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Environmental Factors Affecting Growth of Agarwood (*Aquilaria malaccensis* Lamarck, 1783) Forests of Bhutan

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Abstract

Aquilaria malaccensis Lam., commonly referred by its trade name Agarwood, is an endangered species. Its natural distribution and ecology in Bhutan are poorly known. So, this study aimed to understand the ecological requirements and model suitable habitats for the growth of *A. malaccensis* in the country. Using purposive-non-probability sampling, vegetation data were collected from plot sizes of 20 x 20 m for trees, 5 x 5 m for understory and 2 x 2 m for groundcover. A total of 168 plant species under 67 families were recorded. Lauraceae and Euphorbiaceae were found to be the most dominant and co-dominant families in the natural Agarwood stand. A cluster analysis using PC-ORD revealed that Agarwood prefers habitat with warm-moist evergreen broadleaved forest. The Pearson and Kendall correlation in NMS ordination showed the strongest correlation between Agarwood growth and mean annual rainfall ($r = 0.90$) followed by average soil pH of 6.15 ($r = 0.82$). However, the slope and aspect of the area exhibited a negative correlation with the growth and distribution of Agarwood ($r = -0.46$). An area of 6,490.8 km², which accounts to 16.9% of Bhutan, was found to be suitable for cultivating Agarwood. This could support Agarwood regeneration and plantation to conserve and protect the species from extinction in the wild.

Keywords: Agarwood, Bhutan, ecology, distribution, habitat

Introduction

Agarwood, resinous heartwood giving pleasant fragrance, is formed due to injury or microbial infection on the trees of *Aquilaria* species in the family Thymelaeaceae. According to Hashim *et al*. (2016) the Agarwood is popularly used for traditional medicine, incense, religious purposes and perfumes all over Asia and the Middle East. *Aquilaria* species have a wide range of distribution occurring mostly in Bangladesh, Bhutan, Malaysia, Myanmar, Philippines, Singapore and Thailand (Chowdhery, 2014).

The high market value of Agarwood poses a great conservation threat to the genus

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Aquilaria, where it suffers extensive felling throughout its distributional range. There are around 15 species of *Aquilaria* that produces Agarwood in Asia, out of which two species are found in Bhutan; *Aquilaria malaccensis* and *Aquilaria khasiana* Hallier (Pelzang, 2009) among which *A. malaccensis* is more prevalent (Choden, 2012). *A. malaccensis* is Critically Endangered (IUCN, 2020). Worldwide, over the last three generations, the population of *Aquilaria malaccensis* Lam. in the wild has declined by 80% due to the exploitation of valuable Agarwood (Peng *et al*., 2015).

According to Wangchuk (2003), although Agarwood trees are found in Bhutan, information on the population status and ecology of Agarwood is scanty. Chamling (1996) observed that the trial plantations established in Panbang and Samdrup Jongkhar in the 1980s have been successful in terms of growth but not in terms of Agarwood production. In the Royal Manas National Park the Agarwood plantation was established approximately 25 years ago (Norbu *et al*., 2008). In 2001, the plantation had an estimated 600 to 700 trees (Zich *et al*., 2001).

In Bhutan, the ban on Agarwood export since 1990 has helped in maintaining the population of Agarwood producing species in the wild. However, there is no information on the nature of illegal harvesting and habitat disturbance of Agarwood in its natural habitat. Even though Bhutan has placed Agarwood in Schedule I of Forest and Nature Conservation Rules and Regulation 2017, its natural habitat and ecological requirements are unassessed.

Therefore, this study attempts to explore the associate species, assess ecological attributes and map suitable areas using QGIS modeling for the growth of Agarwood in the country. The information generated is expected to support Agarwood production by local communities and individuals to generate income and conserve the population of *Aquilaria* species in the wild.

Materials and Methods

Study areas

The two study areas selected were based on the limited known occurrence of Agarwood stands in the country, which falls under the tropical ecological life zone of Bhutan described by Ohsawa (1987). These are the Jomotsangkha Wildlife Sanctuary (JWS) in Samdrup Jongkhar district and Royal Manas National Park (RMNP) in Zhemgang district. The JWS, formerly known as the Khaling Wildlife Sanctuary, was established in 1993. It is the smallest protected area with about 334.3 km² and altitude ranging from

