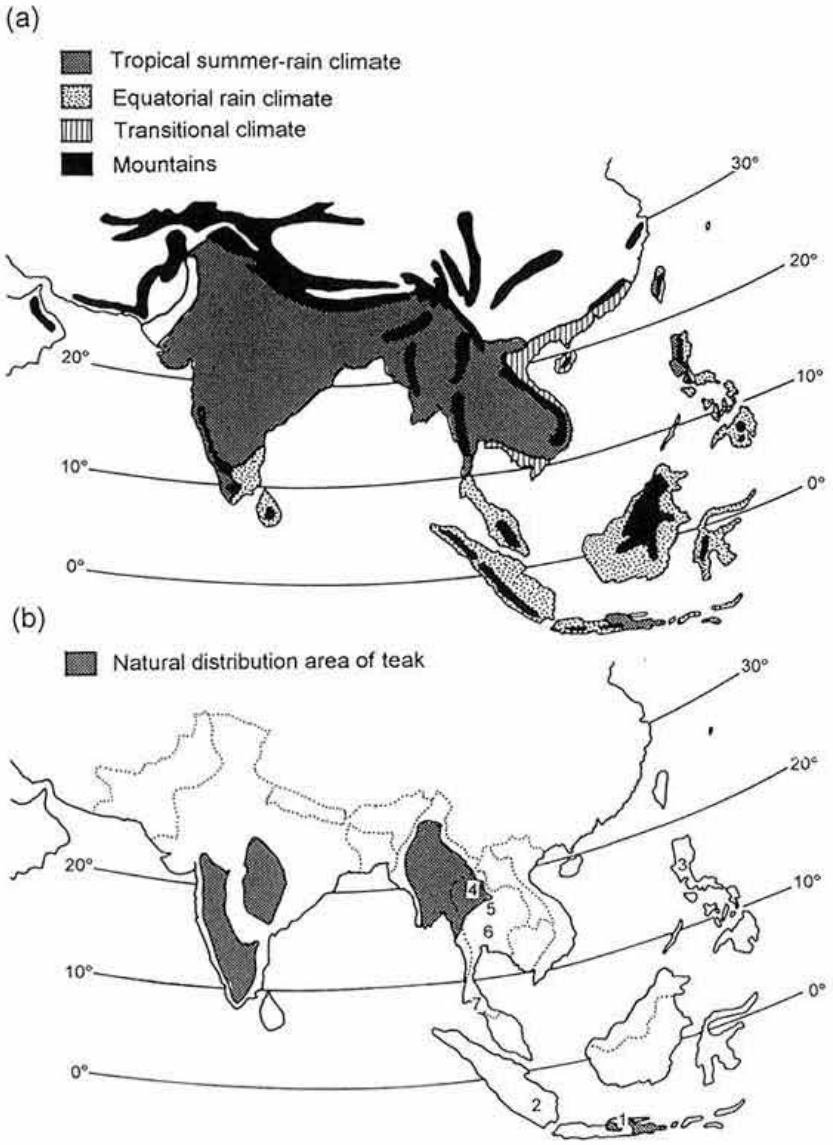

Fig. 1. Maps of (a) climate types[24] and (b) natural distribution of teak[8]
The numbers in the map (b) indicate the locations of teak plantations described in the text as follows:
1; Cepu, 2; Benakat, 3; Carranglan, 4; Lampang, 5; Dong Larn, 6; Klang Dong, 7; Khao Chong.

northwestern Laos along the northern Thai border, as well as central and eastern Java where teak was introduced about 400–600 years ago. Teak is distributed from 73°E longitude in India to 104°30′E in Thailand, and from about 25°30′N lat. in the Kachin State of Myanmar to its southern boundary from 9°N lat. in India through 15°–16°N lat. in Myanmar to 16°30′ lat. in Thailand.

Climate zones and natural distribution areas of teak are presented in Fig. 1. The teak distribution areas are included in zones of the tropical climate with summer rain (zonobiome II) defined by Walter[24]. Zonal vegetation corresponding to this climate type is represented by tropical deciduous forests or savannas which are underlain by zonal red clay or red earth soils. Teak is a characteristic species of tropical monsoon forests, which become partly or completely leafless in the dry season[14]. It is important to note that the teak distribution is not identical with the total area of this climate type (Fig. 1). This suggests that edaphic factors control the distribution of teak in the tropics.

Examples of teak plantations and site conditions

1) Java

The total area of teak plantations in Indonesia is approximately 700,000 ha[9]. Most of these plantations are located in central and eastern Java. The commercial teak plantation program has been implemented for more than 100 years and includes established methods such as seed collection, land preparation, sowing, tending, thinning and felling. Yield tables and site quality maps for all compartments have been used for the silvicultural implementation.

A tract of teak plantations in Cepu, eastern Java (Plate 1), is located on rolling plateaus of Tertiary limestones and calcareous sedimentary rocks at about 100–300 m a.s.l. Based on the meteorological data from Surabaya near Cepu, the climate belongs to the tropical summer-rain type with a mean annual temperature of 26.8°C and mean annual rainfall of 1,837 mm. There is a distinct dry season of 4 months (July–October), based on Walter's definition of a dry period[24].

Under the Taungya agroforestry system (Tumpangsari), teak seedlings are planted at a density of 3,300/ha on open lands. Frequent thinnings (about 11 times) are conducted until the age of 60 years, resulting in 100–150 trees/ha. At the age of 80 years, final logging is undertaken after 2 years' drying of boles with girdling. Average timber volume harvested at the final logging is 160–180 m^3/ha. The oldest stand is more than 90 years of age. The maximum values of tree height and stand volume are 45 m and 200 m^3/ha, respectively at the optimum site of Cepu.

