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Review

Reforestation and Sustainable Management of *Pinus merkusii* Forest Plantation in Indonesia: A Review

Rinaldi Imanuddin [1], Asep Hidayat [1,*], Henti Hendalastuti Rachmat [1], Maman Turjaman [1], Pratiwi [1], Fitri Nurfatriani [2], Yonky Indrajaya [3] and Arida Susilowati [4,*]

[1] Forest Research and Development Center, The Ministry of Environment and Forestry, Jl. Gunung Batu No.5., Bogor 16118, Indonesia; rinaldiimanuddin@yahoo.com (R.I.); hendalastuti@yahoo.co.uk (H.H.R.); turjaman@gmail.com (M.T.); pratiwi.lala@yahoo.com (P.)

[2] Research and Development Center on Social Economic Policy and Climate Change, The Ministry of Environment and Forestry, Jl. Gunung Batu No.5., Bogor 16118, Indonesia; nurfatriani@yahoo.com

[3] Watershed Management Technology Center, The Ministry of Environment and Forestry, Surakarta 57139, Indonesia; yonky_indrajaya@yahoo.com

[4] Faculty of Forestry, Universitas Sumatera Utara, Jl. Padang Bulan, Medan 20155, Indonesia

* Correspondence: ashephidayat12@gmail.com (A.H.); arida_iswanto@yahoo.co.id (A.S.); Tel.: +62-852-80-123-777 (A.H.); +62-61-820-1920 (A.S.)

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Abstract: *Pinus merkusii* Jungh et de Vriese, known as Tusam or Sumatran pine, is the only pine that grows naturally in the south of the Equator with its natural distribution found in Indonesia, the Philippines, Myanmar, Thailand, Laos, Cambodia, and Vietnam. The Sumatran pine is an economically and ecologically important species in Indonesia that covers three native strains, Aceh, Kerinci, and Tapanuli. The resin tapping of the pine has been practiced for hundreds of years while its timber has long been commercially used for various purposes. Although the pine is known as highland species, its adaptability on a wide spectrum environment makes it suitable for various restoration and rehabilitation purposes both in lowland and highland sites. Its high commercial values have also made the species be massively planted in pine plantations outside their natural distribution in Sumatera (i.e., in Java and Sulawesi island). This paper will review the current condition of Sumatran pine and its potential as a restoration and rehabilitation species and delivering its natural and artificial distribution map in Indonesia. In addition, the paper will also show the genetic variability of the species, determine the current innovative practices in silvicultural aspect both at nursery and plantation scales, describe tree improvement program, including its role in agroforestry practices, pine product both timber and non-timber, and its potential resources in relation with climate change mitigation management.

Keywords: Sumatran pine; native species; current condition; tree improvement program; agroforestry; product; climate change mitigation

1. Introduction

Pine is the largest genus of the Pinaceae family covering more than 110 species worldwide [1]. The species most naturally grows in the Northern Hemisphere in various types of forest including temperate, sub-tropical, tropical, and boreal. The natural distribution of the Asian pine species, *Pinus merkusii*, reaches the Southern Hemisphere. The species is the only pine species that crosses the equator and is native to Indonesia [2]. Besides being distributed in Indonesia (Sumatera), *P. merkusii* also grows naturally in Burma, Thailand, Laos, Cambodia, Vietnam, and the Philippines

(Luzon and Mindoro) [3–6]. The plant also has been introduced in different countries, such as Sri Lanka, Papua New Guinea, South Africa, Tanzania, Uganda, and Zambia [7]. *P. merkusii* is known by several local names, including Tusam, Uyam, Sumatran pine (Indonesia), Merkus pine (taring name), Mindoro pine (Philippines), Son Song Bai (Thailand), and Tenasserim pine (En). There are three distinct populations of Sumatran pines representing their geographical strains in Indonesia, namely Aceh, Tapanuli, and Kerinci. Aceh and Tapanuli strains grow in the northern part of the equator, while Kerinci strain is the only pine that crosses to the Southern Hemisphere [8–10].

Aceh strain is the largest population among others. It grows naturally in open areas (i.e., in alang-alang grasslands), spreading from the Seulawah Agam Mountains to the east of Simalungun [11]. The population is divided further into three distinct sub-populations, namely Jantho, Takengon, and Blangkejeren. Jantho sub-population grows at a low altitude of 200–300 m asl and is considered outliers considering that other sub-populations or strains grow at a higher altitude of 500–2000 m asl [12]. Tapanuli strain is distributed from Bukit Barisan Mountain to the south of Lake Toba, especially in Dolok Tusam, Dolok Pardomuan, and Dolok Saut at an elevation of 1000–1500 m asl [8], while Kerinci strain is found in the Kerinci Mountains area, at Sungai Penuh and Bukit Tapan at the elevation of 1500–2000 m asl [13]. Kerinci strain is the smallest population compared to the other two [14]. Each strain is distinctive and can be differentiated based on their morphological differences and resin characteristics [8].

Considering their broad range of natural habitat from lowland to highland, tusam pines also showed good performance of their growth at both low and high elevations. Those, Sumatran pines have been widely used for various purposes, e.g., restoration [15], rehabilitation [16,17], and production purposes [7,18]. The use of native species for restoration and rehabilitation purposes has gained global popularity [19], which is mainly due to ecological consideration, while planting Sumatran pines for production purposes has been conducted to harvest both its timber and resin [16]. Sumatran pine timber can be used in construction to produce matches, while its pulp is useful for paper and furniture [20]. Resin collected from this species was an important commodity and contribute to national income for about US $50 million/year [21]. Due to its characteristics, benefits, and properties, Sumatran pine is one of the main tree species to be established in plantation schemes. Sumatran pine plantations play a significant role as a water regulator, which supplies water in the rainy season into the soil and releases it in the dry season. In terms of the economic value of timber and resin, pine plantations also increase income from resin tapping up to 61%, and they can also play an ecological role through their effects on the water cycle [22].

2. Current Condition of Natural and Artificial Sumatran Pine Population

There are significant concerns about the sustainability of the Sumatran pine natural population due to numerous threats that may alter the future sustainability of the species. The major cause for the decline in population both in size and distribution may be due to logging, conversion of its habitat into agricultural land, extraction for timber, clear-felling, and frequent forest fires [23,24]. Those activities have changed the Sumatran pine conservation status from rare to vulnerable [25]. Genetic contamination and genetic impoverishment are the other major problems that are invisible but have high excess on the sustainability of the species in the future [26,27].

