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Synthesis

Learning from Traditional Knowledge of Non-timber Forest Products: Penan Benalui and the Autecology of *Aquilaria* in Indonesian Borneo

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ABSTRACT. Traditional knowledge, promoted to make conservation and development more relevant and socially acceptable, is shown to have an important role in identifying critical research needs in tropical ecology. Botanists, foresters, and phytochemists, among others, from many countries have sought for decades to understand the process of resin formation in the genus *Aquilaria*, a tropical forest tree of South and Southeast Asia. Not every tree develops the resin and, despite extensive scientific research, this process remains poorly understood. Attempts at cultivating the valuable aromatic resin, *gaharu*, have been uneven at best. Thus, *gaharu* remains largely a natural forest product, increasingly under threat as the trees are overexploited and forest is cleared. In this paper, we compare scientific knowledge and traditional knowledge of the Penan Benalui and other forest product collectors of Indonesian Borneo. Although limited management of wildlings failed to bring the resin-producing species under cultivation, we found that the Penan recognize the complex ecology of resin formation involving two, or maybe three, living organisms—the tree, one or more fungi, and possibly an insect intermediary. Developing a sustainable production system for this resource will require a clear understanding of how these various natural elements function, separately and synergistically. Traditional knowledge can help fill gaps in our information base and identify promising areas for future research. Both correspondence and gaps in knowledge support the call for a greater role for ethnobiological research and interdisciplinary cooperation, especially between ethnobiologists and foresters, in developing sustainable management systems for this traditional resource and its natural habitat.

INTRODUCTION

The increasing number of publications on non-timber forest products (NTFPs) over the past decade indicates growing interest in the management of forest lands for a wider range of outputs than timber alone (see reviews in DeBeer and McDermott 1989, Fox 1995, Ruiz-Pérez and Arnold 1997, Wollenberg and Ingles 1998, Neumann and Hirsch 2000, Kusters and Belcher 2004). Pressed by indigenous people seeking to retain or regain control of their traditional forest resources, many policy makers and planners are investigating the possibility of developing sustainable forest production systems based on a multiplicity of products. Concurrently, traditional ecological knowledge (TEK) and forest management practices are attracting greater attention for the insight they offer into forest ecology and for the potential they hold for increasing forest productivity and ecological resilience. Despite repeated calls for increased use of traditional knowledge in conservation and development, integration of traditional knowledge in natural resource planning and management remains nominal or negligible at best (Brokensha and Vanek 1988, Redford and Padoch 1992, Williams and Baines 1993, DeWalt 1994, Dickson 1999, UNESCO-ICSU 1999, Belcher and Kusters 2004).

There has been considerable ethnobiological research on agriculture, including mixed tree and crop systems, especially in the neotropics (Alcorn 1984, Denevan et al. 1984, Richards et al. 1989, Xu and Ruscoe 1993, Fujisaka 1995, Thapa et al. 1995, Bocco and Toledo 1997, Obua and Muhanguzi 1998, Sinclair and Walker 1998, Eyzaguirre 2000). Investigations by ethnobotanists and anthropologists have revealed that

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indigenous people have been manipulating natural vegetation for several millennia, often in what are widely perceived in the west as “pristine” forests (Posey and Balée 1989, Anderson and Ioris 1992, Ellen 1998). Across all habitat types, there has been a noticeable increase in studies of TEK systems in resource management, including understanding and interpreting ecosystem dynamics (Johannes 1978, Gadgil et al. 1993, Williams and Baines 1993, Berkes and Folke 1998, Berkes 1999, Ford and Martinez 2000, Nabhan 2000, Gadgil et al. 2003). Forestry, however, especially in Asia, has been slow to appreciate these trends. Lagging behind other resource management sciences in acknowledging the importance of traditional knowledge, especially ecological knowledge, it has been slow to apply TEK in developing more productive and more sustainable forest management systems, especially for natural forests and their products (Donovan 2001).

The noticeable gap between the inflated rhetoric that champions traditional knowledge as vital for the conservation and sustainable use of economically and environmentally important forest resources and the demonstration of such claims seems most evident in the area of forestry research (Compton 1989, Hadley 1991, Gunatilleke et al. 1993, Redford and Stearman 1993, Ortiz 1999, Eyzaguirre 2000, Belcher and Kusters 2004). Although numerous studies have demonstrated the complementarity of traditional knowledge and scientific knowledge, particularly with reference to wild animals and agricultural crops (Johannes 1978, Brown 1984, Posey 1986, Berlin 1992, Berkes and Folke 1998, Berkes 1999, Berkes et al. 2000, Nabhan 2000), there are few instances of similar studies on natural forest plant species. Well-studied forest species include teak, mahogany, rubber, tea, and coffee, all of which have become plantation crops and thus removed from their natural forest habitats. The most widely cited cases studying the possible application of traditional knowledge to modern resource management focus on social and institutional arrangements regarding access to the resource, or derived benefits, in almost purely extractive systems (for an exception, see Salafsky et al. 1993). Rarely does analysis include the juxtaposition of traditional techniques of vegetation manipulation and exploitation and recognized scientific practices or ecological principles with an analysis of the impact on the quantity and quality of resource production over time (e.g., Martin et al. 1999, Puri 2001b). Moreover, many reviews are unbalanced, either focusing on negative aspects of traditional management methods—most of the literature on swidden cultivation—or uncritically promoting indigenous practices. Finally, traditional ethnobiological investigations tend to concentrate on the collection and analysis of verbal knowledge concerning biological taxa, whether animals or plants, reports of the use of that taxa, and the cognitive organization of this information (see Berlin 1992), often neglecting close examination of ecological knowledge and the procedural or skill knowledge underlying a group’s interaction with and manipulation of their environment (Bloch 1991, Lawrence et al. 1995, Puri 1997a, Berkes 1999, Ingold 2000).

Traditional knowledge of biotic relationships involving rare plants or animals can help the identification, management, protection and recovery of habitats or species. Increasing calls for preservation of unique ecosystems, restrained use of resources, and ecological restoration in many parts of the world strengthen the mandate for the inclusion of TEK in conservation efforts. Acknowledging that indigenous people recognize ecological interaction and understand ecological principles (Nabhan 2000, Turner et al. 2000) and that traditional knowledge can be used to assist in interpreting and responding to feedbacks from the environment and guide development (Berkes et al. 2000), this paper responds to the urgent call for scientists and scientific communities to increase support for TEK research in concert with local communities and to evaluate traditional knowledge for insights it provides to both the qualitative and quantitative aspects of managing resources and ecosystems (Mauro and Hardison 2000, Nabhan 2000, Donovan 2001). Here, we give a tangible example of how TEK can be used to guide empirical and experimental studies to learn more about autecological relationships of key economic species.

In comparing the two bodies of knowledge, namely scientific and ethnobiological, with a view to integrating them, this study offers the potential not only for expanding our knowledge base but for refining our research agenda for forest management and rural community development. In this paper, we attempt to examine the gap between the two knowledge bases by comparing some of the more technical aspects of traditional knowledge with scientific research findings, using *gaharu*, an NTFP of Southeast Asia, as our example[1]. How far apart are the two information sets? Does the TEK related to *gaharu* and its source, *Aquilaria* spp., hold insights into the ecology or physiology of this species that could bring us closer to developing a better management regime for this forest product? Such information could be critical not only for enhancing productivity, product quality, and earning potential of this species, but also for the sustained production and, indeed, the very survival of this unique product and the villagers who depend on it (Chakrabarty et al. 1994, Donovan 1999). Clearly, TEK can be extremely useful in identifying new directions for institutional research addressing such conservation-cum-development objectives. Through this collaborative study, we offer an example of potential benefits of interdisciplinary cooperation between ethnobiologists and foresters in developing environmentally sound and sustainable management systems for traditional resources and their natural habitat.

BACKGROUND AND METHODS

Valued mainly for its aromatic, fumigatory, and medicinal properties, *gaharu* is the fragrant, resin-impregnated wood found in approximately 17 species of sub-canopy trees of the genus *Aquilaria* (Thymelaeaceae) commonly found in mixed hardwood hill forests across tropical Southeast Asia (Chung and Purwaningsih, 1999)[2]. Generally agreed to be the result of a pathological condition, this aromatic resin is produced as the tree sap thickens in response to injury and fungal infection. The degree to which the resin saturates the heartwood phloem fibers determines the market value of this product. In lesser quality specimens, the resin creates a mottled or speckled appearance in the naturally pale wood, but higher quality specimens are nearly solid in color—glossy and black. Through distillation, the most valuable specimens can yield an essential oil that is a key perfume ingredient; distillation residues and lesser quality material are commonly processed for incense. The species that produce high quality resin include *A. agallocha*, *A. crassna*, *A. bailloni*, and *A. grandiflora* (Burkill 1966, Soehartono 1997).

Morphology, Ecology, and Distribution[3]

A member of the family Thymelaeaceae, *Aquilaria* is a relatively slow-growing, medium-sized tree, on average 15–25 m tall; some of the more than 15 species (e.g., *A. microcarpa*) reach heights of as much as 40 m. Having a moderately straight stem, it can achieve a diameter (dbh) of up to 250 cm, although some species remain considerably smaller and more shrublike, e.g., *A. khasiana*. Most *Aquilaria* species have smooth, thin, pale gray bark with dense, dark foliage of shiny elliptical to oblong leaves (7.5–12 cm long by 2.5–5.5 cm wide) (Ding Hou 1960). The small, pale blooms flowering in clusters on the short stalks of the leaf stems produce 3–5 cm long, bi-valved fruit capsules in August. *Aquilaria* regenerates freely under natural conditions as seedlings around the mother tree or sprouts from the stumps of harvested trees. However, mother trees are becoming scarce in many areas because of over-exploitation (Beniwal 1989, Paoli et al. 1994, Hasnida et al. 2001, Soehartono and Newton 2002, Quan et al. 2003). Although this condition may not lead to local extinction of the species, it may severely affect the availability of the product and, thus, the local *gaharu* economy.

A shade-tolerant tree, *Aquilaria* is an understory tree of mature evergreen and semi-evergreen forest occurring at low to medium altitudes, generally up to 1000 m asl depending on the species. In Indonesia, it also occurs as an emergent (Soehartono and Mardiastuti 1998). La Frankie (1994) found *A. malaccensis* widely distributed but relatively uncommon (2.5 stems per ha, >1 cm dbh) in the Pasoh Forest Reserve of peninsular Malaysia. In West Kalimantan, Paoli et al. (1994) found mature trees (>20 cm dbh) of *A. malaccensis* scarce but widely distributed, ranging from 0.16 stems per ha in alluvial bench and lower montane forests to 0.32 stems per ha in lowland granite and sandstone forests. Patchy distribution throughout the natural forest in Indonesia makes inventory difficult. Scientists estimate stocking at 1.87 trees per ha in Sumatra, 3.37 trees per ha in Kalimantan, and 4.33 trees per ha in Irian Jaya (Soehartono 1997).