The main soil type in teak plantations is Rendzinas derived from limestones with brownish black topsoil and light gray subsoil (Plate 2, Table 1). Rendzinas derived from residual deposits of limestones and Eutric Cambisols derived from calcareous rocks are widely distributed in this region. These soils are locally called Grumusols, which include Vertisols covering lower terraces and alluvial plains. The pH of the surface soil (0–10 cm in depth) of teak plantations ranges between 6.9 and 8.1. Topsoil is shallow, ranging between 11 and 34 cm in thickness, but subsoil is deep as the C horizon is composed of friable angular gravel and silt. This soil is rich in bases with both adequate drainage and water retention although it becomes very dry in the dry season.

The site quality, which is determined by the height growth of teak, is classified into 10 levels (1.0 to 5.5) with an increment of 0.5. The site quality of teak is related to several topographic and soil factors. Gentle slopes, thick topsoil, and low gravel content in the topsoil are characteristic of a high quality site. According to our measurements of forests on lands with a site quality of 3.5–4.0, average stand height is 6.7 m at the age of 2 years (Plate 3), 21 m at 18 to 20 years, and 31 m at 84 years.

2) Benakat in southern Sumatra

There are few commercial teak plantations in southern Sumatra. A trial plantation of teak can be found in Benakat which is located on depressional upper terraces at about 130 m a.s.l. The parent

Table 1. Properties of a soil of teak plantation at Cepu, eastern Java

Horizon	Depth (cm)	Color	Texture	pH (H_2O)	Organic matter (%)	Total N (%)	C/N	P retention[a] (%)
Ah1	0–9	10YR3/1	HC	6.9	5.3	0.26	12	31.5
Ah2	9–20	10YR3/3	LiC	7.5	2.9	0.18	9	37.9
AC	20–40	10YR4/3	L	7.8	1.7	0.11	9	37.5
C	40+	10YR5/4+ 2.5YR8/2	SiL	8.0	1.1	0.08	8	68.5

Horizon	Ex. Ca	Ex. Mg	Ex. K	Ex. Al	CEC[b]	Base saturation[b]	Carbonate as $CaCO_3$
	(me/100 g soil)					(%)	(%)
Ah1	82.4	1.4	0.7	0.1	49.2	172	25.5
Ah2	81.7	0.9	0.6	0.0	53.1	157	23.8
AC	69.8	0.5	0.3	0.1	36.1	196	55.8
C	70.7	0.3	0.3	0.5	25.6	278	94.7

a): Blakemore method. b): NH_4OAc.

Plate 1. An 85-year-old teak plantation with maximum DBH of 111 cm and maximum height of 44 m in Cepu, eastern Java (Oct. 31, 1987)

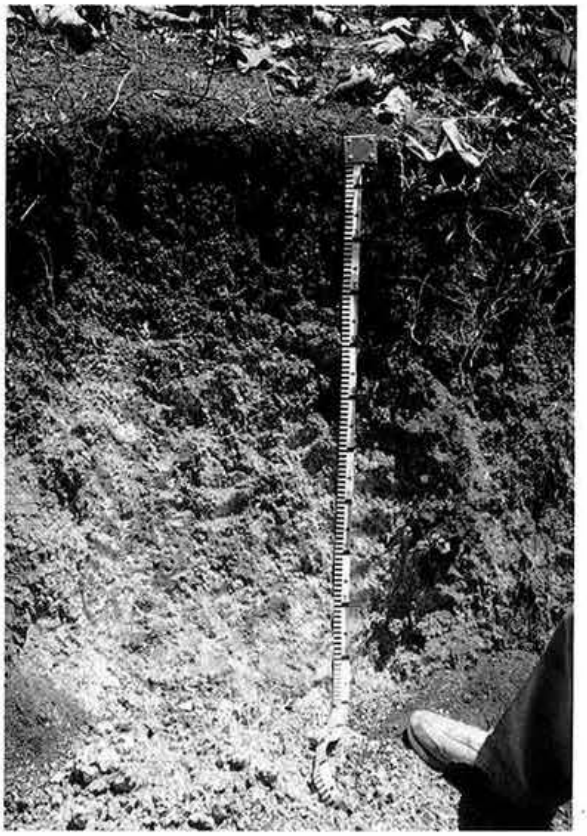

Plate 2. Soil profile of a teak plantation in Cepu (Nov. 2, 1987)

Plate 3. A 2-year-old teak plantation in Cepu (Oct. 31, 1987)

Plate 4. A 2-year-old plantation of teak (center) and *Acacia mangium* (right) in Benakat, southern Sumatra (130 m a.s.l.) (Oct. 21, 1987)

Table 2. Properties of a soil at Benakat, southern Sumatra

Horizon	Depth (cm)	Color	Texture	pH (H_2O)	Organic matter (%)	Total N (%)	C/N	P retention[a] (%)
Ah	0-5	10YR3.5/3	LiC	4.9	5.0	0.19	16	23.6
Bt	5-16	10YR6/4	HC	4.6	2.0	0.13	9	24.4
Btg1	16-28	7.5YR6/4	HC	4.5	1.1	0.09	7	31.3
Btg2	28-60	7.5YR6/4	HC	4.4	0.8	0.08	6	38.1
Btg3	60-86	10YR7/2	HC	4.7	0.4	0.06	5	43.9
Btg4	86+	10YR7/2	HC	4.7	0.4	0.06	4	45