Timber extraction of Aceh strain for paper mills in sub-population of Takengon since 1989 has eroded the population of the trees, while in Jantho and Blangkejeren sub-populations, timber extraction represents minor problems due to poor accessibility [28]. Tapanuli strain has also experienced a decline in population because of the extensive logging activities of both those growing in private lands and in protected areas [15]. However, among the three strains, Kerinci is determined as the most severely threatened strain. The population growing in Kerinci is among the smallest in size and heavily fragmented. Most of the sites occupied by this strain are very small and patchy, which are worsened by the condition that there are only a few trees mixed with other species [29]. Land conversion into agricultural cultivation (e.g., cinnamomum, potatoes, etc.) is very high and popular and it has led to more severe contraction to its natural habitat.

Genetic contamination has been a general problem and has occurred in all strains. As there was a lack of availability of local seed sources, rehabilitation of degraded forest and land in Sumatran pine natural habitat in Sumatra had been carried out by importing seeds from other islands (e.g., Java) with an unclear genetic identification [30]. Timber oriented harvest of Sumatran pines has also led to a selective logging technique. This selective logging is practiced by cutting big, straight, slender, and healthy trees, leaving the unhealthy ones. Juveniles will show deteriorated genetic characteristics in the future generation as many of those unprofitable traits are passed by such remaining mother trees [14].

Regarding the continuous threats to its natural population, efforts to increase the population have been conducted. These involve planting programs in many degraded natural habitats [31,32], improving interconnectivity between sub-population within strains [8], and increase genetic basis of the species by conducting breeding program [33]. However, Sumatran pine has been experiencing intensive domestication and utilization for its product and those breeding programs of the species should be in line with the conservation efforts [27,34].

As Sumatran pines show good growth performance both at low and high altitudes lands, they have become widely planted all over the country in plantations in Java [34] and Sulawesi [35]. The pines have also been included in major tree species for the national rehabilitation program [36]. Java is known as the largest Sumatran pine plantation that covers 900,000 ha and managed mostly under the state-own company and spread from the western to the eastern part of the island [37]. The first Sumatran pine planting in Java started in the early 1970s serving as rehabilitation and reforestation objectives to increase land productivity while intending to meet the supply of wood raw material for the paper industry. Of 900,000 ha in total, 570,000 ha served as production forests and 330,000 ha as protection forests. The Sumatran pine plantation now becomes the second-largest planted species after Teak (Tectona grandis) in Java, standing for more than 30% of the total plantation area on this island [38]. The species is chosen to be planted for rehabilitation and reforestation purposes due to the abundance of seed availability and can act as pioneer species in many degraded lands area [39].

In the island of Sulawesi, the Sumatran pine plantation was more concentrated in South Sulawesi and has been initiated since the 1930s by Forest Research Institute. The pine was later widely planted in the late 1960s in a total area of around 165,000 ha, covering Tana Toraja, Gowa, Bantaeng, Bone, Soppeng, Jabeponto, Bila, Luwu, Lompobattang, Walanae, Makassar, Mapilli, and Saddang [40]. This species planted for rehabilitation purposes and reached a high survival rate of around 54.67%. It was the dominant species used for the rehabilitation covering more than 64% of all of the planted tree species. Planting Sumatran pine for plantation and rehabilitation purposes was not limited to Java and Sulawesi islands only but also covered other regions outside its natural habitat expanding to Sumatera island, i.e., West Sumatera [41], Riau [42], South Sumatera [43], Bengkulu [44], Jambi [45], Lampung [46], Kalimantan Island [47], Bali and Nusa Tenggara Islands [48], Moluccas [49], and also in Papua [50]. The natural and artificial distribution of Sumatran pine in Indonesia can be seen in Figure 1.

Based on the results of the spatial analysis with an image classification approach using the Satellite Pour d. Observation de la Terre (SPOT)2018 Image, it was found that the distribution of pine forests includes natural and artificial pine forests (Figure 1) covering a total area of ± 1,420,950 ha. It consists of natural pine forests covering an area of ± 359,142 ha found in Aceh, Tapanuli, and Kerinci, as well as 1,061,808 ha of artificial pine forests, which are scattered throughout Indonesia.

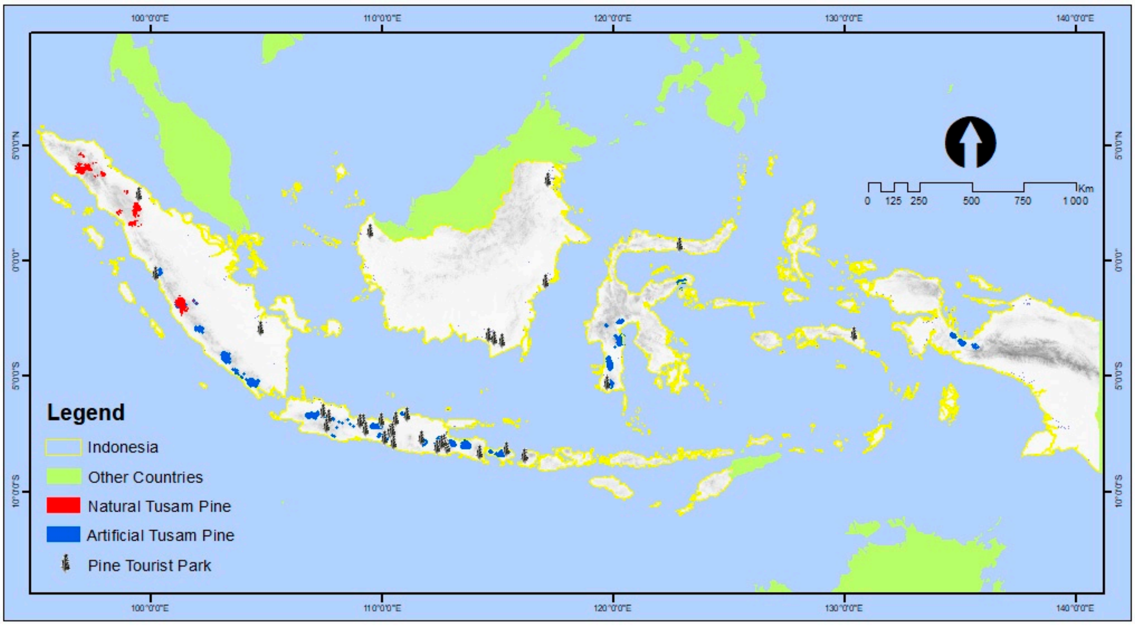


Figure 1. Natural and artificial distribution of Sumatran pine in Indonesia.