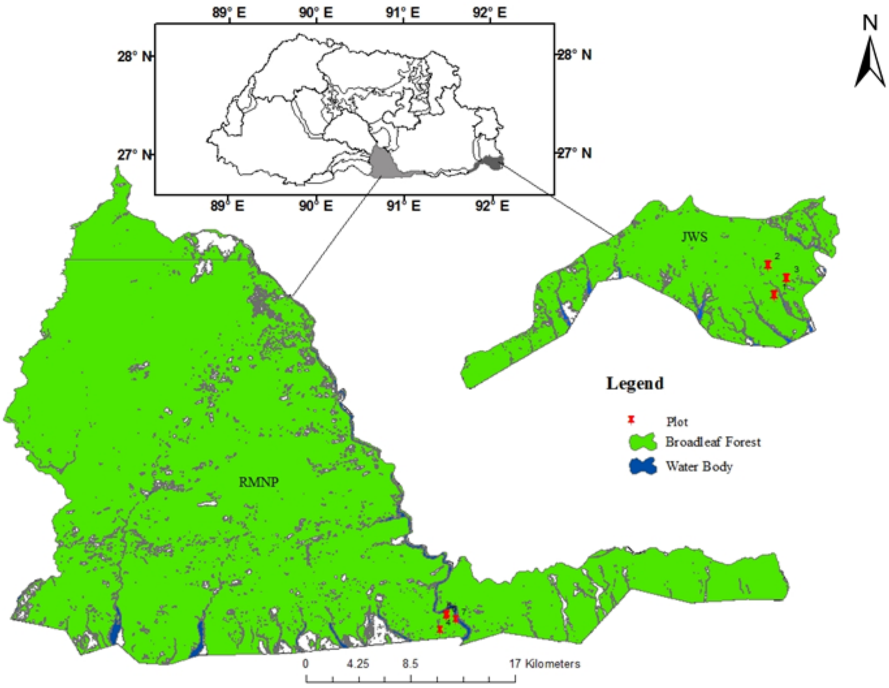

Figure 1: Study area and plot locations

200 m to 2300 m (DOFPS, 2019). The RMNP, the oldest park in the country, has an area of 1,057 km² with altitude ranging from 100 m to 2700 m and forms an integral part of the Trans-boundary Manas Conservation Area (TraMCA) bordering the Manas National Park of India, which is a World Heritage Site (RMNP, 2015). These areas share similar climatic conditions with the mean annual temperature and rainfall of about 22.8 °C and 4,003.3 mm respectively.

These study sites harbour many endemic and globally threatened species such as the Golden Langur (*Trachypithecus geei* Khajuria, 1956), Pygmy Hog (*Porcula salvania* Hodgson, 1847), Hispid Hare (*Caprolagus hispidus*, 1839), Clouded Leopard (*Neofelis nebulosi* Griffith, 1821), Asian Elephant (*Elephas maximus* Linnaeus, 1758), Dhole (*Cuon alpinus* Pallas, 1811), Asiatic Gaur (*Bos gaurus* Smith, 1827) and the Royal Bengal Tiger (*Panthera tigris tigris* Lainnaeus, 1758). More than 558 plant species including the globally rare and endangered species such as the *Dalbergia oliveri* Gamble ex Prain, *Aquilaria malaccensis* Lam. (the focus species), *Taxus wallichiana* Zucc and *Podocarpus neriifolius* Don are known to occur in these study sites (DOFPS, 2019).

Plot design and vegetation survey

Due to limited information available on the occurrence of natural stands of Agarwood in the country, only three plots from JWS and four from RMNP were purposively sampled. In this study, four basic components of ecological attribute (climatic, edaphic, biotic and topographical), which influence the growth of the target species, were collected.

Seven sampling plots with a plot size of 400 m² (20 x 20 m) each were sampled (Wangda and Ohsawa, 2006; Kaka *et al*., 2014). Each of the seven quadrats had 10 x 10 m plots nested for understory (sapling and shrub) and 2 x 2 m for groundcover (regeneration and herb) surveys. Soil sample plots of 10 x 10 x 10 cm were placed at the centre of the groundcover plots. In the tree plots, all the tree species with DBH (Diameter at Breast Height) ≥ 10 cm and height ≥ 1.3 m were enumerated. In the understory plots, all tree saplings (DBH ≤ 10 m and height ≤ 1.3 m) and shrubs were counted to compute the relative density. Under the groundcover plots, seedlings (regeneration) were counted and percentage covers for all herbaceous species were recorded. However, in regeneration count, only the heights of Agarwood seedlings were recorded to see the regeneration status of Agarwood in its natural stand.

Environmental variables

The environmental variables having significant relation with the growth of Agarwood such as the location, altitude, aspect and slope were recorded using GPS, Altimeter, Compass and Clinometers. The climatic factors such as the mean rainfall, temperature, evapotranspiration and water balance were obtained using model developed by Dorji *et al*. (2016).

Data management and analysis

Microsoft Excel was used to record, organize, process and clean the primary data. Basal Area (BA) of species was calculated for all the individual trees with a DBH ≥ 10 cm and height ≥ than 1.3 m and the Relative Basal Area (RBA) in percent was then computed accordingly. The RBA computed was used to draw vegetation structure and explain floristic compositions in the natural stand of Agarwood. The specimens collected in the field were identified by comparing with the herbarium specimens available in the National Herbarium, NBC (National Biodiversity centre), Serbithang and by using artificial keys outlined in the Flora of Bhutan (Grierson, Long and Noltie, 1983-2001). A couple of specimens were identified through online expertise, taxonomists and local guides.

The data were then analyzed to determine species diversity indices and dominant species in the plots by using PC-ORD software. Cluster analysis was performed using distance measure of Relative Sorensen (Bray-Curtis method) and Group Average as Linkage method to determine the forest types. Qualitative similarity among sample groups was determined using

Sørensen's index (Ellenberg and Mueller-Dombois, 1974). To determine the relationship between Agarwood growth and environmental variables, Non-metric Multidimensional Scaling (NMS) ordination was performed on the Agarwood forest structure based on the RBA from each plot as the main matrix data, and the environmental variables as the second matrix data. Pearson and Kendall correlation coefficient were used to explain the strength of correlation of variables with axes and forest types (Wangda and Ohsawa, 2006). The association between the Agarwood and its associate vegetation was determined using species DBH, height, canopy coverage and individual counts to understand the biotic factors enabling the growth of Agarwood in its natural stand. The stand structure and distribution pattern of the study area was carried out using stem density (individual count per plot) and DBH class following Wangda (2003) to understand the future health of the natural Agarwood stands. A comparative study of overall forest stand structure was done for Agarwood stand by taking DBH class 5 and stem density using MS-Excel.