Horizon	Ex. Ca	Ex. Mg	Ex. K	Ex. Al	CEC[b]	Base saturation[b]
	(me/100 g soil)					(%)
Ah	3.6	1.2	0.4	1.6	12.9	41
Bt	2.6	0.7	0.2	3.7	10.1	35
Btg1	1.4	0.3	0.1	5.3	10.7	18
Btg2	0.4	0.2	0.2	9.0	12.2	7
Btg3	0.1	0.2	0.2	12.0	15.4	3
Btg4	0.0	0.2	0.2	12.6	15.5	3

a): Blakemore method, b): NH_4OAc.

materials of the soils in this area consist of either old alluvial deposits or acidic sedimentary rocks of Tertiary shale and sandstone. Based on the meteorological data from Palembang near Benakat, the climate belongs to the equatorial rain type with a mean annual temperature of 26.5°C and mean annual rainfall of 2,480 mm. There is no dry season.

The soils are Gleyic Acrisols or Plinthic Acrisols with mottles or plinthite in shallow horizons. The soils are very acid, with a pH ranging from 4.4 to 4.9 (Table 2). Conspicuous mottling and grayish yellow brown color of the subsoil suggest occasional waterlogging. Soil texture is clayey and porosity is low, indicating poor aeration of the soil.

Compared with the soils of Cepu (Table 1), there is a considerable difference in the physical and chemical properties. The soil drainage is much better in Cepu than in Benakat. Indices of chemical fertility such as pH, CEC and base saturation are higher in Cepu, whereas the index of infertility, content of exchangeable Al, is higher in Benakat.

The early growth of teak is slower in Benakat than in Cepu although there is no dry season in Benakat. The average height of a 2-year-old plantation is 3.4 m in Benakat (Plate 4) and 6.7 m in Cepu (Plate 3). These results indicate that the environmental conditions in Benakat are not suitable for teak growth. *Acacia mangium* trees grow best among planted tree species in Benakat, measuring 4.5 m (Plate 4) and 15 m in height at the age of 2 and 5 years, respectively. *A. mangium* is a fast-growing tree species adapted to acid soils[19].

3) Carranglan, Nueva Ecija, the Philippines

Teak is not native to the Philippines and was introduced sometime before 1910. About 2,000 ha of teak plantations have been established by the Bureau of Forest Development[9].

Here we examine the failure of an experimental teak plantation in Carranglan, Nueva Ecija, Luzon Island. Carranglan is located on rolling hills at 350-450 m a.s.l., mostly covered by open grasslands. There are narrow belts of unburned evergreen dipterocarp forests along the streams. The climate belongs to the tropical summer-rain type with a mean annual temperature of 27.7°C and mean annual rainfall of 2,042 mm. There is a distinct dry season

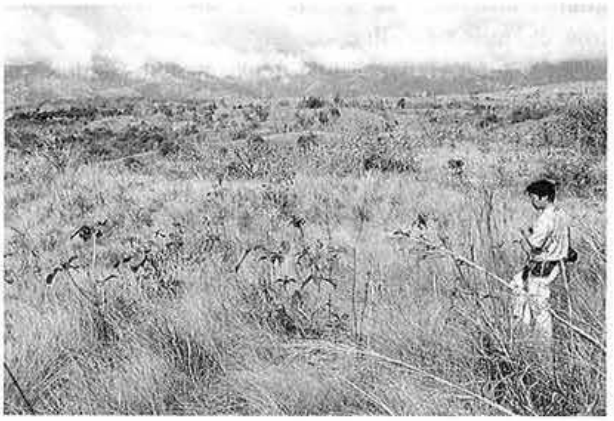

Plate 5. A 7-year-old teak plantation in Carranglan, Nueva Ecija, Luzon Island, the Philippines (March 24, 1989)

Table 3. Properties of a soil of teak plantation at Carranglan

Horizon	Depth (cm)	Color	Texture	Compactness[a] (mm)	pH (H_2O)	Organic matter (%)	Total N (%)	C/N
A	0–20	10YR3/3	SL	27	5.8	5.0	0.19	15.4
AB	20–42	7.5YR4/3.5	SCL	29	5.5	3.6	0.15	13.9
B_{1t}	42–56	5YR3.5/6	SCL	28	5.7	2.2	0.11	11.5
B_{2t}	56–74	5YR4/6	SCL	28	5.7	1.9	0.10	11.3
BC	74+	7.5YR4.5/6	SCL	27	5.8	1.3	0.07	10.4

Horizon	Ex. Ca	Ex. Mg	CEC	(Ca+Mg)/CEC	Available P[b]
	(me/100 g soil)			(%)	(mg/100 g soil)
A	3.1	1.1	7.6	56.8	90
AB	2.9	1.0	6.6	60.4	73
B_{1t}	3.5	1.3	7.6	63.0	31
B_{2t}	4.3	1.8	9.4	64.6	45
BC	5.0	1.9	10.4	66.7	22

a): Yamanaka's cone-penetrometer. b): Bray No. 4 method; after Yagi[27].

of 4 months (January–April). The parent materials of soils consist of Tertiary mudstones, igneous rocks and Quaternary sediments. The surface horizons of soils have been severely degraded due to the repeated burning of herbaceous vegetation over a long period of time. The main soil types consist of Luvisols, Acrisols, Vertisols and Cambisols[28].