The occurrence of the tree itself does not guarantee the presence of the resin. Scientists estimate that only 10% of the *Aquilaria* trees in the forest may contain *gaharu* (Gibson 1977). The resin forms in response to wounding and subsequent fungal infection, and is found in many parts of the tree, according to some sources in the bark and the roots as well as the heartwood (Jalaluddin 1977). Under natural conditions, the resin is more commonly found in trees of about 20 years or older, with trees more than 50 years old reportedly having the highest concentration (Sadgopol 1959). A “good” tree may yield several kilograms of the valuable dark, heavy resinous wood with the characteristic honey-like scent. Distributed broadly through Southeast Asia, the genus *Aquilaria* has been found from Bhutan and northeastern India across to southern China and then south as far as the island of New Guinea (Burkill 1966, Whitmore 1972). Little detailed information exists, however, on its distribution, exploitation, or use in the southeastern edge of its range. In some of the earlier exploited areas, several species are thought to be extremely rare if not extinct in the wild, for example, in Bangladesh and Java (Chakrabarty et al. 1994).

Collection and Trade

Gaharu, also known as aloeswood or eaglewood, has been traded across Europe and Asia for more than 2000 years, mainly to consumers in the Middle East and China (Burkill 1966). Historically, for both local people as well as their governments, the sale of such forest products has been an important source of cash income and means of access to foreign goods. As with many NTFPs, *gaharu* has a history of boom and bust markets (Gianno 1990). The most recent expansion of commercial activity began in the late 1970s. In 1980, the best grade of *gaharu* could be purchased in the Apo Kayan area of Borneo for USD $20 per kilogram (Jessup and Peluso 1986). Lately, prices for the best quality *gaharu* have been quoted at about twenty times that rate, with prices to buyers across the straits in Singapore at ten to twenty times again this price (Hansen 2000, Clear 2000). With much of the best quality material smuggled out of the country, trade records for this product are admittedly poor. Trans-shipment is common both within and between countries. As a result, the true point of origin and even the species of much of the traded material may be difficult to ascertain with the naked eye. Malaysia and Indonesia, however, appear to be the world’s major exporters of this product, which trades in the form of wood chunks, chips, and dust as well as processed goods such as essential oil, perfume, incense, and medicinal preparations (Chung and Purwaningsih 1999, Barden et al. 2000). It is estimated that as much as 70% of the *gaharu* entering the Singapore market comes from Indonesia, with the remainder from Laos, Myanmar, Thailand, Cambodia, and Vietnam (Yamada 1995).

Lured by the anticipation of quick riches, many unskilled collectors are attracted to *gaharu* exploitation and, as a result, the resource has suffered widespread destruction (Broad 1995, Momberg et al. 1997, 2000). With the recent boom, *Aquilaria* throughout the region has experienced heavy exploitation and may now be threatened with commercial if not biological extinction across a large part of its range (Soehartono and Newton 2001a). In the Gunung Palung area of West Kalimantan, for instance, the supply of *gaharu* was depleted in just a few years when well-organized teams of collectors swept through the area (Salafsky et al. 1993). Listing *Aquilaria malaccensis* in the Convention on Trade in Endangered Species (CITES) Appendix II in February 1995 has hardly slowed the pace of commercial activity (Soehartono and Mardiastuti 1998, Barden et al. 2000).

Unconfirmed reports indicate that synthetic eaglewood oil is for sale in Bangkok at a twentieth of the price of the genuine oil. If this substitute is successful in the market, it may absorb some demand, taking some pressure off prices and off the resource. The sophistication of the consumer and the preference revealed for natural products in the herbal medicine market in general would suggest that the demand for naturally produced resinous wood and its product will endure (Donovan 1999). However, given the strength of demand, there may be room for both types of products.

Despite its long trade history, the enduring interest of consumers (as indicated by as many as 20 distinctions of quality in some areas), high prices, and several decades of research, no one yet has succeeded in producing high quality commercial *gaharu* from plantations (Barden et al. 2000, Soehartono and Newton 2001a, Chang et al. 2002, Tabata et al. 2003). In an attempt to address this dilemma, we examine traditional knowledge—the accumulated knowledge of a group of people who have been collecting and trading *gaharu* for several centuries—compared with scientific knowledge published in historical records and scientific journals on the species *Aquilaria* and its product *gaharu*. The literature review covered more than a century of data collection and experimentation in forestry (e.g., van Goor and Kartasubrata 1982). In addition, the authors examined ethnographic literature (using the Human Relations Area Files) for information on the Southeast Asian ethnic groups that have been identified as *gaharu* collectors or traders. Finally, we reviewed publications on the development of trade and market conditions, especially in Borneo (Paoli et al. 1994, Yamada 1995, Momberg et al. 1997, 2000, Soehartono and Mardiastuti 1998, Soehartono and Newton 2000, Paoli et al. 2001).

Ethnobiological research, including participant observation among collectors and interviews with key informants, was conducted among the Kenyah Badeng and Penan Benalui peoples of the Pujungan area in East Kalimantan from 1991 to 1993 and from 1996 to 1997 (Puri 1992 1997a, 1997b), and among the Punan people of the Malinau area of East Kalimantan periodically between 1997 to 2000 (Puri 1998 2001a, b) (Fig. 1). Information collected included local classification systems, people's perception of the growth habits and characteristics of the genus *Aquilaria*, local methods for locating such trees and for determining the presence of *gaharu*, people's explanations of the formation of *gaharu* within the tree, and traditional techniques of extraction.

Fig. 1. Location of field research sites, Pujungan and Malinau Districts, in northern East Kalimantan, Indonesian Borneo

Beyond the standard data collection techniques in anthropology and ethnobiology (e.g., informal and semi-structured interviews with collectors and traders), active participant observation on *gaharu* collecting expeditions proved to be the most fruitful means for acquiring traditional knowledge about *Aquilaria* species, *gaharu* formation, harvesting practices, and local beliefs. This type of knowledge was seldom elicited outside the context of actual collecting expeditions; only through participation and learning by doing could a deeper understanding be gained of how this rare tree is found, assessed for *gaharu*, harvested, and then processed to be sold. Although many questions could be answered more easily by collectors in the field, there were certain times during expeditions when the need for silence and secrecy prevented much communication or explanation. But even these moments were of importance for understanding the emotional life of the collectors, for these silences often reflected local beliefs and superstitions about plants and the forest and human interactions with them.

SCIENTIFIC KNOWLEDGE

Recorded knowledge concerning *gaharu* and *Aquilaria* dates back several centuries to the journals of the first explorers, traders, and naturalists to Asia. Scientific research in tropical forestry and agriculture undertaken in the 19th and early 20th centuries focused on species of significant commercial value to the colonial trading companies—most notably tea, coffee, cacao, and rubber. Research interest in *Aquilaria* and its primary product, *gaharu*, has been sporadic at best. Most publications have focused on *Aquilaria*'s botanical characteristics, its products and their uses, occasionally on processing techniques, and later on mechanical properties, wood structure, and chemical properties. Some of the first controlled, scientific experiments with *Aquilaria* and *gaharu* production began in India in the late 1920s (Beniwal 1989). Over the next few decades, only a handful of research reports were published. Between 1970 and 1994, only 22 articles were produced, with more than three-quarters appearing in the last decade and a half. The pattern that emerges across the range of research topics related to *Aquilaria* indicates an upsurge of interest, both in consumer as well as producer countries, with the increase in commercial activity. Compared with the previous decade, the number of research articles on this species trebled over the last decade. Across the spectrum of topics, including research on chemical, botanical, and mycological aspects, roughly twice as many publications have appeared on chemical analysis, especially from Japanese scientists interested in biosynthesis. Information from researchers and traders in Southeast Asia indicates that field trials testing various regeneration methods and inoculation protocols are being conducted in Bhutan, Burma, Thailand, Indonesia, Vietnam, and Laos. Little of this research has been published and it may well be retained as proprietary information given the potential lucrative profits to be made from the successful domestication of *gaharu* production.

TRADITIONAL KNOWLEDGE: THE CASE OF THE PENAN BENALUI

Traditionally in Asia, forest products have been collected by tribal people, commonly forest dwellers or forest-edge communities. Often a certain product is associated with a specific ethnic group or particular geographic area. In Peninsula Malaya, tribal people are known as the *orang asli*, "original people," and the Semelai in particular have been associated with *gaharu* collection (Gianno 1990). In Assam, it is the Naga and in Central Vietnam, it is the Katu people (Darby 1942). In central Borneo, it is the Dayak, especially the Penan, Punan, Bukat, and Ot peoples, who have traditionally been the primary collectors of *gaharu* (Sellato 1994, Puri 1997a). These minority ethnic groups, linked to the larger world via a commodity chain of trading relationships, are often employed for their knowledge of forest products and skill in organizing and leading collecting expeditions (Fox 1969, Bird-David 1988). This study examines the specialized knowledge of one such group, the Penan Benalui of central Borneo. Traditionally nomadic, their movements were sometimes cyclical within a broad area encompassing several watersheds either nearby or within the territories of swidden agriculturists, such as the Kenyah, with whom they traded. Although still highly mobile, today the Penan live in permanent villages. Their subsistence economy includes the processing of wild tree palms for their starchy pith, hunting, fishing, collecting wild plants and fruits, gardening of manioc and other vegetables, and swidden rice farming. Collecting and trading forest products such as *gaharu*, rattan, medicinal plants, and live animals continues to be an important means for generating cash income to buy manufactured goods (Puri 1997a).

Field work was conducted initially among residents of Long Peliran, a village of approximately 77 Kenyah Badeng and 36 Penan Benalui, located at the mouth of the Lurah River on the Bahau River in Kecamatan (subdistrict) Pujungan of Kabupaten (district) Bulungan in East Kalimantan, Indonesia (Fig. 1). Long Peliran is one of four villages on the Lurah River occupied by these two ethnic groups (total population of about 275 in 1993). The Kenyah Badeng, who migrated to the Pujungan area from the upper Peliran River in Sarawak in the late 1890s, moved to Long Peliran about four decades later, in the early 1930s. Their economic activities include swidden agriculture, gardening, hunting, fishing, and collecting a variety of forest products for food, building materials, and trade items (Puri 1997a). The Penan Benalui, a subgroup of Western Penan of Sarawak, migrated from the Silat River area to the Upper Lurah at the request of the Kenyah Badeng in the late 1890s. Their traditional economic life involved hunting (primarily the bearded pig, *Sus barbatus*), collecting fruit and other wild foods, sago production (from the pith of several species of tree palms including *Eugeissona utilis* and *Arenga undulatifolia*), and trade, especially in NTFPs such as rattan and *gaharu* (Puri 1997a). Traditionally nomadic, the Penan, in living groups of 25 to 75 people, relocated regularly after exhausting local resources of their major food source, the sago palm (*Eugeissona utilis* among others, see Puri 1997b). In times of warfare or following deaths, internal disputes, or the breakdown in relations with trading partners, these groups might fissure or fuse and migrate to set up their base in a new area (Brosius 1991, Puri 1997a, Sellato 1994).