3. Breeding Strategy, Propagation, and Management Practice

Sumatran pine plantation was firstly developed in Java long before Indonesia declared its independence from Dutch colonialism. Early in 1920, Perhutani, a state-owned company responsible for managing production forest in Java Island, introduced Sumatra pine from its natural population in Aceh to Java with the main target at that time as timber production. After the independence, the Indonesian government continued its focus on establishing Sumatran pine plantation and thus expanded it across islands in the country. As the value of pine timber escalated at that time, tree improvement was also started [34,51].

Producing superior genotypes was the main objective for the first Sumatran pine tree improvement program that took place in 1976. The program involved three major institutions: Perhutani, Ministry of Agriculture, and Gadjah Mada University. Selection of elite trees or known as plus trees was the initial activity performed to discover more than 1000 families. This was followed by the establishment of seedling seed orchard in Sumedang (West Java), Sempolan (East Java), and Baturaden (Central Java) [27,33]. During that time, resin production was categorized as a by-product.

As the paradigm developed, Sumatran pine plantation has been experiencing a shifted orientation from wood to non-wood product (resin). Therefore, tree improvement activities with high resin production have become the focus since 2006. Considering the discovery of several high resin yielder candidates with higher productivity than the average, from 2002 to 2009 the improvement activities carried out for the selection of plus tree [9]. This resulted in the selection of candidates plus trees from 5 surveyed locations, namely, 3 Seedling Seed Orchards (SSOs) from previous breeding activities, pine forests in Java, and pine forests in South Sulawesi. During the 2007–2009 period, Perhutani developed offspring test planting for high resin yielder candidates [52].

Population structuring is important for designing plantation, breeding, and conservation strategies. Long-term stability of the species also depends on the characteristics of the genetic variations [53]. Humans have altered the genetic characteristics of the species by their activity on exploitation and utilization [54]. Low genetic diversity has been found on many plantation landscapes as the consequence of intensive human alteration. Isoenzyme study by Siregar and Hattermer (2004) showed that Sumatran pine seed orchard in Java island was genetically similar to that of Aceh sub-population, determining the origin of Javan population from materials exclusively taken from Aceh sub-population. The study also described that SSOs and all plantation areas established using planting stocks originated from this SSO may have low genetic diversity. A genetic study has been conducted to quantify population structuring of Sumatran pines using several methods, such as isozyme analysis [26,55–57], DNA markers such as simple sequence repeat, inter simple sequence repeat (ISSR), and randomly amplified polymorphic DNA RAPDs [33,58–62]. Later genetic study focusing on high resin yielder Sumatran pine showed that this high resin yielder Sumatran pine have different allele pattern compared to normal [27].

Generative propagation by the seed of Sumatran pines was considered to have many constraints [63]. It showed slower germination, lower germination success, and higher susceptibility than that of its relative [64]. Poor germination of Sumatran pine seeds has been reported by several authors stating the average value of less than 40%, and further, it was reported it was less than 20% for certain cases [3,65]. However, Sumatran pine from Indonesia showed better natural regeneration ability than that of others from the South East Asian mainland [3].

As there are special traits that need to be maintained, vegetative propagation, which can copy the entire inherited desirable mother tree characteristics, has become more important. Vegetative propagation is a method for the multiplication of selected plus trees and for the construction of a clonal seed orchard [66]. The methods of vegetative propagation with cuttings and grafting are commonly used, but for Sumatran pine, the percentage of success varies and tends to decrease with the increasing plant age. Furthermore, Reference [67] reported that the success of grafting was ranged around 40% by using young material. A more recent study showed that high yielder Sumatran pine can be propagated by cutting with the rooting ability reaching 71.4–87.5% [68] by using fog cooling technique [69]. The success of the Sumatran pine plantation in Indonesia, managed by a state-owned company Perhutani, is also influenced by the silvicultural practice for improving stand management and the pine stand quality. The silvicultural practice includes thinning, control of spacing, water and nutrient management, pruning, and fertilizing.

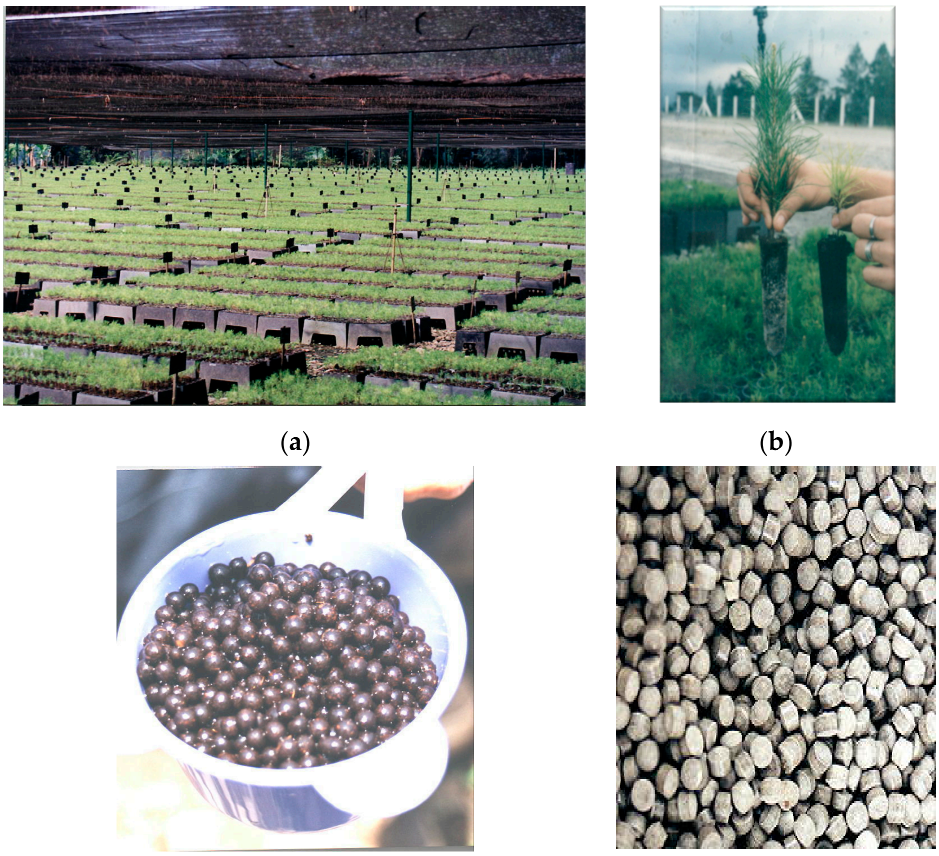
3.1. Silvicultural Practices in Producing High-Quality Sumatran Pine Seedling

Some industrial plantation companies in Indonesia have been producing Sumatran pine seedlings on a mass scale by adopting modern nurseries [70]. The modern nursery applied Standard Operating Procedures (SOP) in their practice that involve container, growing media, sowing, irrigation, fertilization, weed control, pathogen, insects, lifting, packing, and shipping [71]. Sumatran pine is one of the major important trees, thus establishing modern nurseries is critical in growing good-quality Sumatran pine seedlings. A recent technology uses reusable poly tube container (size 100 g) with mixed peat-compost media, inoculated with microbial symbiosis and the addition of slow-release fertilizers (SRF) that provide seedlings with nutrient released for 4–6 months. Misting, automatic watering system, and layered hardening area are also available in the modern nursery. This innovative technology is very important to increase the sustainability of the management of Sumatran pine plantations in Indonesia (Figure 2) [72].