Soil data analysis

All the soil samples were analysed in the laboratory of the College of Natural Resources (CNR) for generating additional edaphic factors such as the Soil texture, pH, NPK, Organic matters, Organic Carbon (OC) and Moisture Content (MC) which would influence the growth of Agarwood. The soil pH was measured in suspension of 20 g of sample in 100 ml of distilled water (pH ratio 1:5) using automatic pH metre. Walkley and Black (1993) method of low temperature oxidation with acidified $K_2Cr_2O_7$ and titration of the excess dichromate was used to determine soil OC and soil MC. Soil NPK (total Nitrogen, Phosphorous and Potassium) was tested with Kjeldahl, Olsen and Flame photometric method respectively after running the soil samples with a number of extraction procedures.

Habitat modelling

The environmental attributes considered for modelling the suitable area for Agarwood forest were based on real-time data taken from the natural habitats (Jomotsangkha and Manas) of *A. malaccensis*. Quantum Geographic Information System (QGIS) was used to model the suitable habitat for Agarwood growth by feeding in with a suitable range of ecological data (slope, precipitation, temperature, and elevation) with Bhutan's LULC, 2010 for the growth of species. The elevation and aspect layers were extracted from DEM layer using spatial analyst tool in ArcGIS. The settlements and permanent structures such as the buildings, dams, airport etc. were avoided using erase tool, while the

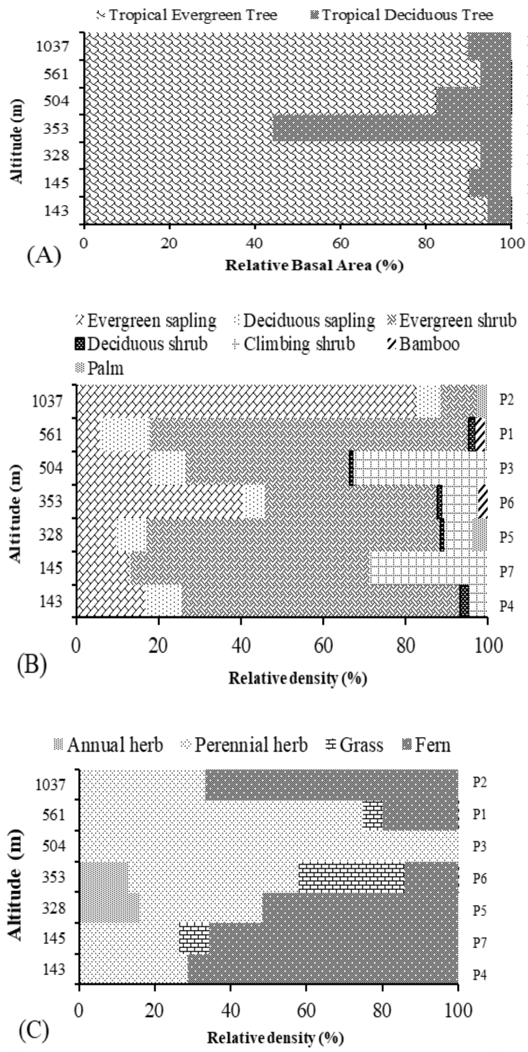

Figure 2: Agarwood vegetation composition; A=Tree lifeform, B=understory lifeform, C=Groundcover lifeform

proximity of 100 m for river and 50 m for road was maintained using buffer tool. The final result was multiplied (Times tool) with the raster data to get the suitable area map of Agarwood.

Results and Discussion

Agarwood vegetation composition

The survey plots had 168 plant species under 67 families. Classification of these species resulted in three major lifeforms; Tree, Understory and Ground cover.

The Tree lifeform in the entire study area had 23 families with 45 tree species. About 75.6% the Tree lifeform was covered with tropical evergreen trees and 24.4% with tropical deciduous trees. Almost all the plots were dominated by evergreen trees except plot 6 (Figure 2A; Table 1). *Aphanamixis polystachya* and *Polyalthia simiarum* were the abundant associated tree species in the Agarwood forest.

The understory comprised of 117 species from 48 families where the evergreen shrubs constituted the maximum portion with 52.12% and the bamboo with a minimum of 0.61% (Figure 2B). This indicates that the Agarwood is able to grow in shade. *Gironniera* sp., *Dracaena* sp., and *Hyptianthera stricta* (Roxburgh ex Schultes) Wight and Arnott were associated understory species with Agarwood. The ground-cover lifeform had 29 species under 21 families. *Elatostema papillosum* Weddell, *Colysis* sp. and *Lygodium flexuosum* (Linnaeus) Swartz were abundant in the Agarwood vegetation (Figure 2C).

Assessment of environmental factors

The Agarwood forest soil pH ranged between 5.13–6.69 with a mean pH value of 6.15 (*SD* ± 0.62) indicating a slightly acidic nature of the soil. Akter and Neelim (2008) also found that *A. malaccensis* grows best in slightly acidic soil with a pH range from 5.5–6.5 in Vietnam Agarwood plantation. The soil organic carbon ranged from 0.98–0.07% with comparatively low average soil moisture content of 2.89%, perhaps attributed to data collection in the dry season (December). According to Mat *et al*. (2012), the species grows exceptionally well at the altitudinal range of 300–850 m with the daily temperature range of 20–22 °C in Malaysia and the current study revealed typical similarities in altitudinal limits of 143–1037 m and mean tempera-