By the 1970s, most Penan had begun to settle in villages and to adopt gardening and rice-swidden agriculture, either on their own or in the villages of the Kenyah. The Kenyah have been subject to modernizing forces introduced by Christian missionaries, health officials, teachers, and other government bureaucrats as well as their own children, many of whom have left the villages for higher education and job opportunities in the coastal cities. Indeed, the migration of Kenyah families—sometimes whole villages—to the outskirts of the coastal cities has increased with the ever-growing use of high-powered outboard engines on traditional canoes and the introduction of larger boats and air transport, all of which reduce travel time to and from the coast. With an increasing volume and diversity of manufactured products available to upland residents, the demand for cash to purchase such items has increased. Correspondingly, the exploitation of various saleable NTFPs, such as damar, timber, rattan, and *gaharu*, has also increased. Although the Penan and the Kenyah have been involved in the collection and trade of forest products for many decades, the recent, full-time commitment to collecting has affected both agricultural expansion as well as traditional food production activities, such as sago processing (Puri 1997b). As their economy is increasingly commoditized and commercialized, the dependence of the Penan and Kenyah on outside trade goods, and even food stuffs, purchased with the proceeds of the sale of NTFPs, is increasing at a faster rate than their power to control the direction of economic development giving them access to the benefits of modernization.

In the study village of Long Peliran, the territory to the east of the Bahau River is in a forest concession that is slated to be logged in the near future. This concession allocation encompasses the village *tana' ulen*, or “reserved land,” held and regulated by the Kenyah *paren*, or “aristocrats,” but sometimes opened to other villagers for use as swidden fields or for the harvest of timber and NTFPs (Momberg et al. 2000). Since 1980, the territory to the west, including the Lurah River, is included in the Kayan Mentarang National Park (known as the Kayan Mentarang Nature Reserve, prior to 1996). With a gazetted area of 1.4 million ha deep in the interior of East Kalimantan, this park is the largest area of officially protected rain forest in Borneo and one of the largest areas of remaining tropical forest in Southeast Asia. With much of the forest of Borneo destroyed or degraded over the past 20 years, the forest of the Kayan Mentarang area—still relatively intact—is a vitally important refuge for many species, both plant and animal. Project Kayan Mentarang began in 1990 as a collaborative effort by the World Wildlife Fund (WWF) Indonesia Program, the Department of Forestry and the Indonesian Institute of Sciences (LIPI). The long-term goal of the project is the establishment and development of conservation management in the Kayan Mentarang National Park integrated with sustainable economic development in the surrounding area. Key elements of this integrated conservation and development project (ICDP) are participation by local communities and local government and the use of scientific methods as a basis for planning and decision-making. In this paper we attempt to shown how TEK may be used in conjunction with scientific knowledge not only to identify a promising research agenda to assist Project Kayan Mentarang in meeting its goals, but to serve as a model for redefining the research agenda for other forest resources in need of sustainable production systems.

Both the Penan Benalui and the Kenyah Badeng use the term *sekau* to designate the genus *Aquilaria* as well as the resin impregnated heartwood. In addition to the resinous wood, the Penan and Kenyah use the white bark of this tree, pulled from the trunk in long strips, to bind animals, to make packs or, if from very large trees, to serve as flooring and roofing material in temporary forest shelters. Locally and among other Kenyah groups, *gaharu* may be ingested as a remedy for various stomach ailments (Chin 1985). Among traders and other non-local people, the Penan use the Bahasa Indonesia term *gaharu*. The Penan consider it unlucky and potentially dangerous to use true names to refer to desired items so many employ avoidance terms, such as *kayu* “wood” or *isi* “filling” rather than the word *gaharu* before and during collecting expeditions. Penan collecting groups were usually small, numbering one to five people, and composed of closely related men, boys, and only rarely women. Both the costs and the profits from the expedition were shared equally among all participants. Larger collecting groups of a dozen or more, sometimes involving Kenyah or other ethnic groups, were usually partitioned into smaller search parties, each provisioned separately and each keeping the profits of their efforts (Momberg et al. 1997, 2000).

There are reportedly three types of *sekau* in the forests of the Penan. The less common, *sekau baya*, "crocodile sekau," tentatively identified as *A. beccariana*, is said to have smaller leaves and grow in wet areas near streams (which may account for its nomenclatural association with crocodiles); however, it does not produce the best quality resin. More valuable resin is found in *sekau nyivung* (*nyivung* being the spiny tree palm *Oncospermae horridum*), tentatively identified as *A. malaccensis*, which is commonly found in drier forests, on steeper hillsides and in mountain ravines. *Sekau modung*, "mountain sekau," reportedly the largest *Aquilaria* species and tentatively identified as *A. microcarpa*, is seldom encountered in the interior mountains of the Bulungan area. Preferring the coastal hill forests, it reportedly produces the most valuable resin but today is uncommon because of extensive exploitation in the past (see Soehartono and Newton 2001b).

Although the Penan know as many as ten different terms designating distinct grades of resin, these are seldom used in actual trade transactions (Momberg et al. 1997). Grades are distinguished by the density of resin in the wood, with the "super-high quality" *gaharu* being very black, oily, and soft. Most of these names are not indigenous, but derive from the terms used by professional collectors and traders who live in the lowland areas and coastal cities (cf. Burkill 1966). Typically, a trader will determine an average grade for a quantity of *gaharu* that may contain several grades, and then pay the price based on the perceived average grade. "Averaging" speeds the transaction, but tends to disadvantage the collector because the difference between the price of the average quality and the higher quality grades is proportionately far greater than the difference between the average and the lower grades. To avoid such losses, collectors may sell their higher quality *gaharu* separately.

Locating *gaharu* in the forest is a complex and uncertain task, even for expert collectors. Penan attempt to reduce the uncertainty of collection through ritual as well as the application of accumulated and experiential knowledge. For the Penan and Kenyah, the forest is perceived as a public domain filled with a variety of beings and thus a place in which one must observe the social norms characteristic of life in any public space. *Gaharu* spirits, malicious ghosts, and other forest-dwelling spirits that deceive collectors are just some of the beings with whom the Penan feel they must contend, so many precautions are taken before and during a collecting expedition. For instance, because the darkest resin is the most valuable, black is the color of choice for most collectors' clothing and other items associated with *gaharu* collecting. Anything black found before or during the trip is taken as a sign of good luck and imminent good fortune. Secondly, as a precaution against prejudicing the fate of the expedition, the collectors will never openly state their intentions, their true goal—to find very black *gaharu*—or their destination for fear of alerting the malevolent spirits (or, indeed, anyone else who may be interested in the location of this valuable resource). Upon encountering a promising tree, a collector would never state aloud his desire to find *gaharu* within, nor would it be appropriate for other members of the team to ask if any *gaharu* had been discovered. Such discretion protects the collector not only from harmful spirits but human competitors and personal disappointment. Only when the *gaharu* collected is safely brought back to the expedition's camp in the forest do collectors feel comfortable talking about their exploits, boasting and gloating over their triumphs. Similar precautions are taken when hunting or collecting other kinds of forest products that involve luck as well as skill. Many collectors refer to the collecting effort as *cari nasib*, "to seek one's fate."

Not all species of *Aquilaria* or all trees contain the resin-impregnated wood. According to Penan informants, *Aquilaria* can be found throughout the forest, whereas *gaharu* tends to be found in trees located on the steep banks of usually dry streambeds high in the headwaters of small streams. Sometimes, a dozen or more individual trees surrounded by smaller saplings can be found in such habitats. Penan recognize that microclimate, soils, and plants differ at different elevations. Accordingly, they look for other plant species that might signal the presence of *Aquilaria* likely to contain *gaharu*. One of these local ecological indicators is a species of tree palm known as *boh* (*Arenga brevipes*), which grows in similar habitats and may be harvested for its edible leaf buds (palm hearts) and starchy pith. Another indicator species is the tree palm, *nyivung* (*Oncospermae horridum*), expected in areas below where one is likely to find *Aquilaria* individuals. Thus, encountering several of these trees, easily recognized by their black spines, encourages the collectors to pursue their search upstream. This perceived association might be why local Kenyah and Penan call *A. malaccensis* trees *sekau nyivung*. Finally, the palm, *silat* (*Licuala valida*), and a small stemless palm known as *lotup* that often grow in the general area of trees containing *gaharu* are also considered indicator species.

Regarding the formation of *gaharu*, many Penan believe that there is a special relationship between *gaharu* and a specific insect. According to local collectors, a spirit inhabiting the body of a nocturnal insect—a type of grasshopper or cicada, known as *bali sekau*, "spirit of sekau"—is said to enter into the trees and cause the heartwood to blacken. It does this by means of drilling small holes into the tree, whereby the spirit can enter the wood. This insect, as yet unidentified, is reportedly red and green, about 2 cm in length, with no antennae and a sharp mouthpiece. Small holes, less than a centimeter in diameter, in the boles of the tree are indications that the insect has entered the trees and that *gaharu* may be present. The insect is distinguished by two distinct calls, a high pitched "ting ting ting" and a short, low pitched call, which, it is believed, indicate both the quality and the location of *gaharu*. Reportedly, a higher pitched call indicates that the *gaharu* is of very good quality, and lower pitched calls indicate second or third quality *gaharu*. Distance from infected trees is said to be inversely related to the distance of the calling insect and, according to some Penan, in a direction diametrically opposed to its source. One Kenyah informant, however, disputed this claim as "disinformation" deliberately spread by the Penan to trick other collectors into searching in the wrong direction. Given the scarcity and high value of this product, and the competitive and sometimes exploitative relationship between the Penan and other ethnic groups, it would not be surprising if this conjecture were true. Indeed, in one of the co-author's numerous collecting expeditions with the Penan, the nightly call of the *bali sekau* was seldom an important factor in determining the direction of the following day's search. As the insect moves around at night and thus can give confusing signals, other more tangible indicators were generally used to orient search activities.

Once the Penan locate the *Aquilaria* trees in the forest, their next job is to determine whether the trees contain any of the precious resinous wood and, if so, what quality it is. Using a large bush knife, the collectors slash into the trunk through to the heartwood to see if any resinous wood is present. Slashes are often made at or adjacent to suspected insect bore holes or other deformations of the bole. The degree of hardness is said to be correlated with the age of the tree and the extent of infection, i.e., the presence of *gaharu*. Collectors often slash the exposed roots or uncover buried ones to check for *gaharu*, explaining that sometimes the formation of *gaharu* starts in the root system and migrates up the stem. Rarely would more than a few cuts be made in a tree that did not immediately show signs (e.g., the correct habitat, insect bore holes) of potential for *gaharu* deposits. Often, only the resinous wood would then be excised and the tree would be left standing. Co-author Puri encountered many trees with indications of previous incisions, which informants claimed were 10 to 15 years old and which continue to yield additional *gaharu* from the now healed wounds. In one 4-day trip in which the co-author participated, the Penan found no trees that had not been previously exploited and yet still did fairly well in terms of collecting quality *gaharu*.