Ectomycorrhizas (ECM) are dual structure bodies between the terminal feeder roots of forest tree species and certain forest fungi [73]. All tropical forest trees depend on the advantageous symbiosis between forest fungi for absorption water and macro and micro-nutrient from forest soils. In this way, ECM fungal mantel can protect the root of the seedlings from fungal pathogen [74]. This symbiosis is important for the mass production of seedlings in the reforestation program; serving as sustainable forest management in an industrial forest plantation, Sumatran pine has a very strong ECM fungal symbiosis relationship. Various families of ECM symbiotic with pine trees have been reported in Thailand and Indonesia. Two pine tree species (*P. merkusii* and *P. kesiya*) are native species growing in a mountain and dryland in Thailand. They showed a high relationship with the occurrence of ECM fruit bodies of *Amanita, Boletus, Inocybe, Laccaria, Lactarius, Russula, Thelephora*, and *Scleroderma* [75]. There are also various genera of ECM fruit body found at Sumatran pine stands in Indonesia, such as *Amanita*, *Astraeus*, *Russula*, *Lactarius*, *Boletus*, *Suillus*, *Lepiota*, *Thelepora*, *Scleroderma*, and *Pisolithus* in its natural habitat of Aceh [70,76], *Suillus granulatus* and *S. placidus* and *Hemioporus retisporus*

(Boletaceae) in mature Sumatran pine plantation [77,78], and *H. retisporus* in heath forests ecosystem under *Tristaniopsis* spp. in Bangka Island (Figure 3) [79].

Sumatran pine is highly dependent on ECM fungi and showed very low growth without ECM inoculation [70,80]. The first inoculation of ECM to Sumatran pine seedlings was reported by Roellofs in 1930 [81]. Through this method, ECM Sumatran pine seedlings or "mother trees" were planted at 1–2 m interval in the nursery beds (5 × 1 m). In the following year, the 6–8 weeks old Sumatran pine seedlings were planted around those mother trees at 10 cm × 10 cm spacing. ECM colonization from the mother trees to the surrounding transplants later was clearly visible. Mother trees were still used in the nursery for approximately the next 20 years to support the establishment of the Sumatran pine plantation. The other method of ECM inoculation in Indonesia has been carried out by taking ECM inoculant from the soil beneath the ECM Sumatran pine mature trees [82]. Top soil inoculum comprises many propagules of unidentified ECM fungal species. That soil inoculum has been widely applied and is very effective in many species of ECM trees [83]. Another effective inoculation method to support the mass production of Sumatran pine seedlings is with ECM spore [84]. Production of inoculum may also be produced by propagating ECM mycelia and incubated in sterilized coconut fiber under dark room temperature. After 1 month, inoculum paste is entrapped by granular calcium alginate according to the method developed in Reference [85].



(**a**) (**b**) (**c**) (**d**)

Figure 2. Mass production of Sumatran pine seedlings using ectomycorrhizal inoculant under nursery conditions in Indonesia (**a**,**b**), ectomycorrhizas (ECM) fungi-inoculant coated by alginate bead (**c**) and clay (**d**).

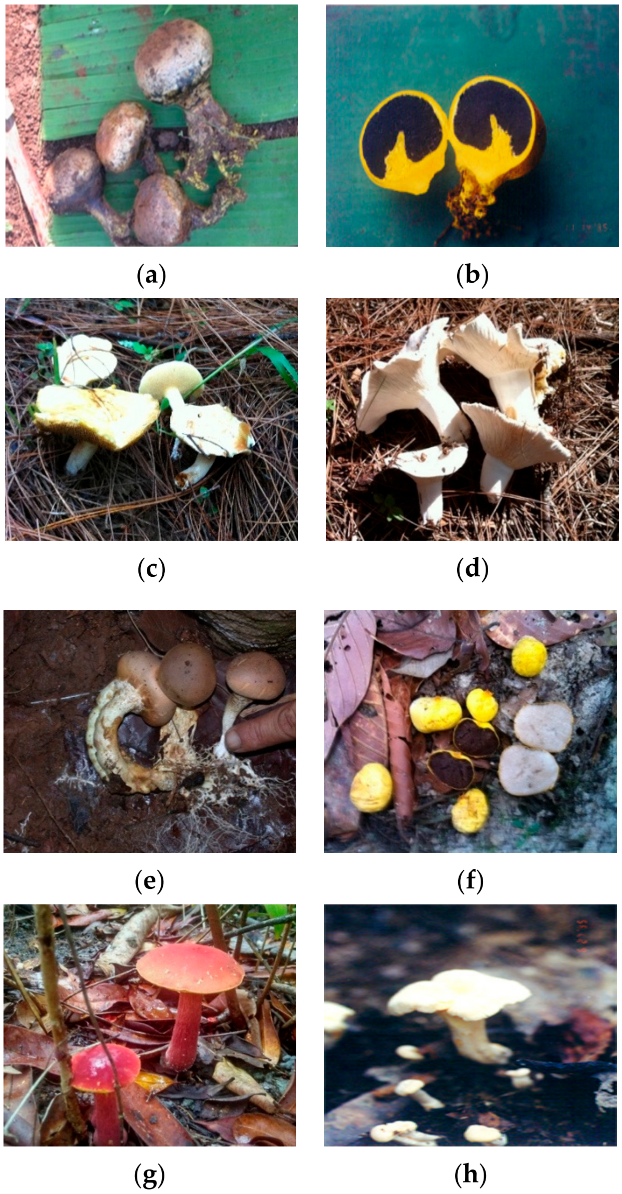


Figure 3. Fruit bodies of ECM fungi recorded in association with Sumatran pine plantation in Java Island, such as (**a**) *Pisolithus arhizus*, (**b**) *Scleroderma sinammariense*, (**c**) *Suillus* sp., (**d**) *Lactarius* sp., (**e**) *Scleroderma columnare*, (**f**) *Rhizopogon* sp., (**g**) *Hemioporus retisporus*, (**h**) *Chantarellus* sp.