Seven-year-old teak trees in the plantation are stunted due to frequent die-back of leading shoots (Plate 5). The soils are shallow and hard. The compactness of soil measured by Yamanaka's cone-penetrometer ranged between 27 and 29 mm for every horizon (Table 3). Based on an analysis of the physicochemical properties of soil near the teak plantation, indices of fertility such as pH, exchangeable Ca, CEC and base saturation were much lower than those in Cepu. Inferior teak growth in Carranglan is attributed to the shallow and hard soil, and low chemical fertility.

Mahaphol[13] described teak growth under unsuitable soil conditions in Thailand as follows: the seedlings, owing to infertility and insufficient depth of the soil, do not grow to any size and quality but invariably get stunted, malformed and stag-headed after attaining a diameter at breast height of 32–38 cm.

4) Northern Thailand

Northern Thailand is one of the main areas of natural distribution of teak. Santisuk[16] described relations of teak to site conditions. Teak is a typical component species of tropical mixed deciduous forests, which mainly occur on soils derived from limestones and fertile alluvium soils in the monsoon tropics.

The total area of teak plantations in Thailand is approximately 133,000 ha and these plantations are mainly located in northern Thailand[9]. Although preserved natural forests comprising teak are very limited, there are many teak plantations around the basin of Lampang (Plate 6). The main bedrock of the area consists of limestone mixed with shale. The climate belongs to the tropical summer-rain type with a mean annual temperature of 25.8°C and mean annual rainfall of 1,099 mm. There is a distinct dry season of 5 months (November–March).

The topsoil is brownish black in teak forests. Based on the soil analysis of 18-year-old teak plantations in Lampang, soil was clayey in texture and

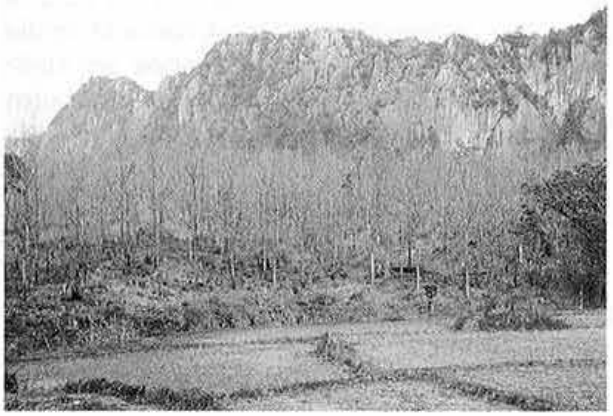

Plate 6. A teak plantation on a piedmont slope between a limestone hill and paddy fields in Lampang, northern Thailand (April 1, 1992)

Table 4. DBH of 5-year-old teak in relation to some soil properties of 0–18 cm soil horizon

DBH (cm)	pH (H_2O)	Organic matter (%)	Available P[a)] (ppm)	Ex. K	Ex. Ca	Ex. Mg	CEC	Base saturation (%)	Clay (%)
				(me/100 g soil)					
11.02a	6.75	3.34	93.09	0.93	58.34	3.06	64.31	97.20	43.90
8.52b	6.15	1.55	16.66	0.77	24.63	4.18	38.86	76.84	50.05
8.11c	6.14	2.52	17.89	0.49	17.41	6.08	31.42	77.09	51.47
8.09c	6.11	2.90	36.76	0.80	12.78	4.28	24.06	75.06	23.22
7.88c	5.69	2.75	12.29	0.21	21.37	15.38	42.16	88.38	24.86
6.18d	6.11	3.66	2.64	0.58	13.88	5.48	22.89	87.76	28.02
6.11d	5.76	1.97	3.39	0.72	9.45	9.81	29.87	67.88	38.45
5.93de	5.93	2.14	2.96	0.91	7.79	4.45	18.26	72.62	34.43
5.61e	6.01	2.10	8.00	0.96	12.13	4.65	25.94	69.15	36.82
5.38f	5.61	3.66	6.60	1.08	12.89	4.78	28.92	65.55	48.19
3.79g	4.68	1.29	3.74	0.10	0.84	0.36	10.77	12.81	9.82
Corelation coefficient, r	0.822**	0.318	0.778**	0.206	0.882**	0.160	0.874**	0.755**	0.449

a): Bray II method; after Jungsuksuntigool & Wichiennopparat[7].

acid, with a pH ranging from 5.0–6.4 in the topsoil (0–15 cm in depth) and 4.8–6.2 in the lower horizons (15–30 cm in depth)[18]. Exchangeable Ca content ranged from 4.7–11.4 (me/100 g soil) in the topsoil and 3.8–10.7 in the lower horizon, being lower than in Cepu. However, another study on 5-year-old teak plantations indicated that teak growth was significantly related to some soil parameters and that adequate growth of teak was found on soils that were moderately acid to nearly neutral with medium to very high available P content, high to very high exchangeable Ca content, medium to high base saturation and high to very high CEC (Table 4)[7]. One of the plantations with optimum growth in Lampang is located on a soil with a very high content of exchangeable Ca (58.3 me/100 g soil).

5) Northeastern Thailand

Teak is not naturally distributed in northeastern Thailand. The soils derived from sandstones and quartzites covering large areas of the region appear to be unsuitable for growth and development of tropical mixed deciduous forests that usually comprise natural teak. This is one of the reasons why such forests are less extensive than deciduous dipterocarp forests in northeastern Thailand[16]. Deciduous dipterocarp forests occur in most parts of this region. There are few teak plantations in the Khorat fine sandy loams derived from sandstones. The main plantation species in this region has recently been *Eucalyptus camaldulensis*.