Table 2: Summary of environmental attributes of study area

Environmental attributes	Maximum	Minimum	Average	± *SD*
Altitude (m asl)	1,037.00	143.00	439.00	308.32
Aspect	W	SW		
Slope (%)	75.00	0.00	23.00	26.29
Canopy %	100.00	50.00	70.00	18.26
Soil pH	6.89	5.13	6.15	0.62
MC (%)	11.11	0.81	2.89	3.67
OC	0.98	0.07	0.26	0.32
N (%)	0.08	0.01	0.02	0.03
P (mg/kg)	8.60	0.40	2.71	2.84
K (mg/kg)	162.46	45.63	98.56	37.67
Temp (°C)	24.31	19.68	22.79	1.58
Ppt (mm)	5,441.69	2,127.03	4,003.29	1,285.81
Eto (mm)	1,012.53	928.92	987.12	28.17
WB (mm)	3,452.62	1,089.81	2,597.49	827.32

Note: *SD*=Standard deviation, Alt=Altitude, MC=moisture content, OC=organic content, N=Total nitrogen, P=phosphorous, K=potassium, Temp=Mean annual temperature, Ppt=Mean annual precipitation, Eto=Evapotranspiration, WB=Water balance

Table 1: Tree vegetation composition

Plot No.	P1	P2	P3	P4	P5	P6	P7	
Altitude (m)	**561**	**1037**	**504**	**143**	**328**	**353**	**145**	
Relative Basal Area (%)	**RBA**	**RBA**	**RBA**	**RBA**	**RBA**	**RBA**	**RBA**	**TBA**
Evergreen trees								
Aphanamixis polystachya	54.7	0.51	43.14					98.36
Heteropanax fragrans	24.1							24.13
Pterospermum acerifolium	12.3						3.56	15.87
Aquilaria malaccensis	1.52	0.11	1.60	83.68	21.92	24.74	15.6	149.2
Aglaia korthalsii					0.91			0.91
Altingia excelsa		35.69						35.69
Syzygium cumini		20.03						20.03
Persea glaucescens		15.22	11.01					26.23
Phoebe lanceolata		5.45		0.58	3.37	1.43		10.84
Beilschmiedia dalzelli		4.46						4.46
Syzygium sp.		2.78			1.69			4.46
Symplocos glomerata		2.77						2.77
Eurya acuminata		1.44						1.44
Saurauja sp.		1.25						1.25
Ailanthus integrifolia					15.58			15.58
Litsea monopetala			18.71					18.71
Garcinia sp.			7.86					7.86
Baccaurea ramiflora					0.76			0.76
Vatica lanceifolia				6.33				6.33
Polyalthia simiarum				3.71			56.8	60.48
Cinnamomum tamala					16.83	3.38		20.21
Beilschmiedia assamica					16.25			16.25
Persea sp.					5.68			5.68
Dysoxylum sp.					2.79		12.6	15.38
Knema tenuinervia					1.92			1.92
Lithocarpus sp.					1.85			1.85
Goniothalamus sesquipedalis					1.31			1.31
Cinnadenia paniculata					0.96			0.96
Gordonia excelsa					0.94			0.94
Syzygium formosum						10.59		10.59
Phoebe sp.						2.22		2.22
Gordonia sp.						1.68		1.68
Mangifera sylvatica							0.81	0.81
Mallotus sp.							0.79	0.79
Subtotal	**92.7**	**89.71**	**82.32**	**94.31**	**92.74**	**44.04**	**90.1**	**585.9**
Deciduous trees								
Elaeocarpus lanceifolius	7.33	0.46						7.78
Sapium sp.		7.18						7.18
Jabkarma shing (Ts)		1.64						1.64
Shapshing (Ts)		1.00						1.00
Yoo shing (Ts)			14.38					14.38
Stereospermum chelonoides			3.30					3.30
Casearia glomerata				5.69		2.17		7.86
Miliusa roxburghiana					5.62			5.62
Sterculia sp.					0.83	44.06		44.89
Miliusa longipes					0.81			0.81
Verbenaceae member						9.73	9.87	19.60
Subtotal	**7.33**	**10.29**	**17.68**	**5.69**	**7.26**	**55.96**	**9.87**	**114.1**
Grand total	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**700.0**

Note: Species are arranged by life-form groups; TBA = total basal area. (Dominant and co-dominant species are highlighted with shade)

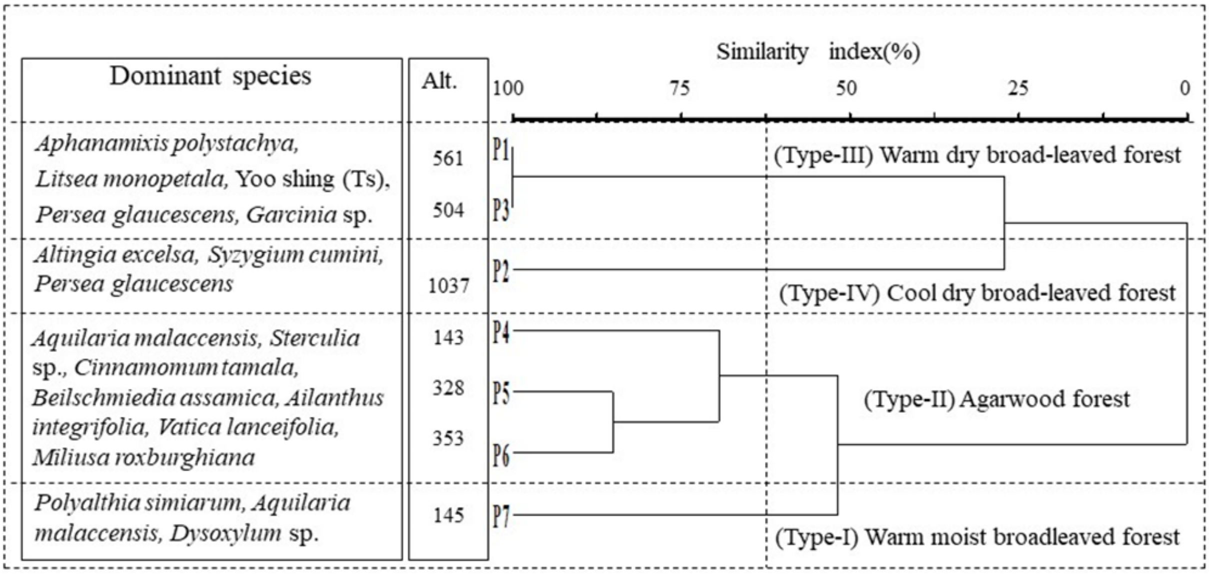

Figure 3: Dendrogram showing four types of forests in the natural Agarwood stands