Inoculated Sumatran pine seedling is a key element for the success of reforestation actions where compatible ECM fungi inoculant is not available at the site [78,81]. *Scleroderma* spp. and *Pisolithus* spp. (Gasteromycetes) has been utilized to accelerate plant height and survival rates of many pine seedling species under nursery conditions [82,86]. Both genera have wide-range host plants and abundant spores to be collected from mature fruiting bodies compared with other ECM fungi [87]. ECM spores can be applied by mixing tap water (10 g L^{-1}), which are directly inoculated to pine seedling in the nursery. The *P. arhizus* and *S. columnare* fruit bodies are selected and made into a dried powder, which were later pelletized in a tableting machine to have uniform size and weight (0.4 g/tablet) [88]. Most Sumatran pine seedlings are colonized by *P. arhizus* after 2–3 months of inoculation. ECM Pisolithus is widely known to be adaptive to new reforestation areas in Java island, giving a high significant survival rate and plant growth, especially outside the native Sumatran pine habitat [70]. Moreover, *Pisolithus* genus has the capability of growing exotic pines (*P. radiata* and *P. caribaeae*) that are planted in Central and West Africa [84]. ECM fungi originated from Sumatran pine are also proven to improve the growth of *Shorea seminis* seedlings [88,89] after seven months of inoculation.

Sumatran pine has some deadly pathogenic diseases when proper treatment is abandoned. Damping-off disease caused by *Fusarium subglutinans* is among the major problem found in Sumatran pine seedlings at the nursery stage [90]. On a mass scale production of Sumatran pine seedlings, they may also be attacked by Pestalotiopsis foliage blight (PFB caused by *Pestalotia theae*) [91]. Seedlings were attacked at the age of 2–3 months old with symptoms of small yellowish spots along their needles, which move progressively toward the needle tips [91,92]. These PFB fungi have also been recognized as having an association with damping-off and other pathogens in a nursery stage [92]. Infected Sumatran pine seedlings should not be planted in the field because it will give high mortality and low survival rates. Soil sterilization treatment has been proven to be effective in minimizing the PFB. In the other method, the pine media can be dried under the sunlight for several days or steamed for 60 min [88]. Some research showed pine disease could be minimized by applying effective ECM fungi in the nursery stage and improving pine seedling healthy growth for managing the regeneration process in pine forest plantation (Figure 4) [93].

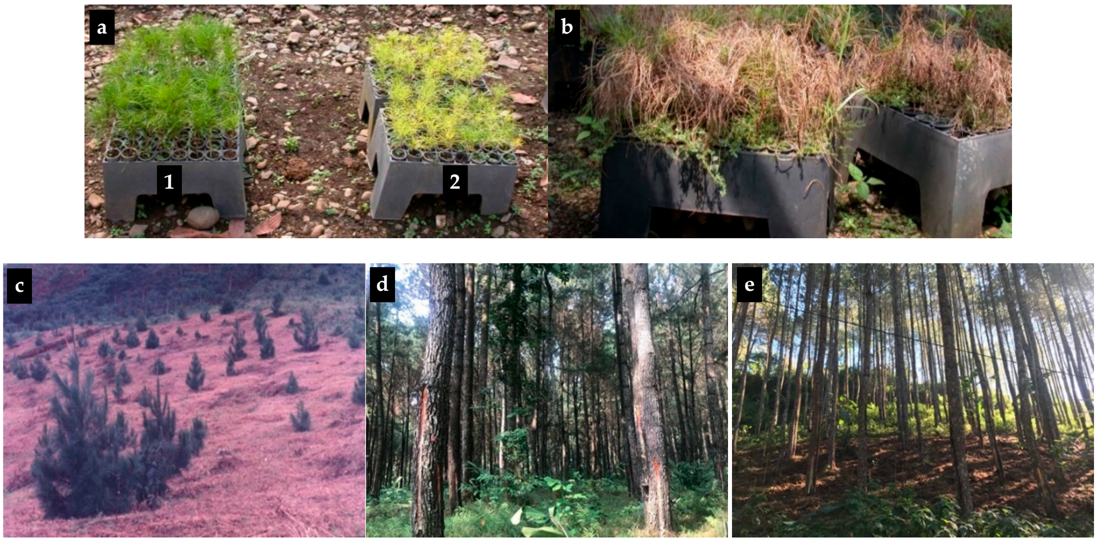


Figure 4. Comparison between Sumatran pine seedlings inoculated with ECM fungi (**a**1) and control (without inoculation) (**a**2); Sumatran pine seedlings attacked by Pestalotiopsis foliage blight (PFB) disease (**b**); Sumatran pine plantation 3-years old (**c**) and 23 years old (**d**,**e**) to produce ECM fruit bodies.

3.2. Management Practice of Tusam Pine Stand in Indonesia

The establishment of pine plantations in Indonesia is conducted with two systems that depend on the population density of the site. In densely Java Island site, Sumatran pine plantation usually takes agroforestry form (i.e., taungya system/intercropping of young tree plantations with food crops) that consists of Sumatran pine and food crops for the first two years. The 3 × 1 or 3 × 2 m spacing is preferred for Sumatran pine plantation in Java using an agroforestry system [3]. In contrast, in Sumatera Island where the population is relatively sparse, the pine plantation is conducted by contractors or by day labor.

Agroforestry may produce multiple outputs and has the flexibility of several management options so that it is more attractive than conventional agriculture and forestry [94]. In Java, Sumatran pine trees were mostly planted in volcanic soils that are highly fertile. With this condition, high-quality crops like tobacco, potato, or vegetables often compete with the pine trees for land availability [95]. In several cases when high-quality crops give more instant cash, Sumatran pine trees are often neglected or even damaged. Some of the original Sumatran pine forests in North Sumatera have been converted into benzoin gardens. Local communities mostly cultivate the *Styrax paralleloneurus* Perk in the secondary pine forest ranging from 0.5 to 3 ha per household [96]. The latest condition shows that benzoin trees are still often found in the former Sumatran pine forest in North Sumatera. However, with a relatively low management intensity to the benzoin stand that is growing together with Sumatran pine, the resin production is lower than that of monoculture benzoin stands.

Sumatran pine plantation in form of agroforestry practices provides more alternatives for income cash. In the early development of Sumatran pine plantations, there were relatively many types of agricultural plants that could be intercropped due to the lack of dense canopy of pine stands and the abundance of sunlight. Intolerant food crops such as rice, corn, soybean, etc. are usually intercropped with Sumatran pine trees. Studies on the agroforestry system under the Sumatran pine stand have been reported in several locations in Indonesia. Planting agricultural crop is indicated to have a positive impact in promoting faster growth of the Sumatran pine. The application of fertilizer and tillage on food crops will automatically support the growth of Sumatran pine [97].