Teak plantations are found in limited areas in northeastern Thailand, such as Dong Larn in northern Chum Phae Province, where the plantations were established along the valley bottom. Mixed deciduous forests without teak are found in some protected areas. The climate belongs to the tropical summer-rain type with a mean annual temperature of 26.7°C and mean annual rainfall of 1,675 mm. There is a distinct dry season of 5 months (November–March). The main bedrock consists of limestone mixed with sandstone and shale. The topsoil is brownish black in color and the subsoil is reddish brown. The soil texture varies from clay to sandy loam.

Teak growth in this area is acceptable for silviculture. However, chlorosis is occasionally observed on the leaves of some young trees growing on a

Plate 7. A 23-year-old teak plantation with maximum DBH of 25 cm and maximum height of 19 m in Klang Dong, northeastern Thailand (Sept. 25, 1992)

clayey soil, indicating a deficiency in bases such as Ca and Mg probably due to the low content of available elements and insufficient development of root systems.

Another plantation was found in Klang Dong, Nakhon Ratchasima Province. Teak plantations are located on plains and gentle hills at 400–500 m a.s.l. Crops such as maize and rice are cultivated in heavily thinned teak plantations (Plate 7). The adequate growth of these crops indicates that the soil is fertile for crop species. The climate belongs to the tropical summer-rain type with a mean annual temperature of 28.2°C and mean annual rainfall of 1,544 mm. There is a distinct dry season of 3–4 months (November–February). Topsoil is brownish black. The soil is rich in bases and its pH is approximately neutral[11]. However, the soil is shallow and the drainage is not particularly adequate. The soil is clay loam in texture and sticky when wet. Chlorosis has also been observed in young leaves of some shoot tops of teak trees.

Height growth of teak at Dong Larn and Klang Dong was similar until 25 years after planting, when the average tree height reached 18 m (Fig. 2). However, after that age the height growth continued at Dong Larn but almost stopped at Klang Dong. Adverse soil conditions such as shallowness and rather poor drainage may explain the lower maximum tree height at Klang Dong.

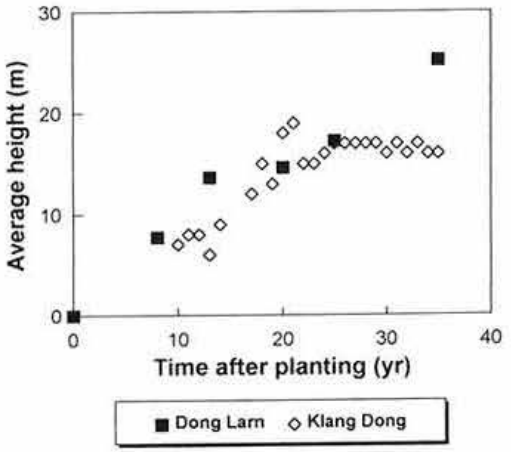

Fig. 2. Height growth of teak plantation at 2 sites in northeastern Thailand

6) Southern Thailand

Teak plantations are very limited in southern Thailand, where the climate is more humid than in northern regions. There are only plantations covering small areas, teak-lined avenues and individual teak trees in dispersed places.

There is a teak stand (planted in 1968) on the lower part of a gentle hillslope in the Peninsula Khao Chong Botanical Garden, Royal Forest Department, Trang Province (Plate 8). The growth of teak is satisfactory as the 24-year-old plantation shows a maximum DBH of 47 cm and maximum tree height

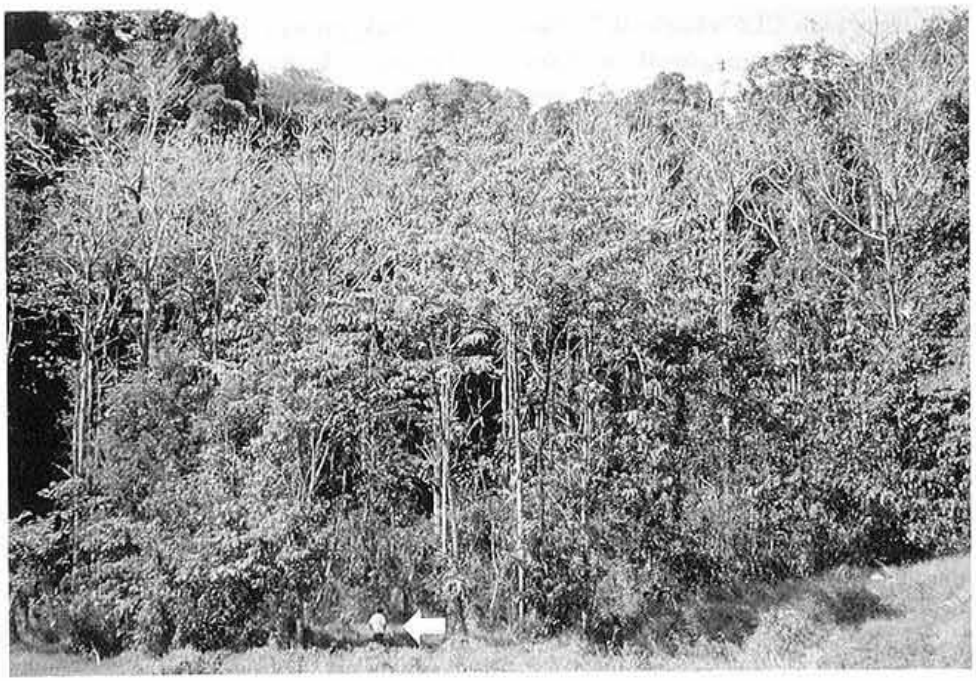

Plate 8. A 24-year-old teak plantation in Khao Chong, southern Thailand (April 18, 1992)