ture range of 19.68–24.31 °C. Provided the right amount of rainfall Agarwood can grow in a wide range of elevation. Suharti *et al*. (2011) mentioned that the precipitation range of 1,800-3,500 mm is best suited for Agarwood growth and the study area also has similar mean annual range of precipitation, 2,127.68–5,441.69 mm (Table 2). These results indicate that Agarwood grows well in areas with slightly acidic soil having good rainfall.

The analysis of environmental factors showed that there is a strong significant correlation of soil pH with altitude and temperature; ($r = .73$, $p < .05$), whereas the soil MC in the study area had no association with the soil pH; ($r = .42$, $p > .05$). The annual average precipitation and water balance of natural Agarwood forest in the tropical life zone revealed strong correlation with the mean annual temperature; ($r = .92$, $p < .05$), while the soil NPK and evapotranspiration had no association with the mean annual temperature. These associations show that besides soil pH and rainfall, temperature is another important environmental factor that supports Agarwood forest growth.

Agarwood forest classification

Four different forest types (Type I = warm moist broadleaved forest, Type II = Agarwood forest, Type III = cool dry broadleaved forest and Type IV = warm-dry broadleaved forest) could be classified arbitrarily at 65% similarity threshold (Figure 3) following Wangda (2003). These four forest types were named based on temperature, moisture condition, precipitation and major dominant species following the Holdridge's life zone classification system (Holdridge, 1967).

* *Type I (Warm-moist broadleaved forest)*

Plot 7 was clustered in Type I as warm-moist broadleaved forest owing to its exceptionally high soil moisture content of 11.11% compared with the rest of the plots with below 3% MC. Also, the annual rainfall received by this forest type was 5,433.81 mm, the highest among all the plots. The low elevation (145 m) was also noted in this group with vegetation cover dominated by *Polyalthia simiarum* (Benth. and Hook.) and *Dysoxylum* sp. which performs best in high rain forest (Kumar *et al*., 2006).

* *Type II (Agarwood forest)*

Plots 4, 5 and 6 were clubbed under the forest Type II as Agarwood forest since the dominant species in these plots was Agarwood (*A. malaccensis*) with co-dominant species such as *Sterculia* sp., *Cinnamomum tamala, Beilschmiedia assamica, Ailanthus integrifolia, Vatica lanceifolia,* and *Miliusa roxburghiana.* Relative dominance of Agarwood in P4, P5 and P6 were 83.68, 21.92 and 24.74 respectively, being in the top compared to other species present in the plots. The average annual temperature in the forest type was 23.6 °C, which is the best mean temperature for the growth of Agarwood (Elias *et al*., 2017).

** Type III (Warm-dry broadleaved forest)*

Forest Type III comprised of P1 and P3 located both in Jomotsangkha with altitudinal range of 504–561 m. This forest type was named warm-dry broadleaved forest owing to the presence of warm and dry environment with high mean annual temperature of 22.3 °C and soil moisture content of about 1.7%. The forest type is dominated by *Aphanamixis polystachya, Litsea monopetala,* Yoo shing (Ts)*, Persea glaucescens* and *Garcinia* sp.

** Type IV (Cool-dry broadleaved forest)*

Type IV forest class had P2 which is located at *Agurtar* top in Jomotsangkha. The peculiar character of this forest type IV was relatively a high altitude of 1,037 m and low temperature (19.6 °C) with soil MC of 2.67%. So, the name cool-dry broadleaved forest was assigned to this cluster. The dominant species in this forest were *Altingia excelsa, Syzygium cumini* and *Persea glaucescens*. Shukla *et al*. (2014) reported that those species are indicator of transition from tropical forest to sub-tropical dry forest and are found growing in moderately humid environment with average annual rainfall of 2,500 mm. Through the cluster analysis, we concluded that the natural Agarwood forests in the country can be classified based on altitudinal range and soil MC as the determinant factors (Type I at 100 metres with 11.11% soil MC, Type II at 300 metres with < 2% soil MC, Type III at 500 metres with < 2% soil MC and Type IV at 1000 metres with < 2% soil MC). Faridah-Hanum *et at*. (2009) also reported that Agarwood in Malaysia is also found to grow in various soil types and slopes with wide range of altitude (0–2000 m asl) in warm moist evergreen broadleaved forest, if it receives the right amount of mean annual precipitation (2,500 mm) and temperature (25 °C).

Diversity indices

The highest species diversity (Shannon's diversity index) was observed in plot 5 (H = 2.27) and lowest in plot 4 (H = 0.63). Plot 4 was mainly dominated by Agarwood trees and the diversity analysis indicated that Agarwood performs well in habitats with low species diversity (Table 3). This could be attributed to low soil pH as many species many not grow well in acidic soil.