At the later stage, the agroforestry model in Sumatran pine plantation may form a combination of shade-tolerant species such as coffee, rhizome, and tuber. The agroforestry at the later stage of pine plantation may give both positive and negative effects on both Sumatran pine growth and also agricultural crop production. The average DBH and the volume of Sumatran pines per ha may get lower in an agroforestry system than that of a monoculture, while agricultural crop yields can also have a lower production compared to pure agricultural cultivation [98]. Access for the local community to Sumatran pine forest in rotation period within an agroforestry scheme gives many sources of income from resin production, staple crops, rhizome, tuber, and coffee. This agroforestry scheme incentivizes farmers to protect pine forests. This is in line with the findings from a study by Subarna [99] that the economic pressure strongly affects the community to encroach the forest area. A good partnership between the local community and Perhutani through Community-Based Forest Management (CBFM), including agroforestry, will enhance the prosperity of the local community and maintain forest preservation [100].

An agroforestry practice of pine–coffee increases the abundance, structure, and population of soil invertebrates and maintain soil temperature and humidity [101,102]. Soil macrofauna has an important role in influencing soil structure and soil physical properties [103], It also maintains soil fertility through the decomposition of organic matter, nutrient distribution, and increasing soil aeration. Another well-adapted crop with high economic value to be intercropped with Tusam pine is ginger (*Zingiber officinale*) that can together be planted with other shade-tolerant vegetables [104] at young Tusam pine stand (0–10 years old).

Agroforestry in Sumatran pine plantation generates income for farmers residing in the surrounding plantation area. Agroforestry practice by intercropping Sumatran pine with coffee, cloves, and corn or soybeans at the marginal lands in South Sulawesi gives a larger income to farmers than that of a non-agroforestry model. Therefore, the Sumatran pine agroforestry practice is more profitable compared to non-agroforestry/monoculture farming, as the pine agroforestry system may produce various types of high-value commodities [105]. Higher benefits from agroforestry practices of Sumatran pine plantation can be seen at coffee plantation under pine stand in Bandung, West Java [106].

As the previous discussion focused on agroforestry, the Sumatran pine monoculture stand is also practiced in Indonesia. Perhutani functions as the management unit that manages most of the monoculture Sumatran pine plantations in Indonesia. Along with a higher value from its resin, there has been a shifted orientation of Sumatran pine product management from timber to non-timber. Resin product is among the most popular yield and may contribute to the income of the communities around the forest by providing jobs for communities to collect pine resin [107]. To increase the resin production, Perhutani not only increases the number of trees being tapped but also improves tapping technology to increase sap production per tree. Pine resin production reaches its peak at the age of 26 years (1152 kg/year) and decreases at the age of 50 years (710 kg/ha) [108].

4. Valuation of Sumatran Pine Product

Sumatran pine provides tangible and non-tangible multiple benefits for the human being. In terms of its tangible benefit, the pine produces non-timber forest products such as resin or pine resin, as well as wood forest products. Meanwhile, the intangible benefit is provided in the form of environmental services such as pine forests as a nature tourism location, land and water protection services, and hydrological function [22,35,109,110]. In addition, the Sumatran pine forest also provides social benefits for people residing near the forest. Through the social forestry program, the pine forest is allocated to be managed by the community. The community is given access to manage the state forests with a shared revenue mechanism. This shows that Sumatran pine forests in Indonesia provide multiple benefits that are very important for human welfare, as shown in Figure 4 (Figure 5).

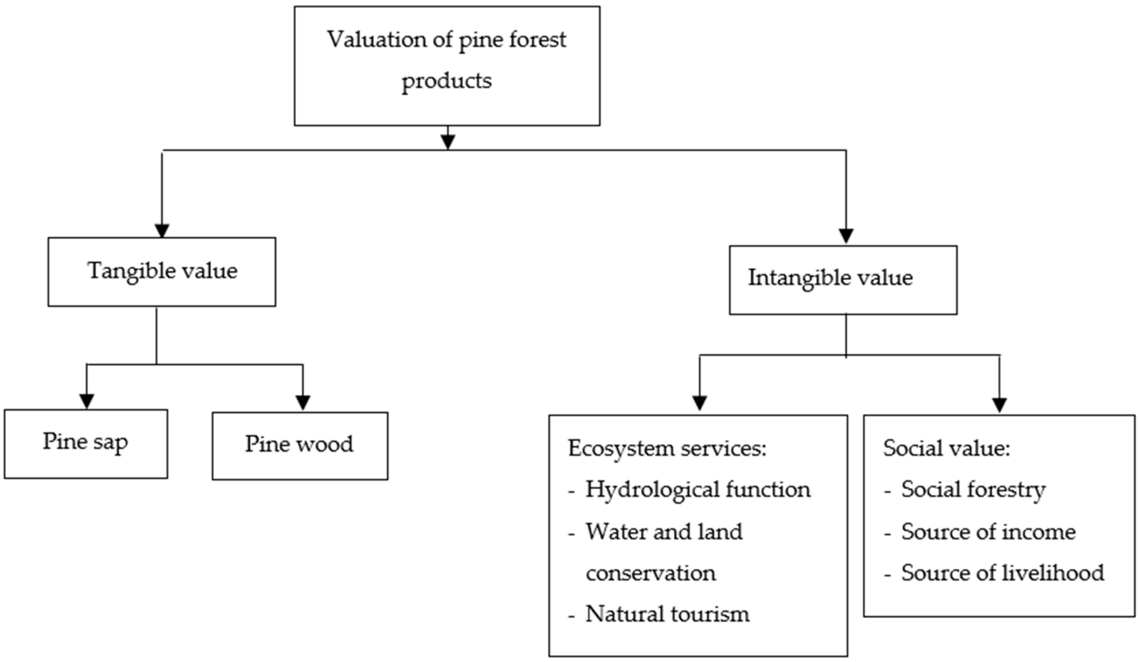


Figure 5. Multiple benefits of pine forest [111].

4.1. Sumatran Pine Sap

The use of pine sap has been known for many purposes. It is known as a raw material for the manufacture of gum rosin, soap, adhesives, paints, and cosmetic ingredients [112]. Meanwhile, the gum rosin is a processed product from the pine sap. This commodity is a net residue from the pine resin distillation process. Its shape is in the form of golden yellow solid pieces. Another processed pine resin that is also in demand by the industry is turpentine oil. This clear liquid-shaped oil is the result of the distillation of pine sap. Gum rosin and its derivatives are widely used as raw materials for the paper industry, ceramics, plastics, paints, batik, soap, printing inks, pharmaceuticals, cosmetics, glues, coatings, vehicle tires, as well as for the food industry. Turpentine oil, on the other hand, is used as a solvent for organic oils and resins. In the pharmaceutical industry, turpentine oil is used as a raw material for disinfectants, fragrance, shoe polish, and synthetic camphor in the metal and wood industry [113,114].