COMPARATIVE ANALYSIS

Traditional knowledge regarding *gaharu* can generally be classified into two categories, both primarily associated with exploitation, namely location and extraction. Yet, embedded in this information is ecological knowledge, which could be useful for developing a sustainable management regime for this species and production of the resin. The location of the tree in the landscape, various site characteristics, and companion species may all yield clues to the mystery of *gaharu* formation. Table 1 sorts the ethnobotanical information collected from the Penan into several distinct categories according to its silvical relevance. From this summary, we can identify several aspects potentially important to tree growth and resin formation. In the following section, we examine ethnobotanical knowledge in each category against the scientific information both on the species in particular and from the field of tropical forest ecology in general. As most of the research and published literature concerns *Aquilaria malaccensis* (synonym *A. agallocha*), the information presented in this section relates most specifically to this species.

Table 1. Summary of Penan knowledge on *gaharu* exploitation

Silvical Characteristics	Indigenous Knowledge
Species yielding resin	*A. malaccensis* * *A. beccariana* *A. microcarpa*
Forest type	Mixed lowland to hill dipterocarp forest
Favorable sites	
Topography	Steeper hillsides, ravines
Soil	Thin, nutrient poor
Microclimate	Dry
Distribution pattern	Scarce, but widely distributed sometimes patchy, infected trees clumped, i.e., a dozen or more saplings within a 50 m radius
Associated species	
Plants	Palms, including: *Arenga brevipes* *Oncospermae horridum* *Licuala valida*
Animals	Insect, unidentified but maybe cicada, which bores holes in the tree
Regeneration	
From seeds	No report
from wildlings	Observed attempts, but unsuccessful
From coppice	Observed, good
From cuttings	No report
Morphology	
Tree	Irregular shape, apparent injury, insect attack; misshapen bole, leaf drop

* Because of the scarcity of *A. microcarpa*, and the lack of data specific to *A. beccariana*, the information above applies to the species *A. malaccensis* only.

On Species Differentiation

The Penan distinguish at least three distinct categories of tree in the genus taxonomists recognize as *Aquilaria*. Over a range extending from Nepal to Papua New Guinea, some 15 species have been identified in the genus *Aquilaria* (Ding Hou 1960,1964, Chung and Purwaningsih 1999). Only a few, essentially three, have been associated with the production of the much-prized aromatic resin, *gaharu*. It could be, however, as indicated by the Penan, that other species, such as *A. microcarpa*, which they believe actually provides better quality *gaharu*, have become rare due to over-exploitation. *A. agallocha*, *A. malaccensis*, *A. crassna*, and *A. sinensis* are the species most discussed in the literature with regard to *gaharu* production. Scientists generally agree that *A. agallocha* and *A. malaccensis* are actually one and the same species (Ding Hou 1964). Following morphological studies, researchers in Japan report "no significant anatomical differences among *A. sinensis*, *A. agalloccha*, and *A. malaccensis*" (Yoneda et al. 1986b). The greater inter-population variation common among the plants of the tropical rain forest reflects the wide variety of breeding systems and high degree of spatial variation in this environment (Bawa 1976, Simons et al. 1994). It is now recognized that biochemical and molecular, as well as morphological, analysis may be necessary to distinguish genetic differences (Mabberly 1992, Newton et al. 1994).

It is very possible that two or more varieties, provenances, or genetic strains exist within one or more species of *Aquilaria* (Rao and Dayal 1992). Throughout history, traders have reported better quality resin coming from specific areas, Cambodia in particular (Chau ju-kua 11th c. as noted in Hirth and Rockhill (1911), Hansen (2000)). Pharmacognostical studies by researchers in Japan have confirmed that the chemical composition of essential oils from agarwood samples with reference to nine major sesquiterpene compounds differs between specimens obtained from different regions (Yoneda et al. 1986a). In comparing extracts from *A. agallocha* and *A. sinensis*, Japanese researchers also found that the chemical composition of the solvent extracts from four different samples of *gaharu* differed between species and within species (Ishihara et al. 1993). This is not unlikely. Substantial differences are recognized between the populations of *Pinus merkusii* on Sumatra vs. mainland Southeast Asia in terms of morphology, ecology, timber characteristics, and resin chemistry (Whitmore 1985).

On Forest Habitat and Site Characteristics

Although research indicates that seed availability overrides all other reasons for the variation and distribution of tree species in the tropical forest, the second most important factor is geology, "which manifests itself in various interlinked ways relating to topography and soil chemical and physical factors" (Whitmore 1985). With most of the nutrients of the tropical forest ecosystem held in the vegetation or soil surface layer, soil moisture and soil texture are two key factors in determining a plant's success at accessing these nutrients (Lal 1987). As animals respond to food availability, plants respond essentially to weather and climate, the primary factors influencing the availability of nutrients, water, and sunlight, the three elements essential to plant metabolism (Richards 1996). These factors in turn determine a plant's ability to generate the food, and the flowers, fruit, and seeds needed for reproduction, as well as to mount a successful defense against pests or pathogens.

The Penan recognized that trees containing *gaharu* tend to be located on the steep banks of usually dry streambeds high in the headwaters of small streams (Puri 1992). Similarly, Yamada (1995), working with Penan informants, located a greater abundance of *Aquilaria* on steep slopes. Paoli et al. (2001) also reported finding that trees at higher elevation contained more than those found at lower elevations. There could be several factors associated with this location that predispose *Aquilaria* trees in this habitat to produce the aromatic resin. Shallower soils may mean more stress on the plant. Location on the ridge may provide a less sheltered environment than riverine forest. Such circumstances may expose these trees to storms and associated wind damage, the wounding necessary for the entry of the fungi. Alternatively, such sites could also provide better habitat for the pathogen or the vector associated with its transmission.

On the Spatial Pattern of Distribution

Reports regarding the abundance of this species in the forest are fairly consistent, although perceptions of the spatial pattern of *Aquilaria* distribution appear to vary. The National Forest Inventory of Indonesia reports on average less than 1.2 stems per hectare (Soehartono and Newton 2001a, see also LaFrankie 1994). An analysis of forest inventory data on the mainland indicates that the average density of this species is about 0.75% (Wyatt-Smith 1995 [Malaya], Beniwal 1989 [India]). Whereas Wyatt-Smith (1995) reported that the species is "rare to uncommon, and usually of poor form," Foxworthy (1922) noted that it is "widely distributed but nowhere abundant."

The Penan, among others, recognize the rarity of *Aquilaria* and claim that it regenerates in pure patches around a mother tree (Beniwal 1989, Soehartono and Newton 2001b). Indeed, many rain forest trees exhibit clumped or clustered distribution. Clumping is related primarily to the efficiency of seed dispersal and is especially evident in families where the means of seed dispersal is inefficient, unreliable or non-existent (Richards 1996). Other factors that may result in a clumped distribution pattern include those affecting seed germination and seedling establishment and growth (Whitmore 1985). Many rain forest trees have symbiotic relationships with soil fungi, which not only help them exploit nutrients in the soil and humus layers but are critical to good growth. A clumped distribution pattern may reflect seedlings profiting from symbiotic mycorrhizal fungi in the soil surrounding the mother tree (Oldeman 1990). Under evolutionary pressure, species with such clustering tendencies—a characteristic rendering them vulnerable to decimation by disease and pests—often develop secondary metabolites (e.g., gums, resins, and latex) to make them unpalatable to herbivores or to improve ability to resist the infestation of insects and pathogens (Whitmore 1985).

On Plant Associations

The Penan noted that several species, especially palms, were often found near *gaharu*-producing trees. There has been a lot of interest in the extent to which discrete species association, or consociations, are correlated with site factors in the tropical forest (Wyatt-Smith 1995). Species associations on alluvial valley floors, as distinct from those on hillsides and ridges, have been detected in numerical analysis of small plots in Malaya, Brunei, and Sabah (Whitmore 1985). Data collected in Brunei revealed that species associations were correlated with complex soil factors not clearly defined (Brunig 1970). Although Ashton (1967) found species diversity correlated with total soil phosphorus, especially at low concentrations, plant-available phosphorus is difficult to correlate with total phosphorus. Baillie (1972) found topography, which also reflects soil conditions, most closely associated with floristic composition. Most research has shown, however, that consociations result from the influence of several factors, not just soil conditions (Whitmore 1985). Thus, it may be the synergistic effect of the confluence of environmental factors that determines species composition in the *gaharu* habitat.

On the Morphology of the Infected Tree

Indigenous people rely on several phenomena as external indicators of the presence of *gaharu* within a tree. Symptoms of infection recognized by the Penan include insect bore holes, knots, a hollow sound upon thumping, tumor-like growths, bark drop, and excessive leaf fall. Other traditional collectors throughout the region similarly recognize many of these and other signs as outward indicators of resinous contents (among others, Burkill 1966, Gibson 1977, Andaya and Andaya 1982, Beniwal 1989, Soehartono and Mardiastuti, 1998). Such symptoms of infection, as observed by local collectors, coincide with those recognized by professional arboriculturalists and silviculturalists (Dolwin et al. 1998).

On Animal Associations

As reported by the Penan, an insect may be implicated in the etiology of *gaharu* formation. Insects often bore through the cracks and crevices in bark, in the process carrying infection to the underlying heartwood. As is argued by Jalaluddin (1977), the hypothesis of an insect vector is supported by irregular occurrence of infection in the trunk. Other scientists have also noted the possibility of such a connection, but no specific research could be found on this subject with respect to *gaharu* (Gibson 1977). It should also be considered, however, that the insect could be attracted to the infection site *ex post facto* as a result of the volatiles released by the wounded tree attempting to repel a fungal attack (Mabberly 1992). Although not definitively identified, the “noisy” insect to which the Penan refer may be a type of cicada. Cicadas deposit their eggs in slits made in the twigs of a tree. When the young hatch, they fall to the ground and, after leading a subterranean life for many years, nourished by the juices extracted from various plant roots, they emerge, climb into surrounding trees, mate, and begin the cycle once more (Imms 1960). The cicada lifecycle demonstrates how an insect could serve as a vector for transmitting fungal spores from the soil into the tree, from the tree back to the soil, and on to other trees as well.

On Regeneration

Although the Penan do not collect seed of this species, they have made attempts to transplant wildlings from the forest into abandoned swidden plots and home gardens, reportedly without much success. According to most reports, *Aquilaria* regenerates freely under natural conditions, with the tree flowering and fruiting after 7–9 years (Beniwal 1989). Good seed years are infrequent, however. Although seed viability is low (approximately 1 month), hand-sown seed have good germination rates (67% for those planted immediately, falling to 47% for those sown after 1 week) and the resultant seedlings are easy to handle (Chung and Purwaningsih 1999; J. Foppes 2000, *personal* *communication*). Experimental plantings, first reported from India in the 1920s, were never expanded to commercial scale because of seed scarcity and poor seed viability as well as poor resin formation (Bhaskar 1984, Beniwal 1989). Unconfirmed reports from researchers across Southeast Asia suggest that almost every country in the region has some experimental plantings of this species.