Influence of environmental variables on Agarwood growth and distribution

The biplot of NMS ordination (Figure 4) depicts the distribution of individual species under study area with its ecological similarities. The species under warm-moist broadleaved habitat (*Aquilaria malaccensis, Sterculia* sp.*, Cinnamomum tamala, Beilschmiedia assamica,*

Table 3: Diversity indices for the seven plots with forty-five species

Plot	Mean	*SD*	Max	*S*	*E*	*H*	*D*
P1	2.22	8.99	54.71	5	0.73	1.18	0.62
P2	2.22	6.41	35.69	15	0.72	1.95	0.79
P3	2.22	7.37	43.14	7	0.81	1.57	0.73
P4	2.22	12.49	83.68	5	0.39	0.63	0.29
P5	2.22	5.1	21.92	18	0.78	2.27	0.86
P6	2.22	7.63	44.06	9	0.72	1.58	0.72
P7	2.22	8.93	56.77	7	0.66	1.29	0.62
Mean	2.22	8.13	48.57	9.4	0.69	1.5	0.66

Note: S=Richness, E=Evenness, H=Shannon's diversity index and D=Simpson's diversity index

Polyalthia simiarum, Vatica lanceifolia, Miliusa roxburghiana and *Ailanthus integrifolia*) and Agarwood dominated plots (P4, P5, P6 and P7) of forest Type (I and II) are present below the positive side of Axis 1. The species under this cluster are shade tolerant and requires comparatively moderately to high soil moisture content (11.11%), precipitation (4,500–5,500 mm) and temperature (23–25 °C) (Kundu and Kachari, 2000). The species with warm dry broadleaved habitat (*Aphanamixis polystachya, Litsea monopetala,* Yoo shing (Ts)*, Persea glaucescens* and *Garcinia* sp.) of forest Type III (P1and P3) are placed at top left of Axis 2, those species generally grows best in well drained open canopy (50%) areas with low soil moisture content (1-2%) and all the species are light demanding species as per Reddy and Ugle (2008). The cool-dry broadleaved species (*Altingia excelsa, Syzygium cumini* and *Persea glaucescens*) of forest Type IV (P1) are distributed at the bottom left of Axis 2. The species under forest type IV are indicator species of forest transition from tropical to temperate forest and emerge at the edge of warm tropical forest in southern foothills, where required atmosphere and environmental conditions are moderately cool and dry with mean temperature of 19 °C and annual rainfall of 2,500 mm (Bruggeman *et al*., 2016).

The length of arrow indicates the magnitude of environmental factors' effect on the vegetation distribution and the position of each environmental arrow concerning each Axis indicates its correlation with that factor (Wangda and Ohsawa, 2006). Axis 1 was determined strongly by annual rainfall (Ppt) and soil pH followed by soil potassium (soil K), altitude (Alt) and temperature (Temp), whereas the Axis 2 was determined by canopy percent alone. According to Lok and Zuhaidi (2010), Agarwood performs exceptionally well in 80% humidity level with an average temperature of 22-28 °C and average rainfall of 2,000–4,000 mm, but it performs poorly on inundated waterlogged soil with pH of < 4. Suharti *et al*. (2011) also reported that natural Agarwood species grows well at low hills (< 750 m asl) on yellow red podzolic, clay-sandy soil with moderate to good drainage system.

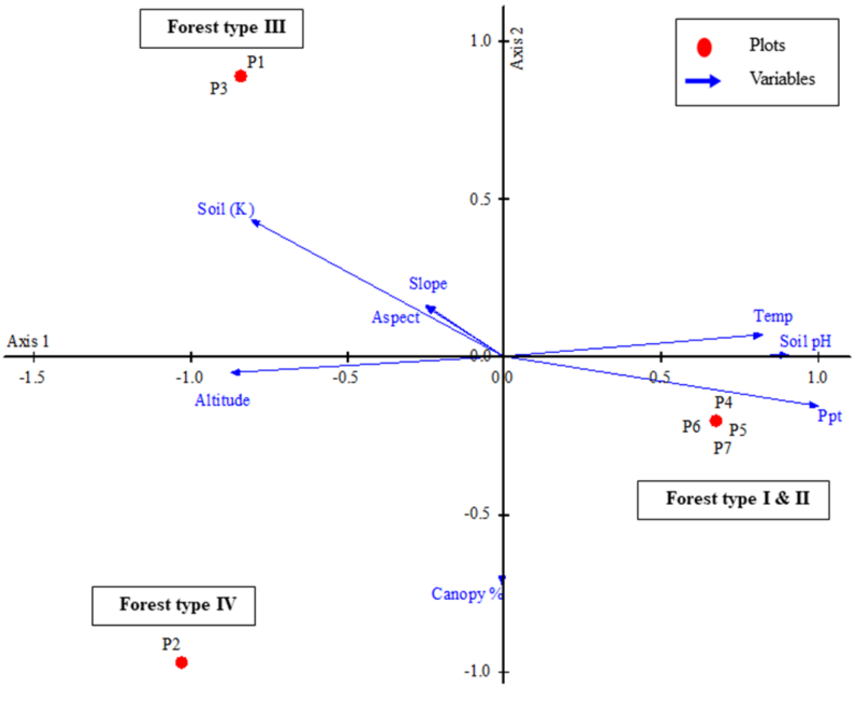

Figure 4: Influence of environmental factors on Agarwood

Similarly, ordination biplot showed annual average rainfall (Ppt) with the longest arrow length in the direction of Agarwood dominated forest Type I and II (P4, P5, P6 and P7) with strong Pearson and Kendall correlation (r = .90). This indicates strong influence of annual average rainfall on the growth and distribution of Agarwood trees followed by soil pH (r = .82) and mean annual temperature (r = .76). Whereas, aspect and slope had shortest arrow length (r = .44 and .45) in the opposite direction