The demand for pine sap commodity and its derivative products in the local and international markets is quite high. Around 80% of gum rosin and turpentine oil production is allocated for export to several countries including India, Japan, Taiwan, Singapore, Spain, England, Germany, France, Nigeria, and the United States [115]. Most pine sap production in Java is produced by Perhutani (a state-owned enterprise), while outside the Java area the pine sap is produced by several business license holders for non-timber forest product utilization (IUPHHBK). The license holder can be a community through the Social Forestry scheme in the Forest Management Unit (KPH) as well as permit holders from the private sector.

Based on the Ministry of Environment and Forestry data, the production volume of pine resin in Indonesia from 2015 to 2018 was relatively stable with an average of 115,730.9 tons per year. The level of production did not fluctuate greatly as can be seen in Figure 6.

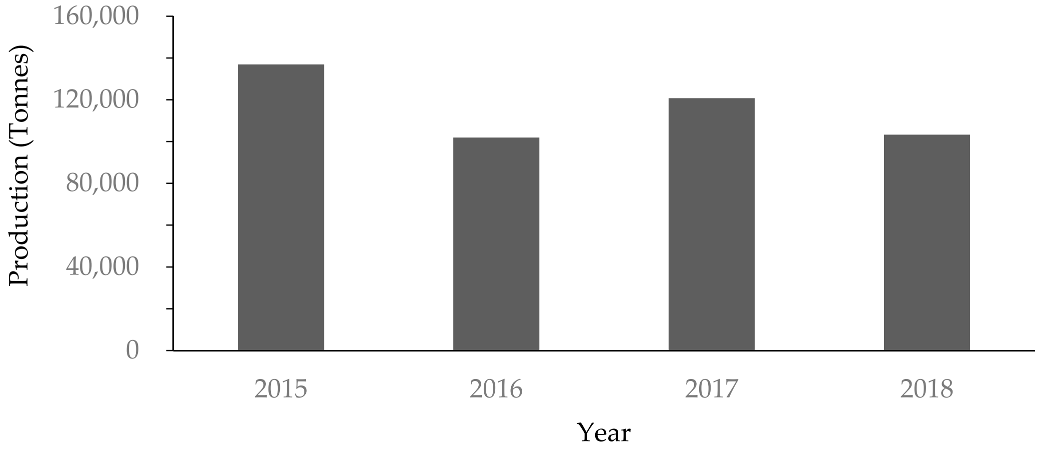


Figure 6. Production volume of pine resin in Indonesia.

Perhutani noted that the production of pine resin is now becoming a mainstay of Perhutani's revenue apart from timber products. Based on Reference [116], the contribution of revenue from gum rosin and turpentine oil to Perhutani's total income is quite large, reaching around 45%. Perhutani has eight gum rosin and turpentine processing plants with a total production capacity of 92,550 tons spreading across Central Java, East Java, and West Java. The average area of pine sap tapping in the Perhutani area from 2015 to 2018 was 1,635,375 ha per year with an average level of pine resin production of 90,422 tons per year. With an average yield of 71% for processing pine resin into gum rosin and 19% for turpentine oil, gum rosin and turpentine oil production volumes from 2015 to 2018 are shown in Figure 7.

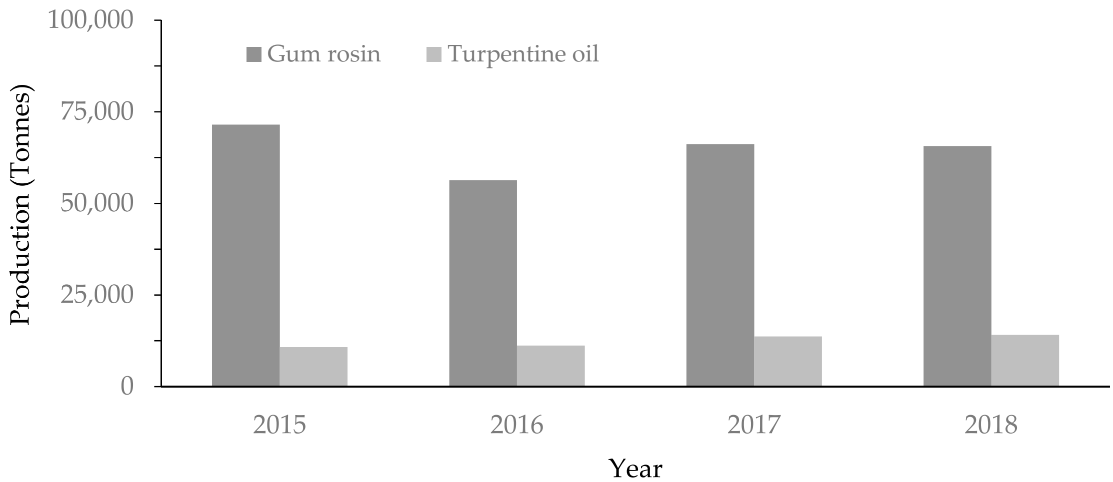


Figure 7. Production volume of Perhutani gum rosin and turpentine oil in 2015–2018.

Further processed product is latex that is originated from processed plant sap. The export value generated from the latex commodity as issued by the Indonesian Ministry of Trade was USD 68.6 million or IDR 960.9 billion in the period of 2015 to 2018 and it showed an increasing trend.

This increasing trend shows that Indonesia still has a chance to increase exports of processed pine resin because its market share is still widely open.

4.2. Sumatran Pine Wood

Sumatran pine wood has many uses, as carpentry wood, imitation boards, furniture, molding, matches, pulp and paper, and craft [112]. Light-colored Sumatran pine wood is strong and durable. It is lightweight and has an anti-shock character, making it suitable for furniture [114]. Due to its bright color, pine timber usually is coated with a transparent coating, so that the natural color of the wood can be further highlighted. Pine logs can also be used for the paper industry, making Indonesia one of the largest producers of pulp in the paper industry.

Similar to those of non-timber products, Sumatran pine wood in Indonesia is produced mainly by Perhutani. Perhutani sells wood products in the form of logs and processed wood, where the log market share is 100% in the domestic market due to the log export ban policy. Based on Perhutani's statistical data [114], pinewood production volume and domestic sales volume from 2014 to 2018 can be seen in Table 1.

Table 1. Volume of domestic Sumatran pine wood sales.