of 30 m. Since the teak trees shed leaves in February and flush new leaves immediately, the leafless period is short. The climate belongs to the equatorial rain type with a mean annual temperature of 28.4°C and mean annual rainfall of 1,741 mm. There is a short dry season of 2 months (January–February). The main bedrock consists of granite mixed with sandstone, shale and limestone in this area. The topsoil is light brown in color and loamy sand in texture. The pH of soil ranges between 4.5 and 5.4 in the topsoil (0–15 cm in depth) and between 4.1 and 5.1 in the lower horizon (15–30 cm in depth). Exchangeable Ca content is low, ranging from 0.3–1.8 (me/100 g soil) in the topsoil and 0.3–1.0 in the subsoil[17]. Although the soil is acid with a low exchangeable Ca content, the good growth may be due to the presence of adequate drainage, deep subsoil and a long growing season with sufficient rainfall.

The success of this plantation indicates that teak can grow well in humid tropics as long as such topographic and soil conditions are fulfilled. Although teak is absent in tropical rain forests, this does not mean that the equatorial rain climate is unsuitable for teak growth.

Climatic requirements

Webb et al.[25] described the climatic requirements of teak as follows:

Mean annual rainfall;	1,250–3,000 mm
Dry season (months with less than 40 mm rainfall);	3–6 months
Mean annual temperature;	22–26°C
Mean max. temp. of the hottest month;	25–32°C
Mean min. temp. of the coldest month;	18–24°C

These values seem to indicate the optimal conditions since there are many plantations on sites with values out of these ranges. For example, the mean annual rainfall in Lampang (one of the main teak plantation areas in Thailand) and the mean annual temperature in Klang Dong, northeastern Thailand are out of the respective ranges.

The elevational range of teak in Thailand lies under 900 m a.s.l., where frost has never been experienced. In the main teak zone of Thailand, the lowest temperature recorded was 2.0°C at Chiengrai, while the mean minimum temperature of the coldest month, January, is 11.3°C[13].

Kaosa-ard[8] noted in his review that teak grows best at locations with a mean monthly maximum temperature of 40°C for the hottest month and mean monthly minimum temperature of 13°C for the coldest month. Based on studies under controlled environment, teak seedlings grow best under day/night temperatures ranging from 27/22°C to 36/31°C with an optimum temperature of 30/25°C while the critical minimum day/night temperature for growth and development is 21/16°C.

Teak trees of exceptional sizes occur occasionally, growing among evergreen trees in sheltered humid valleys where the soil is suitable[13]. Teak grows best and reaches its largest dimensions in the humid tropics although under this climate it is replaced by evergreen forest species[26]. Teak can grow fast with a short or without a leafless period under equatorial rain climate as long as the soil conditions are suitable. However, teak does not appear to compete with evergreen members of tropical rain forests.

More detailed climatic requirements expressed as optimum and limiting conditions of temperature and rainfall must be estimated quantitatively by analyzing the relationships of growth and distribution of teak with climatic conditions in the field.

Soil requirements

1) Topography, geology and soil

Although teak is capable of growing over a wide range of edaphic conditions, the quality and distribution of natural teak is related to the nature of edaphic conditions[21]. According to Mahaphol[13], the majority of teak forests are located on hilly or undulating grounds of well-drained soil, leaving the drier lateritic soil on hill tops to be occupied by deciduous dipterocarp forests and the poorly drained depressions to be occupied by grasslands. Teak forests are also found on plains of well-drained alluvial flats along river banks. Teak does not tolerate "wet feet", avoiding stiff clayey soil and waterlogged areas, and does not thrive on excessively dry sandy soils. Teak does not occur on lateritic soils[23] and its growth is stunted in shallow soils and on ridge tops[26].

There is a wide range of growth rates due to the differences in soils. Teak growth is much faster in deep, fertile, well-drained soil along stream banks than on hills where the soil is less fertile, shallower and drier while teak growth in soils derived from limestones is almost as fast as that in well-drained basin deposits (Table 5).

A good correlation of teak regions with lime-

Table 5. Time required for teak trees in northern Thailand to attain 68 cm in diameter at breast height (DBH) in various types of soil

DBH (cm)	No. of years	Mean annual DBH increment (cm/yr)	Soil or underlying rocks
68	85	0.80	Well-drained basin deposits
68	133	0.51	Limestone
68	160	0.43	Shale and sandstone
68	170	0.40	Metamorphic rocks

After Mahaphol[13].

stone areas is observed in Thailand (Fig. 3). Natural and man-made teak forests are widely distributed in the northern and western regions, where limestone outcrops cover many parts of the area. A few small detached areas with teak in northeastern Thailand consist mainly of plantations and are not within the range of natural teak distribution. Teak forests are very rare in southern Thailand although there are several small limestone areas.

Limestone areas are usually suitable for teak growth because of high pH, high base content and adequate drainage of soil if the limestone undergoes weathering to a deep loam. However, hard, slowly disintegrating limestone with shallow soil leads to poor growth[26].