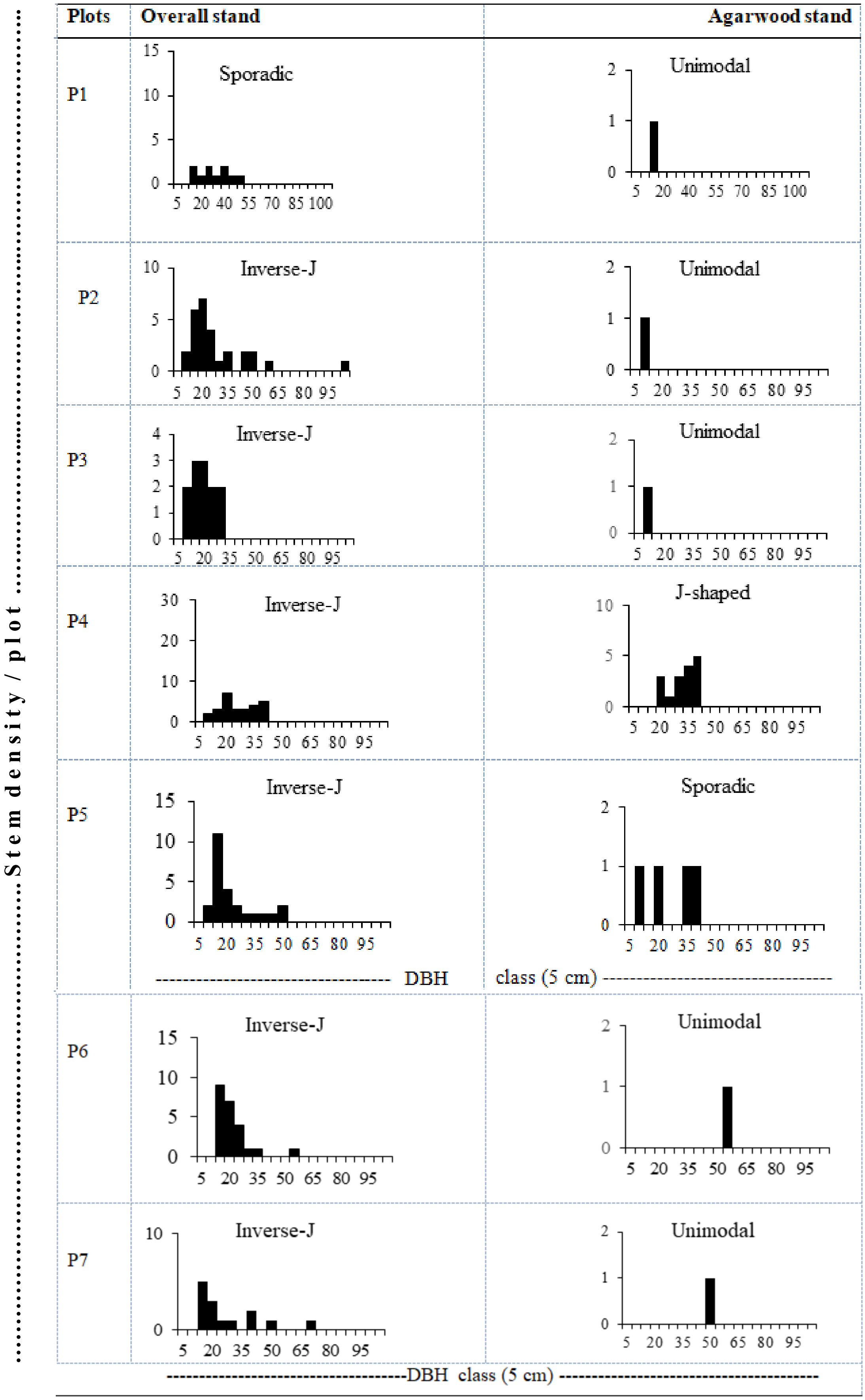

Figure 5: Stand structure and distribution pattern of natural Agarwood forest

indicating weak and negative relation with Agarwood tree distribution and growth. Three environmental variables [soil moisture content (MC), soil Nitrogen (N) and soil Phosphorous (P)] were found to have a negligible effect on growth and distribution of Agarwood vegetation in the study area, thus they were eliminated from the ordination biplot (Figure 4; Table 4).

The research carried out in Indonesia, Vietnam and Bangladesh by Soehartono and Newton (2000), Nakashima *et al*. (2005), and Ahmed (2010) also found that Agarwood grows well with a mean annual rainfall of 1,300–3,500 mm, soil pH between 4.0–6.0 and mean annual temperature of 22–28 °C, but is less dependent on altitude, slope and aspect. However, the study area revealed that Agarwood had strong negative correlation with altitude (r = -.78). This could be attributed to low temperature at higher altitude.