Production using a coppice system may also be possible. Traditionally, Penan collectors have followed the practice of only excising the resinous wood, as opposed to felling the whole tree, when the *gaharu* appears to be of small amount and low quality. This permits the tree to live, with the wound usually healing and producing more resinous wood that can be harvested in the future. Experienced indigenous collectors in other areas also reportedly follow this practice (Beniwal 1989, Gianno 1990, DeBeer 1993, *unpublished manuscript*) Although regrowth on coppiced stumps is, according to some reports, often shrubby and never produces the quality resin of the original excision, others report the tree to be a good coppicer (Tirant 1885, Beniwal 1989). The authors found that the Penan regularly obtain resin from such sustainable sources.

DISCUSSION OF FINDINGS VIS-À-VIS *GAHARU* PRODUCTION

In the analysis above, we have focused on the tree as the primary resource. In fact, however, it is the production of the resin that is the goal of the forest manager, e.g., the Penan. From a forestry or management perspective, the information above is of primary interest to the extent that it enhances understanding of the growth and development of the species that is host to the process of resin formation. Drawing on the information and analysis in the previous sections, we now explore the implications for *gaharu*, or resin, production.

The Fungal Connection

Good quality *gaharu* does not occur in all species of the genus *Aquilaria*, nor in all trees of the subset of species capable of producing the highly desirable aromatic wood. It is estimated that, under natural conditions, only one out of ten trees (of the appropriate species) contain the valuable resin (Gianno 1990, Foppes 2000, *personal communication*)[4]. As early as the 18th century, it was recognized that the perfumed wood known as *gaharu* was the result of a pathological condition (Loureiro 1790 as cited in Ding Hou 1960).

Much of the early research on *Aquilaria* focused on identifying the specific fungi that might stimulate resin production. Attempts at inoculation began in the 1930s (Beniwal 1989). The discovery of several species of fungi in association with *gaharu* and the unpredictability of response to inoculation with the various fungal species have been disappointing. Given that the level of response has been highly variable, as the desired morphological changes in the phloem take place in some but not all trees, inoculation trials can be judged only a limited success. Most scientists agree that it is unlikely that a single, specific fungal cause will be associated with the formation of the resin, as more than 20 varieties or genetic strains of fungus have been identified in the presence of resin (Gibson 1977, Jalaluddin 1977, Rahman and Khisa 1984, Rao and Dayal 1992, Tamuli et al. 2000, Tabata et al. 2003).

The formation of abnormal tissue and anomalous flow of resin (resinosis) that is apparent in infected material is a common response brought about by physiological factors, i.e., wounding or the attack of insects or pathogens, such as fungi (Bakshi 1954, Kramer and Kozlowski 1979, Heath 1989, Rao and Dayal 1992). Fungal spores can be dispersed by wind, water, or insects from reservoirs in the soil or diseased tissues in the same or neighboring trees (Jalaluddin 1977, Ivory and Speight 1993). Resin formation and dispersal is the tree’s attempt to inhibit the growth and spread of the pathogen. In the case of *Aquilaria*, one research report concluded that the range of fungal colonists decreased as the oleoresin content increased (Rahman and Basaki 1980). Wounds suffered when a branch is broken or an insect invades provide entry for a variety of parasites and pathogens. Pioneer microorganisms that infect such wounds are usually bacteria and non-decay fungi—for example, *Ascomycetes, Phycomycetes* and *Fungi imperfecti*—that are able to use the food materials in the chemically altered cells (Shigo 1969). Ultimately, it is usually “not one but a succession and combination of organisms and processes” that leads to what is observed as the infection or decay (Shigo 1967). Research is unclear whether variation in secondary metabolites in tropical plants is genetically or environmentally based. Geographical (interpopulation) variation in secondary chemistry has been shown for several rain forest plants

(Waterman and McKey 1989) There is no indication in the literature that the extent of infection is related to the type or degree of injury assumed to be the necessary prerequisite of an infection and resin formation.

Influence of Genetic Diversity

The fact that not all trees wounded or inoculated develop the aromatic resin may indicate a significant degree of phenotypic variation with regard to disease resistance in natural populations (Alexander 1992). Experimental results show that different genotypes of woody plants differ in their behavior as host when attacked by fungi or insects. Moreover, different genotypes of the same fungal or insect species may be successful to different degrees as parasites with different genotypes of the host (Hattemer and Melchior 1993). It could be that several varieties exist within the relevant *Aquilaria* species and that certain strains or varieties are more sensitive or responsive than others to fungal attack (Rao and Dayal 1992).

Over the long term, fungal parasites, which usually have a restricted host range, do worse in mixed stands than in solid or single-species stands (Bakshi 1954). Accordingly, the clustering habit of *Aquilaria* may have maintained the species' or, more likely, a provenance's unique *gaharu*-producing capabilities. As noted by Parker (1992), any limitation on pollen dispersal may constrain the potential benefits of sexual reproduction vis-à-vis reducing the pathogen impact. Thus, a clustering habit may work against the tree but to the advantage of pathogens. Alternatively, it could be that the prodigious output of resin by some trees, especially found in the same cluster, may be an evolutionary response to a particularly virulent local pest.

Information on the extent of pathogen diversity and the effect of host species diversity on pathogen populations is poor. As is increasingly recognized, host–parasite relationships are complex and constantly evolving (Hines and Marx 2001). Research on the impact of plant–host genetic diversification on genetic diversity of plant pathogenic microorganisms, especially fungi, is scarce and generally focused on agricultural crops (Fritz and Simms 1992, Groth and Christ 1992, Hattemer and Melchior 1993). In some wild host pathogen systems, extinction and recolonization events occur with noticeable frequency (Burdon and Silk 1997). Patch distribution of a natural host population tends to result in fungal populations that show large amplitudes in size, relatively local and frequent extinctions, and asynchrony in the dynamics of neighboring genes (Burdon and Silk 1997). Thus, the etiology of *gaharu* formation may be the result of a long and constantly changing relationship between several biological elements.

Other Important Factors

Additional factors that could influence the quantity or quality of resin produced include the age of the tree, edaphic conditions, and the season of the attack (Kramer and Kozlowski 1979). *Gaharu* is found in trees as young as 20 years old, but the best quality resin reportedly comes from specimens of 50 years or more (Beniwal 1989). There may be a considerable lag time between the occurrence of infection, its manifestation, and the expression of its full impact on plant growth (Alexander 1992). No scientific research has actually been done on the influence of age on the quantity and quality of resin production.

Edaphic conditions, as discussed above, provide a challenge to some organisms but offer opportunities to others. Competition among organisms is intense and much influenced by environmental factors, such as temperature and moisture (Shigo 1967). Normally, the resistance of the tree is greater than the infestation force and the pioneers make little headway. Exposed mountain crests, besides being generally well leached and therefore deficient in many minerals and nutrients, are also susceptible to drought. Bark moisture is an important factor affecting the success of an invasion of bark parasites. A reduction in bark moisture, which may reflect arid site conditions, creates conditions favorable to the parasite. The Penan's noting of the location of better *gaharu*-producing trees on just such poorer sites, up toward the ridges, may be an indication that edaphic conditions, perhaps water stress, are important in enabling the infection to take hold and promoting resin formation. Moreover, as Bakshi (1954) noted, "[the] fundamental cause of many tree diseases is to be found in the state of the soil. The soil harbors a large number of parasites, which are normally harmless under good conditions of growth but become pathogenic when plants are grown under adverse conditions...."

Environmental factors influence many aspects of plant growth, affecting not only the volume of resin formation but the composition of essential oils as well

(Oyen and Nguyen 1999). Some scientists report that some plants on poorer sites are actually better able to defend themselves than their better nourished cousins. The difference may be a matter of what you can afford to sacrifice. Mabberly (1992) points out that "...for a given herbivore pressure, the advantage of defense should increase as the potential maximum growth rate declines." This was confirmed by research in Africa and Malaysia that indicated that nutrient-poor soils had no "poorly defended, fast-growing trees." Research in Africa showed that trees on poorer soils had higher concentrations of tannins and other phenolics, but on better soils there were more species that produced alkaloids. A similar situation is reported from the Malay Peninsula and Borneo, where it was found that "dipterocarp trees on less fertile soils had higher levels of quantitative defenses than those on richer soils" (Mabberly 1992).

Finally, timing may be a particularly important aspect. One research report from India indicated that more resin was produced from artificial wounding done in September (wet season) than in May (dry season) (Rahman and Khisa 1984). Timing could be important, not only with regard to prevailing seasonal or microclimatic conditions and thus the level of stress experienced by the individual plant, but with respect to the availability or activity of suitable vectors. Timing may also be important with regard to the availability of spores from relevant fungi. As Whitmore (1985) noted, the fruiting bodies of the higher fungi in southern Malaya appear only twice annually with the flush of mycelial growth following a rain just after a dry spell. Many pathogens, particularly those of perennial plants such as trees, survive adverse conditions inside host tissues and, when favorable conditions return, are able to multiply. In the humid tropics, periods of unfavorable climatic conditions may be short or non-existent, and many pathogens that survive as noted above exhibit some periodicity in the multiplication phase (Ivory and Speight 1993).

Timing may be important as well for the insect population, a possible vector for disease transmission. In forest undergrowth, most insect activity takes place under the cover of darkness or in conditions of low light, including heavy cloud cover during daylight hours (Karr 1989, Sutton 1989). Tropical insects also exhibit seasonality in their activities, generally of longer duration than those in temperate zones and with a wider range of patterns (Mabberly 1992). Insect infestation or injury to the tree that takes place just prior to or during the period of spore dispersal might facilitate the establishment of the infection.

CONCLUSIONS

For many forest species, the sequence of increasing prices, overexploitation, resource scarcity, and increasing extraction costs has been sufficient to initiate cultivation and domestication (Homma 1992, Smith et al. 1992). For *Aquilaria*, however, several decades of scientific research has made seemingly little significant progress toward domesticating *gaharu* production. Consequently, all of this internationally traded resinous wood is a product of a rapidly diminishing area of natural rainforest, especially of Indonesia, where the Penan and related groups still live. Inexperienced outsiders attempting to cash in on what they perceive as a "free good" have caused unnecessary damage to *Aquilaria* stands, in some cases threatening their continued existence in some areas. Although granting groups such as the Penan tenurial rights over the resource or its range might forestall some damage, enforcement is a perilous and persistent problem. Inarguably, better management of this resource is urgently needed if a long-term solution is to be found to these problems. In this respect, developing a firm knowledge base is critical to the development of a more sustainable production system for *gaharu*.

As indicated by the above analysis, traditional knowledge shares much in common with scientific knowledge. Although the former is often considered "unscientific," presumably because it was not developed according to the "scientific method" as tribal naturalists do not use the protocols familiar to modern science, there is no reason to believe that this information has not been developed on a trial-and-error basis, a form of hypothesis testing. Nor was it recorded and published, but transferred by traditional, generally multi-dimensional, methods. Traditional knowledge of plant resources and their manipulation and exploitation is a complex tapestry of natural history and technical skills developed through traditional instruction methods (e.g., story telling) and experience (both apprenticeship and self-directed learning-while-doing). To date, however, most of the traditional knowledge collected has been botanical information and details regarding use and processing. More systematic collection needs to be made of the ecological knowledge and management practices of traditional cultures, especially with regard to natural vegetation, local ecosystems, and manipulation regimes, if we are to address long-term forest management needs.