2) Soil properties controlling teak distribution

Teak is, to some extent, quite exacting as regards soil[13]. Soil drainage is one of the most important factors for teak growth. Teak trial planting at Sakaerat Experimental Station, northeastern Thailand, showed that teak growth was especially

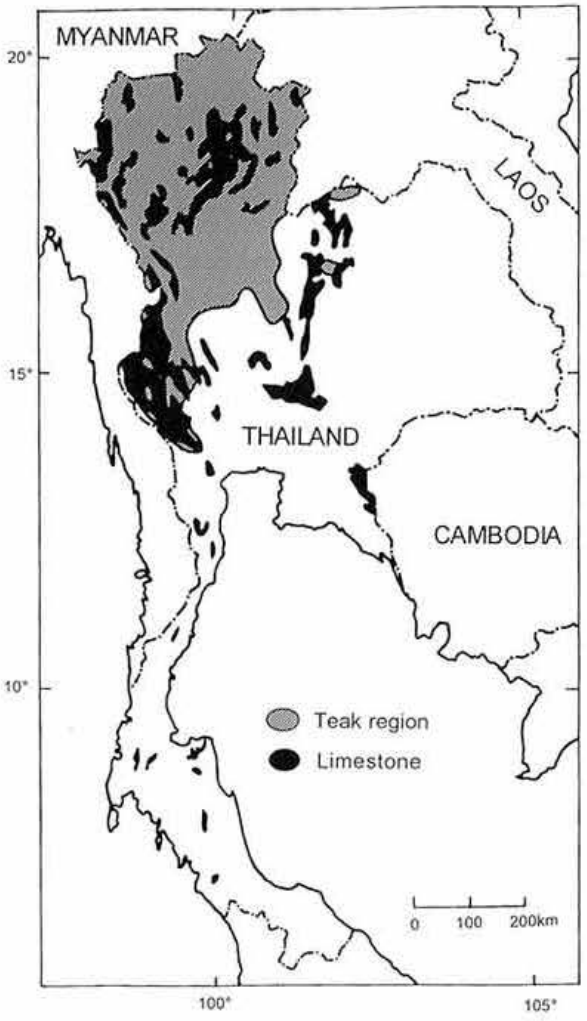

Fig. 3. Distribution of teak and limestone in Thailand After Mahaphol[13].

Table 6. Relationship between geological formation, pH of soils and distribution of teak

Geological formation	Average pH value of the resultant soils	Component species	
		Teak (%)	Non-teak (%)
Deccan trap (volcanic rock)	7.0	80	20
Alluvium	7.0	80	20
Granitic gneisses	7.5	75	25
Calcareous crystalline rock	7.7	60	40
Phyllites and schists	7.2	50	50
Bagra conglomerate	6.8	45	55
Jabalpur conglomerate and haematite	6.5	15	85
Talchirs and Barakars conglomerate	—	8	92
Bijoris sandstone	6.0	3	97
Pachmarhi sandstone	5.6	0	100
Denwa sandstone	5.5	0	100
Jabalpur sandstone	6.0	0	100

After Kulkarni[12].

poor in Gleysols formed in areas with inadequate drainage such as flats or concave lands. Waterlogging adversely affects teak growth. Teak grows well on well-drained porous soils, and loam and sandy loam soils are most suitable.

The relationship between geological formation, pH of soils and dominance of teak is shown in Table 6. Here we can see that teak was dominant on soils with a pH higher than 6.5 whereas it was absent on soils with a pH lower than 6.0. Teak growth is not satisfactory above pH 8.5[23]. These studies suggest that teak requires slightly acid to slightly alkaline soils, with the most suitable soil pH apparently ranging between 6.5 and 7.5. However, teak plantations with a soil pH below 6.5 such as at Lampang and Khao Chong in Thailand show acceptable growth, as mentioned before. This fact indicates that teak plantation silviculture is possible even on acid soils under 6.5 pH as long as physical soil conditions such as drainage and soil depth are suitable for teak growth.

Apart from soil pH, a number of elements in the soil such as Ca, P, K, Mg, N have been found to play important roles in controlling the distribution and growth of teak. Teak is known to be a calcicolous species, which requires a large amount of Ca for its growth[8]. Puri and Gupta[15] compared the Ca content in leaves of teak and sal (*Shorea robusta*) grown under the same site conditions and reported that the Ca content of the teak leaves (2.9%) was almost double that of the sal leaves (1.5%). Kaul et al.[10] extracted Ca, Mg, P, K and N from various parts (i.e. leaves, twigs, live branches, dead branches, stem-bole and barks) of teak trees grown in a 38-year-old plantation in India and observed that Ca was the major base contained in all parts.

In general, suitable sites for teak plantation depend on soil conditions under the tropical climate. Adverse soil conditions such as waterlogging, strong acidity, shallowness and compactness remarkably slow down teak growth. The most suitable soil conditions include good drainage, deep subsoil, slightly acid to alkali and high base content, especially Ca. These soil conditions can be found in soils derived from limestones, base-rich igneous rocks and alluvial materials.

Ecological significance of the natural distribution and site requirements of teak

Teak is normally absent in dipterocarp forests regardless of whether the trees are evergreen or deciduous. Teak is naturally distributed within the tropical summer-rain climate, mixed with various non-dipterocarp species such as *Pterocarpus, Xylia, Afzelia, Dalbergia, Lagerstroemia, Diospyros* and *Irvingia* spp. Under the equatorial rain climates of Southeast Asia, various evergreen dipterocarp species dominate, and teak and most other deciduous non-dipterocarp trees appear to be excluded under humid climates due to the competition with members of evergreen forests.