Table 4: Pearson and Kendall correlations with ordination axes, N = 7

	Axis 1			Axis 2		
	r	***r²***	***tau***	***r***	***r²***	***tau***
Altitude	-0.787	0.62	-0.238	0.344	0.118	-0.143
Aspect	-0.461	0.213	-0.117	-0.304	0.092	0.467
Slope	0.462	0.213	0	-0.299	0.089	0.293
Canopy %	0.011	0	0.206	0.799	0.638	0.411
Temp	0.766	0.587	0.238	-0.373	0.139	0.143
Ppt	0.901	0.812	0.238	0.226	0.051	0.333
Soil pH	0.822	0.675	0.488	-0.176	0.031	0.293
Soil MC	0.236	0.056	-0.25	0.12	0.014	0.35
Soil (N)	0.227	0.051	-0.233	0.116	0.013	0.35
Soil (P)	0.43	0.185	-0.048	-0.07	-0.005	0.333
Soil (K)	-0.829	0.688	-0.905	-0.484	0.234	-0.048

Stand structure and distribution pattern of natural A. malaccensis

Three major types of stand distribution patterns; Uni-modal, Sporadic and Inverse-J were noted (Figure 5). The presence of unimodal distribution pattern indicates poor recruitment of tree species. If the regeneration is poor, this could lead to loss or extinction of species.

Suitable areas for growing A. malaccensis

The QGIS suitability analysis resulted in a total suitable area of 6,490.8 km² (16.9% of the total area of the country) which is potential for *A. malaccensis* growing in the 16 Dzongkhags (Table 4). Zhemgang Dzongkhag had the largest suitable habitat for Agarwood forest growth with a total area of 1,109.7 km² and Punakha Dzongkhag had the least suitable area with about 20.4 km² (Figure 4). However, inner valleys of the mid Himalayas may not be logically suitable mainly due to cold draft that could inflict frost damage to the seedlings.

Conclusions

The natural habitat assessment showed that *A. malaccensis* performs well in the tropical warm-moist broadleaved forest of Bhutan. Though the altitude explains well the distribution of general vegetation composition, the study revealed that the growth of *A. malaccensis* is predominantly influenced by annual average rainfall in combination with soil pH and mean annual temperature. *A. malaccensis* demands slightly acidic soil with an average annual rainfall and temperature ranges of 2,100–5,500 mm and 19–25 °C respectively.

The *A. malaccensis* forest structure and distribution showed 71.4% of the study area with Uni-modal distribution pattern, which indicates a high risk of losing the current natural stands. This is supported by low natural regeneration and extensive wild seedling collection for domestication. Nevertheless, a total area of 6,490.89 km^2 in the country was found to be suitable for growing *A. malaccensis*, which is good to help complement natural population through plantation and management interventions.

Table 4: Suitable environmental variables range for the growth of Agarwood forest

Variables	Suitable range *	Materials / source
Slope	0-75^0	Real-time data collected from
Mean annual temperature	19-25^{0}c	natural Agarwood habitat in
Elevation	90-1,300 m asl	Jomotsangkha and Manas supported by Saikia and Khan (2014) and Suharti *et al.* (2011)
Mean annual rainfall	2,000-5,500 mm	
Aspect	Northwest	

* Agarwood habitat

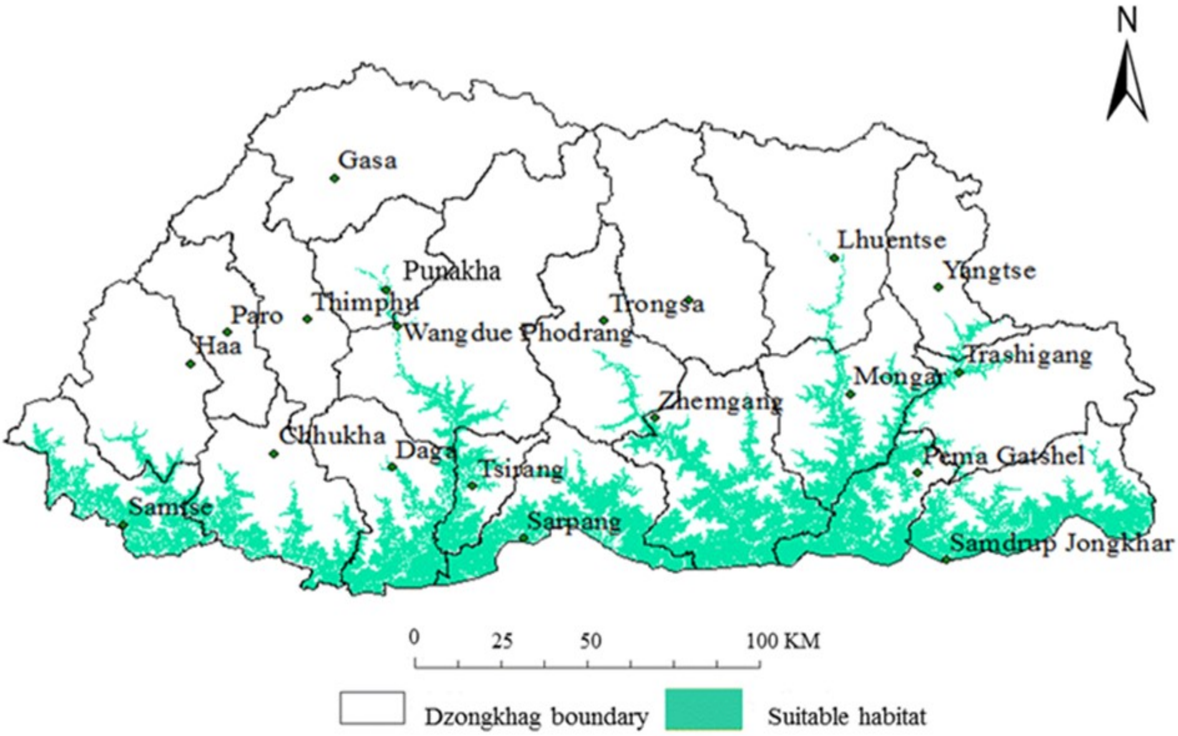

Figure 4: Map representing suitable areas for growing *A. malaccensis*

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