The failure to successfully domesticate *gaharu* production is undoubtedly due to several factors, largely biological and ecological. Unlike other tree species exploited for their resin, *Aquilaria* apparently does not produce resin in response to physical injury alone. The analysis above indicates that the aromatic resin-filled wood, *gaharu*, is the result of a sequence of events, probably an injury, perhaps followed by an insect attack, and the invasion of one or more fungi. The complex ecology of resin formation involving two, or maybe three or more, living organisms—the tree, one or more fungi and possibly an insect intermediary—has so far confounded investigators. To develop a sustainable management system for this resource will require a clear understanding of how the various elements of the natural system work, separately and synergistically. Traditional knowledge can not only fill gaps in our knowledge base for these species but assist in identifying areas of research, such as the influence of edaphic factors or the role of an insect vector.

With the enormous social, economic, and cultural changes that have occurred in rural areas of Asia over the past decade, it would be too easy to dismiss traditional knowledge and traditional forest management practices as no longer relevant. Any program tasked with assessing the potential for the cultivation and domestication, including enhanced productivity, of this species must begin with an examination of its geographic extent and the kind, causes, and amount of variability within the population. The people who have been working with this species for centuries, that is, the traditional knowledge holders, are uniquely positioned, both intellectually and geographically, to provide this information. If the information required does not exist within the integrated knowledge base, certainly these local "experts" would be best equipped to assist outside scientists to generate the hypotheses necessary for further research. Thus, the research agenda to develop an enhanced knowledge base for this species should be rooted in traditional knowledge, expanded through scientific methods of investigation, and tested with the participation of local people. The most culturally appropriate, cost efficient and effective method of developing NTFPs is through the involvement of local people. Peoples such as the Penan need to be participants throughout the process of research and development right through to sharing in the profits of sustainable production.

The most significant inconsistency that emerged in this comparison was not between the two information sets but rather between the two knowledge-development systems. Greater effort is needed to reconcile and repair the links between the holders of traditional knowledge and the scientists of our research institutions. Traditional knowledge remains important as an information resource, and it can and should serve as the starting point for the development of new paradigms better suited to the changing demands of society, both consumers and producers, and the evolving concepts of development and conservation of tropical forests. Clearly, these conclusions support the call for more ethnobiological and community-level forestry research and better cooperation between ethnobiologists and forestry researchers as the starting point for the development of improved systems of forest conservation and development.

[1] Also known as aloeswood, agarwood, eaglewood, sandalwood, and a variety of local names.
[2] Recently scientists have recognized that resinous wood of the genus *Gyrinops* is also marketed as *gaharu* (Compton and Zich 2002, Mandang and Wiyono 2002, Watanabe 2003).
[3] For details by species, refer to Ding Hou 1960, Burkill 1966, Soehartono 1997.
[4] More recently, Paoli et al. (2001) reported *gaharu*-containing trees at 50% overall in West Kalimantan.

Responses to this article can be read online at: http://www.ecologyandsociety.org/vol9/iss3/art3/responses/index.html

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LITERATURE CITED

Alexander, H. M. 1992. Evolution of disease resistance in natural plant populations. Pages 326–344 *in* R. S. Fritz and E. L. Simms, editors. *Plant resistance to herbivores and pathogens: ecology, evolution and genetics.* University of Chicago Press, Chicago, Illinois, USA.

Alcorn, J. B. 1984. *Huastec Mayan ethnobotany.* University of Texas Press, Austin, Texas, USA.

Andaya, B. W., and L. Y. Andaya. 1982. *A history of Malaysia.* MacMillan Press, London, UK.

Anderson, A. B., and E. M. Ioris. 1992. Valuing the rainforest: economic strategies by small-scale forest extractivists in the Amazon estuary. *Human Ecology* **20**(3):337–369.

Ashton, P. S. 1967. Climate versus soil in classification of Southeast Asian tropical lowland vegetation. *Journal of Ecology* **55**:67–68.

Baillie, I. C. 1972. *Report on soil observations made in forest reconnaissance inventory units 1 and 3 in the Upper Rejang Basin.* Soil Survey Report F5. Sarawak Forest Department, Kuching, Sarawak, Malaysia.

Bakshi, K. B. 1954. Principles of tree disease control with reference to Indian forests. Pages 800–803 *in Volume 2, Proceedings of Fourth World Forestry Congress*, Dehra Dun, India.

Barden, A., N. Awang Anak, T. Mulliken, and M. Song. 2000. *Heart of the matter: agarwood use and trade and CITES implementation for* Aquilaria malaccensis. TRAFFIC International, Cambridge, UK.

Bawa, K. A. 1976. Breeding tropical hardwoods: an evaluation of underlying bases, current status and future trends. Pages 43–59 *in* J. Burley and B. T. Styles, editors. *Tropical trees, variation, breeding and conservation.* Linnean Society Symposium Series no. 2. Academic Press, London, UK.

Belcher, B., and K. Kusters. 2004. Non-timber forest product commercialization: development and conservation lessons. Pages 1– 22 *in* K. Kusters and B. Belcher, editors. *Forest products, livelihoods and conservation: case studies of non-timber forest product systems.* Volume 1, Asia. Center for International Forestry Research, Bogor, Indonesia.

Beniwal, B. S. 1989. Silvical characteristics of *Aquilaria agallocha. Indian Forester* **115**:17–21.

Berkes, F. 1999. *Sacred ecology: traditional ecological knowledge and resource management.* Taylor and Francis, Philadelphia, Pennsylvania, USA.

Berkes, F., and C. Folke, editors. 1998. *Linking social and ecological systems: management practices and social mechanisms for building resilience.* Cambridge University Press, Cambridge, UK.

Berkes, F., J. Colding, and C. Folke. 2000. Rediscovery of traditional ecological knowledge as adaptive management. *Ecological Applications* **10**(5):1251–1262.

Berkes, F., J. Colding, and C. Folke, editors. 2003. *Navigating social-ecological systems: building resilience for complexity and change.* Cambridge University Press, Cambridge, UK.

Berlin, B. 1992. *Ethnobiological classification systems.* Princeton University Press, Princeton, New Jersey, USA.

Bhaskar, V. 1984. Seed germination of agarwood tree (*Aquilaria agallocha* Roxb.) under Bangalore conditions. *Myforest* **20**:2–3.

Bird-David, N. H. 1988. Hunter-gatherers and other people: a re-examination. Pages 17–29 *in* T. Ingold, D. Riches, and J. Woodburn, editors. *Hunters and gatherers I: history, evolution and social change.* Berg Publishers, Oxford, UK.

Bloch, M. 1991. Language, anthropology and cognitive science. *Man* (N.S.) **26**:183–198.

Bocco, G., and V. M. Toledo. 1997. Integrating peasant knowledge and geographic information systems: a spatial approach to sustainable agriculture. *Indigenous Knowledge and Development Monitor* **5**(2):10–13.

Broad, S. 1995. Agarwood harvesting in Vietnam. *TRAFFIC Bulletin* **15**:96.

Brokensha, D., and E. Vanek. 1988. Enhancing environmental resource management in developing nations through improved attitudes towards indigenous agricultural knowledge systems. *Science, Technology and Human Values* **13**:10–101.

Brosius, J. P. 1991. Foraging in tropical rain forests: the case of the Penan Gang of Sarawak, East Malaysia (Borneo). *Human Ecology* **19**(2):123–150.

Brown, C. H. 1984. *Language and living things: uniformities in folk classification and naming.* Rutgers University Press, New Brunswick, New Jersey, USA.

Brunig, E. F. 1970. Stand structure, physiognomy and environmental factors in some lowland forests in Sarawak. *Journal of Tropical Ecology* **11**:26–43.

Burdon, J. J., and J. Silk. 1997. Sources and patterns of diversity in plant-pathogenic fungi. *Phytopathology* **87**(7):664–669.

Burkill, I. H. 1966. *A dictionary of the economic products of the Malay Peninsula.* Ministry of Agriculture and Cooperatives, Kuala Lumpur, Malaysia.

Chakrabarty, K. A., V. Kumar, and V. Menon. 1994. *Trade in agarwood.* TRAFFIC, New Delhi, India.

Chang, Y. S., M. A. Nor Azah, A. Abu Said, E. H. Lok, S. Reader, and A. Spiers. 2002. *Gaharu*. FRIM Technical Information Bulletin No. 69. Forest Research Institute of Malaysia, Kuala Lumpur, Malaysia.

Chung, R. C. K., and Purawaningsih. 1999. *Aquilaria malaccensis* Lamk. Pages ? *in* L. Oyen, and X. D. Nguyen, editors. *Plant resources of South-East Asia No. 19: essential-oil plants.* Backhuys Publishers, Leiden, the Netherlands.

Chin, S. C. 1985. *Agriculture and resource utilization in a lowland rainforest Kenyah community.* Sarawak Museum Journal, Special Monograph No. 4. Sarawak Museum, Kuching, Sarawak, Malaysia.

Clear, A. 2000. *Gaharu* mania sweeps across Irian-Java. Crazy-Man Documentaries. (Online.) URL: http://www.kabar-irian.com/int-feb00.htm.

Compton, J. G. S., and F. A. Zich. 2002. *Gyrinops ledermannii* (Thymelaceae) being an agarwood-producing species prompts call for further examination of taxonomic implications in the generic delimitation between *Aquilaria* and *Gyrinops. Flora Malesiana Bulletin* **13**(1): 61–65.

Compton, J. L., editor. 1989. *The transformation of international agricultural research and development.* Lynne Reiner, Boulder, Colorado, USA.

Darby, H. C. 1942. *Indo-China. Geographical handbook.* Naval Intelligence Division, Cambridge, UK.

DeBeer, J. H. 1993. *Rattan for rice, eaglewood for salt. Some notes on Punan resource utilization in Bulungan, East Kalimantan.* Unpublished manuscript.

DeBeer, J. H., and M. J. McDermott. 1989. *The economic value of non-timber forest products in Southeast Asia.* Netherlands Committee for International Union for the Conservation of Nature and Natural Resources, Amsterdam, the Netherlands.

Denevan, W. M., J. M. Treacy, J. B. Alcorn, C. Padoch, J. Denslow, and S. F. Paitan. 1984. Indigenous agroforestry in the Peruvian Amazon: Bora Indian management of swidden fallows. *Interciencia* **9**:346–357.

DeWalt, B. 1994. Using indigenous knowledge to improve agricultural and natural resource management. *Human Organization* **53**(2):123–131.

Dickson, D. 1999. ICSU seeks to classify "traditional knowledge." *Nature* **401**:631.

Ding Hou. 1960. *Aquilaria*. *Flora Malesiana* (Series 1) **6**:6–15.

Ding Hou. 1964. Notes on some Asiatic species of *Aquilaria* (Thymelaeaceae). *Blumea* **12**(2):285–288.