Teak thrives in soils derived from limestones and base-rich igneous rocks under the summer-rain climate. It requires fertile soils that are well-drained, with a deep subsoil, slightly acid to alkaline and rich in bases. These fertile soils are intrazonal and azonal soils derived from base-rich rocks. Zonal soils under tropical summer-rain climate are red and yellow soils such as Acrisols and Ferralsols. The discontinuous distribution of teak is attributed to the discontinuous occurrence of suitable intrazonal and azonal soils. On the other hand, deciduous dipterocarp species such as *Dipterocarpus obtusifolius, D. tuberculatus* and *Shorea siamensis* predominate in poor soils which are characteristically shallow, gravelly to sandy, or lateritic although they occur under the same climate type in the Indo-China region.

The distributional segregation of teak and sal (*Shorea robusta*), a deciduous dipterocarp species endemic to South Asia, is found in India (Fig. 4). Teak is distributed in the western and central parts of Peninsular India, where extensive areas of

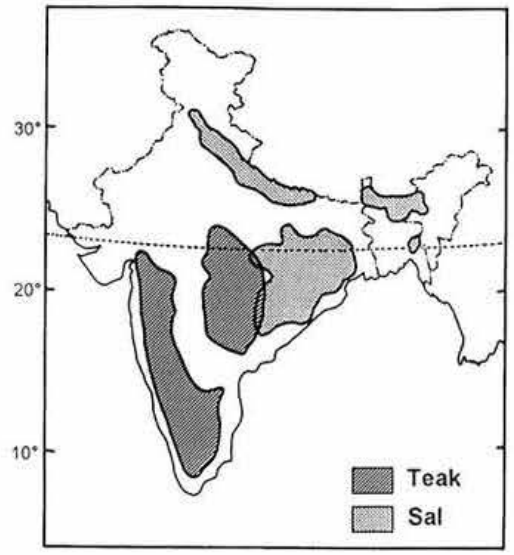

Fig. 4. Distribution of teak and sal (*Shorea robusta*) in India
After Tewari[22] and Kaosa-ard[8].

Vertisols and Chromic Luvisols developed mainly from Cretaceous-Eocene basalts or alluvium derived from them. The Vertisols are slightly to moderately calcareous. Sal is distributed in the northeastern region of Peninsular India and northern regions along the Himalayan range. These regions mainly contain Ferric Luvisols and Dystric Cambisols, respectively[6]. The distributional segregation of teak and sal in India is similar to that of teak and deciduous dipterocarp species in the Indo-China region.

The reasons why these deciduous non-dipterocarp species dominate in intrazonal and azonal soils with a high fertility and why deciduous dipterocarp species dominate in zonal soils with a low fertility will be important topics for future studies. Soil requirements of these tree species must be examined to clarify the habitat segregation of non-dipterocarp and dipterocarp species along soil gradients. Determination of site requirements expressed as optimum and limiting conditions for a plant species is important to estimate its status in the natural ecosystem. Plant distribution is usually more limited than its potential distribution corresponding to its site requirements. Discrepancies between the natural and potential distribution areas suggest the consequence of competition with other plant species in natural ecosystems.

Natural and economic conditions for teak plantations

Since teak requires fertile soils for adequate growth, suitable areas for teak plantations usually overlap with farmlands where upland crops such as rice, maize, coffee and tobacco are grown. Therefore, there are usually conflicts of land use between teak silviculture and agriculture because of the similar soil requirements of teak and the crops.

For rational and productive land use, it is important to identify slight differences in soil requirements between teak and agricultural crops and to allocate every plot of land to the most suitable plant species. The teak plantation area in Cepu, eastern Java, provides a good example. Here, teak plantations cover mainly hilly and drier areas whereas farmlands occupy alluvial plains and gentle slopes. Although teak also grows well in the agricultural areas, the cultivation of agricultural crops there is more profitable than teak plantations. In hilly areas, teak plantations may be more profitable because agricultural productivity decreases there to a greater degree than teak productivity due to less fertile soil conditions and differences in soil requirements of teak and agricultural crops. In addition, it is important to establish forests on steep hills for soil conservation because the forested lands generally prevent soil erosion more than agricultural lands.

Recommendation for teak silviculture

A yield table based on forest age and site quality for every region of teak plantation is necessary for the efficient management since teak growth is sensitive to soil fertility. Yield tables are already available for old plantation regions such as India[21,23], Java[2,3] and Thailand[4]. Site quality maps corresponding to yield tables are also necessary for site selection and management.

For the success of teak plantations, especially in areas outside of its natural distribution, it is most important to identify suitable sites for teak growth. The suitable sites should be determined based on environmental factors of 3 overlaid levels, that is, (1) climatic (temperature, rainfall, etc.), (2) edaphic (geology, topography and soil) and (3) community levels (light, soil moisture, etc.), although environmental factors of the community level have not been discussed in this paper. These factors, which operate on different scales, always affect plants in a community. The spatial extent of climatic influence is large (in general, more than 1 km horizontally and 100 m vertically), while that of a community is small (less than 100 m) and that of soil is intermediate (100 m to 1 km). Under the frost-free tropical climate, edaphic considerations are most important for site selection of teak plantations because of teak's characteristic soil requirements.

In order to identify suitable sites for teak plantations, analysis of soil physical properties (drainage, texture, etc.) and chemical ones (pH, exchangeable cations, etc.) helps to estimate the fertility of each site. However, we would like to recommend the following 2 plant indicator methods because they are applicable at every location. The first is trial planting in small areas with variable site conditions. This method is practical and provides reliable information on site quality for examined plant species although it sometimes requires a long period of time. The second is the plant indicator method. For instance, the healthy growth of *Lagerstroemia calyculata*, *L. balansae*, *Xylia dolabriformis* and bamboos is a good indicator of suitable sites[13]. It is useful to find plants indicating suitable site conditions in every region for teak planting.

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