Dolwin, J. A., D. Lonsdale, and J. Barnet. 1998. Detection of decay in trees. *Commonwealth Forestry Review* **77**(4):277–280.

Donovan, D. G. 1999. Strapped for cash: Asians plunder their forests and endanger their future. *Asia-Pacific Issues*

Paper No.39. East-West Center, Honolulu, Hawaii, USA.

Donovan, D. G. 2001. Where's the forestry in community forestry? Pages 3–23 *in* M. Victor and A. Barash, editors. *Cultivating forests: alternative forest management practices and techniques for community forestry.* Proceedings of an International Seminar, September 23–25, 1998. RECOFTC, Bangkok, Thailand.

Ellen, R. F. 1998. Indigenous knowledge of the rainforest: perception, extraction and conservation. Pages 87–99 *in* B. K. Maloney, editor. *Human activities and the tropical rainforest.* Kluwer Academic Publishers, Dordrecht, the Netherlands.

Eyzaguirre, P. 2000. *Ethnobotany of traditional crop plants and the impact of local knowledge systems on crop genetic resources and agricultural science.* Paper. VIIth International Congress of Ethnobiology, October 22–28, 2000, University of Georgia, Athens, Georgia, USA.

Foppes, J. 2000. *Aloeswood comes from Laos.* << jfoppes@loxinfo.co.th>>

Ford, J., and D. Martinez, editors. 2000. Traditional ecological knowledge, ecosystem science and environmental management. Invited Feature. *Ecological Applications* **10**(5):1249–1340.

Fox, J. M., editor. 1995. *Society and non-timber forest products in tropical Asia.* East–West Center Occasional Papers: Environment Series No. 19. East-West Center, Honolulu, Hawaii, USA.

Fox, R. G. 1969. Professional primitives: hunters and gatherers of nuclear South Asia. *Man in India* **49**:139–160.

Foxworthy, F. W. 1922. Minor forest products of the Malay Peninsula. *Malayan Forest Records* **2**:151–217.

Fritz, R. S., and E. L. Simms, editors. 1992. *Plant resistance to herbivores and pathogens: ecology, evolution and genetics.* University of Chicago Press, Chicago, Illinois, USA.

Fujisaka, S. 1995. Incorporating farmers' knowledge in international rice research. Pages 124–139 *in* D. M. Warren, L. J. Slikkerveer, and D. Brokensha, editors. *The cultural dimension of development: indigenous knowledge systems.* Intermediate Technology Publications, London, UK.

Gadgil, M., F. Berkes, and C. Folke. 1993. Indigenous knowledge for biodiversity conservation. *Ambio* **22**:151–156.

Gadgil, M., P. Olsson, F. Berkes, and C. Folke. 2003. Exploring the role of ecological knowledge in ecosystem management: three case studies. Pages 189–209 *in* F. Berkes, J. Colding, and C. Folke, editors. *Navigating social-ecological systems: building resilience for complexity and change.* Cambridge University Press, Cambridge, UK.

Gianno, R. 1990. *Semelai culture and resin technology.* Connecticut Academy of Arts and Sciences, New Haven, Connecticut, USA.

Gibson, I. A. S. 1977. The role of fungi in the origin of oleoresin deposits of agaru in the wood of *Aquilaria agallocha* Roxb. *Bano Biggyan Patrika* **6**:16–26.

Groth, J. V., and B. J. Christ. 1992. Diversity in plant pathogenic fungi as influenced by host characteristics. Pages 172–191 *in* R. S. Fritz and E. L. Simms, editors. *Plant resistance to herbivores and pathogens: ecology, evolution and genetics.* University of Chicago Press, Chicago, Illinois, USA.

Gunatilleke, I., C. V. Gunatilleke, and P. Abeygunawardena. 1993. Interdisciplinary research towards management of non-timber forest resources in lowland rain forests of Sri Lanka. *Economic Botany* **47**(3):282–290.

Hadley, M. 1991. Rain forest regeneration and management: strengthening the research–management connection. Pages ??? *in* A. Gomez-Pompa, T. C. Whitmore, and M. Hadley, editors. *Rain forest regeneration and management.* Man and Biosphere Series, No. 6. UNESCO and Parthenon Publishing Group, Paris, France.

Hansen, E. 2000. The hidden history of a scented wood. *Saudi Aramco World* **XX**:2–13.

Hasnida, H. N., M.Y. Aziah, M. Salbiah, Z. Fadhilah, I. Haliza, and H. J. M. Azmy. 2001. Multiplication of shoots from *in vitro* germinated seedlings of *Eurycoma longifolia* and *Aquilaria malaccensis.* Pages 269–276 *in Tropical Forestry research in the new millennium: meeting the challenges.* Proceedings of the International Conference on Forestry and Forest Products Research, 1–3 October 2001, Kuala Lumpur, Malaysia.

Hattemer, H. H., and G. H. Melchior. 1993. Genetics and its application in tropical forestry. Pages 334–375 *in* L. Pancel, editor. *Tropical forestry handbook, Vol. 1*. Springer-Verlag, Berlin, Germany.

Heath, M. C. 1989. Defense mechanisms of plants against fungal pathogens. Pages 155–172 *in* D. W. Roberts and J. R. Arst, editors. *Conference report of the infection processes of fungi.* Rockefeller Foundation, New York, New York, USA.

Hines, P. J., and J. Marx. 2001. The endless race between plant and pathogen. *Science* **292**:2269.

Hirth, F., and W. W. Rockhill. 1911. *Chau Ju-kua: his work on the Chinese and Arab trade in the twelfth and thirteenth centuries, entitled Chu-fan-chi.* Printing Office of the Imperial Academy of Sciences, St. Petersburg, Russia.

Homma, A. K. O. 1992. The dynamics of extraction in Amazonia: a historical perspective. Pages 23–31 *in* D. C. Nepstad and S. Schwartzman, editors. *Non-timber products from tropical forests.* The New York Botanical Gardens, Bronx, New York, USA.

Imms, A. D. 1960. *Entomology.* Methuen and Co., London, UK.

Ingold, T. 2000. *The perception of the environment: essays in livelihood, dwelling and skill.* Routledge, London, UK.

Ishihara, M., T. Tsuneya, and K. Uneyama. 1993. Components of the volatile concentrate of agarwood. *Journal of Essential Oil Research* **5**(3):283–289.

Ivory, M. H., and M. R. Speight. 1993. Pest management. Pages 1142–1219 *in* L. Pancel, editor. *Tropical forestry handbook, Vol. 2*. Springer-Verlag, Berlin, Germany.

Jalaluddin, M. 1977. A useful pathological condition of wood. *Economic Botany* **31**:222–224.

Jessup, T. C., and N. L. Peluso. 1986. Minor forest products as common property resources in East Kalimantan, Indonesia. Pages 505–531 *in Proceedings of the Conference on common property resource management.* National Academy Press, Washington, D.C., USA.

Johannes, R. E. 1978. Traditional marine conservation methods in Oceania and their demise. *Annual Review of Ecology and Systematics* **9**:349–364.

Karr, J. R. 1989. Birds. Pages 401–416 *in* H. Lieth and M. J. A. Werger, editors. *Tropical rain forest ecosystems: biogeographical and ecological studies.* Ecosystems of the World Series, 14B. Elsevier, Amsterdam, the Netherlands.

Kramer, P. J., and T. T. Kozlowski. 1979. *Physiology of woody plants.* Academic Press, New York, New York, USA.

Kusters, K., and B. Belcher, editors. 2004. *Forest products, livelihoods and conservation: case studies of non-timber forest product systems. Vol. 1, Asia.* Center for International Forestry Research, Bogor, Indonesia.

La Frankie, J. V. 1994. Population dynamics of some tropical trees that yield non-timber forest products. *Economic Botany* **48**:301–309.

Lal, R. 1987. *Tropical ecology and physical edaphology*. Wiley, New York, New York, USA.

Lawrence, D. C., M. Leighton, and D. M. Peart. 1995. Availability of products in managed and primary forest around a Dayak village in West Kalimantan, Indonesia. *Conservation Biology* **9**:76–88.

Mabberly, D. J. 1992. *Tropical rain forest ecology.* 2nd edition. Blackie and Son Ltd, London, UK.

Mandang, Y. I., and B. Wiyono. 2002. Anatomi kayu *gaharu* (*Aquilaria malaccensis* Lamk.) dan beberapa jenis sekerabat [Anatomy of eagle wood (*Aquilaria malaccensis* Lamk.) and several related species]. *Bulletin Penelitian Hasil Hutan* **20**(2):107–126.

Martin, G. J., A. L. Agama, and R. Leakey, editors. 1999. *People and plants handbook: cultivating trees, Issue 5.* UNESCO, Paris, France.

Mauro, F., and P. D. Hardison. 2000. Traditional knowledge of indigenous and local communities: international debate and policy issues. *Ecological Applications* **10**(5):1263–1269.

Momberg, F., R. K. Puri, and T. Jessup. 1997. Extractivism and extractive reserves: the sustainability of *gaharu* extraction in the Kayan Mentarang. Pages 165–180 *in* K. W. Sorensen and B. Morris, editors. *People and plants of Kayan Mentarang.* WWF-IP/UNESCO, London, UK.

Momberg, F., R. K. Puri, and T. Jessup. 2000.

Exploitation of gaharu, and forest conservation efforts in the Kayan Mentarang National Park, East Kalimantan, Indonesia. Pages 259–284 *in* C. Zerner, editor. *People, plants, and justice: the politics of nature conservation.* Columbia University Press, New York, New York, USA.

Nabhan, G. P. 2000. Interspecific relationships affecting species recognized by O'odham and Coamcaac cultures. *Ecological Applications* **10**(5):1288–1295.

Neumann, R. P., and E. Hirsch. 2000. *Commercialization of non-timber forest products: review and analysis of research.* Center for International Forestry Research, Bogor, Indonesia.

Newton, A. C., R. R. B. Leakey, W. Powell, K. Chalmers, R. Wangh, Z. Tchoundjeu, P. J. Mathias, P. G. Alderson, J. Meseu, P. Baker, and S. Ramnarine. 1994. Domestication of mahoganies. Pages 256–266 *in* R. Leakey and A. C. Newton, editors. *Tropical trees, the potential for domestication and rebuilding of forest resources.* HMSO Books, London, UK.

Obua, J., and G. Muhanguzi. 1998. Farmers' knowledge of indigenous tree cultivation around Bwindi Impenetrable Forest National Park, Uganda. *Indigenous Knowledge and Development Monitor* **6**(2):11–13.

Oldeman, R. A. 1990. *Forests: elements of silvicology.* Springer-Verlag, Berlin, Germany.

Ortiz, O. 1999. Understanding interactions between indigenous knowledge and scientific information. *Indigenous Knowledge and Development Monitor* **7**(3):7–10.

Oyen, L. P. A., and X. D. Nguyen, editors. 1999. *Plant resources of South-East Asia, No. 19. Essential-oil plants.* Backhuys Publishers, Leiden, the Netherlands.

Paoli, G. D., M. Leighton, D. R. Peart, and I. Samsoedin. 1994. Economic ecology of *gaharu* (*Aquilaria malaccensis*) in Gunung Palung National Park: valuation of extraction and ecology of the residual population. Unpublished manuscript.

Paoli, G. D., D. R. Peart, M. Leighton, and I. Samsoedin. 2001. An ecological and economic assessment of the non-timber forest product *gaharu* wood in Gunung Palung National Park, West Kalimantan, Indonesia. *Conservation Biology* **15**(6):1721–1732.

Parker, M. A. 1992. Disease and plant population genetic structure. Pages 345–361 *in* R. Fritz and E. L. Simms, editors. *Plant resistance to herbivores and pathogens.*University of Chicago Press, Chicago, Illinois, USA.

Posey, D. A. 1986. Topics and issues in ethnoentomology with some suggestions for the development of hypothesis-generation and testing in ethnobiology. *Journal of Ethnobiology* **6**:99–120.

Posey, D. A., and W. Balée, editors. 1989. Resource management in Amazonia: indigenous and folk strategies. *Advances in Economic Botany* **7**: 1–287.

Puri, R. K. 1992. Mammals and hunting on the Lurah River: recommendations for management of faunal resources in the Cagar Alam Kayan Mentarang. Paper presented at Borneo Research Council, Second Biennial International Conference, 13–17 July, 1992, Kota Kinabalu, Sabah, Malaysia.

Puri, R. K. 1997a. *Hunting knowledge of the Penan Benalui of East Kalimantan, Indonesia.* Dissertation. Department of Anthropology, University of Hawaii, Honolulu, Hawaii, USA.

Puri, R. K. 1997b. Penan Benalui knowledge and use of tree palms. Page 194–226 *in* K. W. Sorensen and B. Morris, editors. *People and plants of Kayan Mentarang.* WWF-IP/UNESCO, London, UK.

Puri, R. K. 1998. *Assessment of the biodiversity of the Bulungan Research Forest: ethnoecology of the Punan Tubu'.* Consultant Report, Wildlife Conservation Society (WCS)/Center for International Forestry Research (CIFOR), Bogor, Indonesia.

Puri, R. K. 2001a. Local knowledge and manipulation of the fruit "mata kucing" (*Dimocarpus longan*) in East Kalimantan. Pages 98–110 *in* M. Victor and A. Barash, editors. *Cultivating forests: alternative forest management practices and techniques for community forestry.* Proceedings of an International Seminar, September 23–25, 1998, Bangkok, Thailand. RECOFTC, Bangkok, Thailand.

Puri, R. K. 2001b. *The Bulungan ethnobiology handbook.* Center for International Forestry Research, Bogor, Indonesia.

Quan Le Tran, Qui Kim Tran, K. Kouda, N. T. Nguyen,

Y. Maruyama, I. Saiki, and S. Kadota. 2003. A survey on agarwood in Vietnam. *Journal of Traditional Medicine* **20**(3):124–131.

Rahman, M. A., and A. C. Basaki. 1980. Agar production in agar tree by artificial inoculation and wounding. Part I. *Bano Biggyan Patrika* **9**:86–93.

Rahman, M. A., and K. S. Khisa. 1984. Agar production in agar tree by artificial inoculation and wounding. Part II. Further evidence in favour of agar formation. *Bano Biggyan Patrika* **13**:57–63.

Rao, R. K., and R. Dayal. 1992. The secondary xylem of *Aquilaria agallocha* (Thymelaeaceae) and the formation of "agar." *IAWA Bulletin* **13**:163–172.

Redford, K. H., and C. Padoch, editors. 1992. *Conservation of neotropical forests: working from traditional resource use.* Columbia University Press, New York, New York, USA.

Redford, K. H., and A. M. Stearman. 1993. On common ground—response. *Conservation Biology* **7**:427–428.

Richards, P. W. 1996. *The tropical rainforest: an ecological study.* Cambridge University Press, Cambridge, UK.

Richards, P., L. J. Slikkerveer, and A. O. Phillips, editors. 1989. *Indigenous knowledge systems for agricultural and rural development: The CIKARD inaugural lectures.* Studies in Technology and Social Change 13. Iowa State University, Ames, Iowa, USA.

Ruiz-Pérez, M., and M. Arnold, editors. 1997. *Current issues in non-timber forest products.* Center for International Forestry Research, Bogor, Indonesia.

Sadgopol, D. 1959. Experimental studies on the development of essential oils and their components in aromatic plants. *La France et Sa Parfums* **3**: 62–71.

Salafsky, N., B. Dugelby, and J. P. Terborgh. 1993. Can extractive reserves save the rainforest? An ecological and socioeconomic comparison of non-timber forest product extraction systems in Peten, Guatemala, and West Kalimantan, Indonesia. *Conservation Biology* **7**:39–52.

Sellato, B. J. L. 1994. *Nomads of the Borneo rainforest: the economics, politics and ideology of settling down.* University of Hawaii Press, Honolulu, Hawaii, USA.

Shigo, A. L. 1967. Successions of organisms in discoloration and decay of wood. *International Review of Forestry Research* **2**:237–299.

Shigo, A. L. 1969. Death and decay of trees. *Natural History* **78**:43–47.

Simons, A. J., D. J. MacQueen, and J. L. Stewart. 1994. Strategic concepts in the domestication of non-industrial trees. Pages 91–102 *in* R. Leakey and A. C. Newton, editors. *Tropical trees, the potential for domestication and rebuilding of forest resources.* HMSO Books, London, UK.

Sinclair, F. L., and D. H. Walker. 1998. Acquiring qualitative knowledge about complex agroecosystems. Part 1: Representation as natural language. *Agricultural Systems* **56**(3):341–363.

Smith, N. J. H., J. T. Williams, D. L. Plucknett, and J. P. Talbot. 1992. *Tropical forests and their crops.* Comstock Publishing Associates, Ithaca, New York, USA.

Soehartono, T. 1997. Overview of trade in *gaharu* in Indonesia. Paper. Third Regional Workshop for Conservation and Sustainable Management of Trees. August 18–21, 1997, Hanoi, Vietnam.

Soehartono, T., and A. Mardiastuti. 1998. The current trade in *gaharu* in West Kalimantan. *Biodiversitas Indonesia* **1**:1–10.

Soehartono, T., and A. C. Newton. 2000. Conservation and sustainable use of tropical trees in the genus *Aquilaria*. I. Status and distribution in Indonesia. *Biological Conservation* **96**:83–94.

Soehartono, T., and A. C. Newton. 2001a. Conservation and sustainable use of tropical trees in the genus *Aquilaria*. II. The impact of *gaharu* harvesting in Indonesia. *Biological Conservation* **97**:29–41.

Soehartono, T., and A. C. Newton. 2001b. Reproductive ecology of *Aquilaria* spp. in Indonesia. *Forest Ecology and Management* **152**(1-3):59–71.

Soehartono, T., and A. C. Newton. 2002. The *gaharu* trade in Indonesia: is it sustainable? *Economic Botany* **56**(3):271–284.

Sutton, S. L. 1989. The spatial distribution of flying insects. Pages 427–436 *in* H. Lieth and M. J. A. Werger, editors. *Tropical rain forest ecosystems: biogeographical and ecological studies.* Ecosystems of the World Series, 14B. Elsevier, Amsterdam, the Netherlands.

Tabata, Y., E. Widjaja, T. Mulyaningsih, I. Parman, H. Wiriadinata, Y. I. Mandang, and T. Itoh. 2003. Structural survey and artificial induction of aloeswood. *Wood Research* **90**:11–12

Tamuli, P., P. Boruah, S. C. Nath, and R. Samanta. 2000. Fungi from diseased agarwood tree (*Aquilaria agallocha* Roxb.): two new records. *Advances in Forestry Research in India* **22**:182–187.

Thapa, B., F. L. Sinclair, and D. H. Walker. 1995. Incorporation of indigenous knowledge and perspectives in agroforestry development. Part 2: Case study on impact of explicit representation of farmers' knowledge. *Agroforestry Systems* **30**:249–261.

Tirant, G. 1885. Les bois odoriférants de la Cochinchine. *Bulletin de la Société des Études indochinoises de Saigon* I:13–24.

Turner, N. J., M. B. Ignace, and R. Ignace. 2000. Traditional ecological knowledge and wisdom of aboriginal peoples in British Columbia. *Ecological Application* **10**(5):1275–1287.

UNESCO-ICSU. 1999. *Declaration on science and the use of scientific knowledge.* World Conference on Science for the Twenty-first Century. June 26–July 1, 1999, Budapest, Hungary.

van Goor, C. P., and J. Kartasubrata. 1982. *Indonesian forestry abstracts: Dutch literature until about 1960.* PUDOC, Wageningen, the Netherlands.

Watanabe, H. 2003. A trial on the practical production of aloewood in Lombok, Indonesia. *Tropical Forestry* **58**:2–7.

Waterman, P. G., and D. McKey. 1989. Herbivory and secondary compounds in rain-forests plants. Pages 513–536 *in* H. Lieth and M. J. A. Werger, editors. *Tropical rain forest ecosystems: biogeographical and ecological studies.* Ecosystems of the World Series, 14B. Elsevier, Amsterdam, the Netherlands.

Whitmore, T. C. 1972. Thymelaeaceae. Pages 383–391 *in* T. C. Whitmore, editor. *Tree flora of Malaya, Vol. 2.* Malayan Forest Records No. 26, Forest Research Institute, Kepong, Malaysia.

Whitmore, T. C. 1985. *Tropical rainforest of the Far East.* Oxford University Press, Oxford, UK.

Williams, N. M., and G. Baines, editors. 1993. *Traditional ecological knowledge: wisdom for sustainable development.* Centre for Resource and Environmental Studies, Australia National University, Canberra, Australia.

Wollenberg, E., and A. Ingles, editors. 1998. *Incomes from the forest: methods for the development and conservation of forest products for local communities.* Center for International Forestry Research, Bogor, Indonesia.

Wyatt-Smith, J. 1995. *Manual of Malayan silviculture for inland forest.* 2nd ed. Malayan Forest Records No. 23. Forest Research Institute of Malaysia, Kepong, Malaysia.

Xu Jianchu and M. T. Ruscoe. 1993. *The use of indigenous knowledge in agroecosystem management for biodiversity conservation: a case study in Baranguy Haliap, Kingan, Ifugao, Central Philippines Cordillera, Philippines.* Institute of Environmental Science and Management, Los Banos, Philippines.

Yamada, I. 1995. Aloewood forest and the maritime world. *Southeast Asian Studies* **33**(3):463–468.

Yoneda, K., E. Yamagata, Y. Sugimoto, and T. Nakanishi. 1986a. Pharmocognostical studies on the crude drug of "agarwood" (I): comparison of constituents of essential oil from agarwood by means of GLC and GC-MS. *Shoyakugaku Zasshi* **40**(3):252–258.

Yoneda, K., E. Yamagata, and M. Mizuno. 1986b. Pharmocognostical studies on the crude drug of "agarwood" (II): on Chinese agarwood. *Shoyakugaku Zasshi* **40**(3):259–265.