Year	Volume (m^3)	Value (× IDR 1000)	USD * (× 1000)
2014	125,024	93,918,909	6708.5
2015	100,781	75,302,953	5378.8
2016	97,687	67,206,024	4800.4
2017	139,706	107,307,645	7664.8
2018	162,443	101,350,109	7239.3

Remarks: * 1 USD = IDR 14.000.

4.3. Environmental Services

Other benefits generated from Sumatran pine forest is providing ecotourism services, controlling landslide with vegetative way, and regulating hydrological aspect. Sumatran pine is also widely planted for the rehabilitation of critical forests and land due to the availability of seeds, rapid growth rate, and its pioneer characteristic that can grow on marginal lands [35]. Another important function of the Sumatran pine forest ecosystem is as an ecotourism area, functioning as the ecosystem service provider. The value of the forest ecosystem service as ecotourism is part of the forest's contribution to society's welfare. Sumatran pine forest is well known as popular ecotourism in Indonesia, particularly in some areas in Java and North Sumatra. At present, nature ecotourism in Sumatran pine forests is established as indicated by the increasing number of tourist visits. Those Sumatran pine forests ecotourism are generally located in mountainous areas providing fresh air to visitors.

The successful management of pine forest ecotourism spots has been practiced by Perhutani. In 2018, Perhutani managed 724 tourist sites spreading across Java. Income revenue from this nature tourism in 2018 contributed 5% of the total company's revenue. From this nature tourism sector, Perhutani received an income of IDR 117.676 Billion (USD 8.4 Million) in 2018, an increase of 23% compared to the revenue received in 2017 [116]. This emerging business has attracted many stakeholders. Several studies have calculated the economic value of this forest tourism area and showed that Sumatran pine forest may contribute a significant economic value, i.e., USD 321,459/year from Mangunan Sumatran pine forest in Yogyakarta, USD 793,464.7/year from Siogung-Ogung in North Sumatera, and USD 563,954.7/year from Kemit Sumatran pine forest in Cilacap, Central Java. Those economic values of pine forest ecotourism show the benefits that can be received by the community as well as the government from the existence of pine forests.

The economic benefits of pine forest environmental services can be calculated using the economic valuation method of forest ecosystem services. The economic value of the environmental services is based on the perception and appreciation of the community or individuals for the benefits of goods and services produced by the forest and land resources in terms of their tangible or intangible benefits. This is indicated by the value of environmental services provided by the protected forest area in the western part of Mount Lawu, in Central Java. This protected forest area consists of pine, mahogany, and rosewood stands. The research shows that the ecosystem service value of this protected forest at Mount Lawu reaches the amount of IDR 7.03 Billion (USD 502,142.9) within a year. This means if the protected forest area is damaged, thus it will lose its ecosystem service value that consists of the value of woods/pulp, hydrological function, flora and fauna, and socio-cultural value [117].

4.4. Hydrological Value

Water circulation in tree stands occurs through five processes, namely: crown interception, throughfall, stem flow, evapotranspiration (consumptive use), and surface runoff [118–120]. Sumatran pine stand gives ecological value in controlling water yield. It has an interception value of 22–23% from annual rainfall, 77% of net rainwater absorption through the stem, and through flow [120]. However, its evaporation rate is quite high (64.5% of rainfall) [121]. Based on this result, Reference [120] suggested that establishing Sumatran pine plantation should be concerned more with the water yield consequences, thus the recommended spacing distance to be applied is 4 m x 4 m. Sumatran pine is recommended to be planted with those of slippery tree trunk species. There has been a long debate on which the best locations for Sumatran pine plantation should be established in the point of water yield control. Some scientists and practitioners recommended to plant Sumatran pine in areas with a rainfall of >3000 mm/year to avoid an extreme decrease in groundwater level during the dry season. However, Suryatmojo [39] stated that Sumatran pine can be developed in areas with >2000 mm/year, and it is still possible to develop Sumatran pine plantation in the area with the rainfall ranging from 1500 to 2000 mm/year as long as it is combined with some trees that have a low evapotranspiration rate, such as *Altingia excelsa* and *Agathis* sp. Establishing Sumatran pine plantation in the area with less than 1500 mm/year rainfall should be avoided due to the possibility of a water deficit.

Furthermore, Siswamartana, et al. [122] said that due to the thick litter cover under the old Sumatran pine stand and also its numerous and deep roots, the surface runoff could be reduced, thus decreasing the erosion significantly. According to Sidle et al. [123], this species could reduce direct runoff and peak discharge because it has a high interception and evaporation rate. On the other hand, Pramono [124] showed that in the medium rainfall sub-watersheds (<65 mm/rainfall events), the occurrence of 33% Sumatran pine forest from the total watershed area could reduce peak flows up to 74% compared to the sub-watersheds with 13% Sumatran pine forested watershed. However, when rainfall exceeds 65 mm/rainfall, Sumatran pine forest may not be able to significantly reduce peak flooding.

Forested watersheds have higher infiltration and show higher and more sustainable base flow [125]. Sumatran pine forests have a significant role in regulating the base flow and maintaining forest with a higher base flow (86.68%) than those of other factors (33.2%) including geology, soil type, slope, and others. A study by Price and Jackson [126] showed that the coefficient of determination between Sumatran pine forest and base flow was varied from 0.52 to 0.80. Areas covered by 40% of Sumatran pine forest showed a rising trend in their specific base flow [124].

Sumatran pine forests affect fluctuations of groundwater level. A farther distance will result in a greater fluctuation with the value of coefficient determination (r2) reaching 0.73 [127]. However, another study showed that the Sumatran pine forest also consumed more water than other commodities (i.e., rice fields, mixed gardens, and agricultural fields) [126]. The vast Sumatran pine forests produce less water with young pine forests consuming more than that of the old ones [128].

4.5. Social Value

Sumatran pine forests also have social benefits because they provide a source of livelihood for the communities residing around the forests. The government has currently provided legal access for the communities around the forest area to managing the forest areas through the Social Forestry programs, such as the Community Forest (HKM), Village Forest (HD), Community Forest Plantation (HTR), and Partnership schemes. In addition, these programs also consist of the development of community forests and the empowerment of indigenous people. Some Sumatran pine forests become the locations of the Social Forestry programs. The community forms the Social Forestry Business Group (KUPS) with a focus on Sumatran pine sap. Based on the Perhutanan Sosial (Social Forestry/SF) navigation system database [128], licensing of SF for Sumatran pine sap business commodities has been granted an area of 7969.2 ha spreading in the provinces of South Sulawesi, Lampung, East Java, Central Java, North Sulawesi, Central Kalimantan, North Kalimantan, and Jambi. Some forest areas at the site level managed by the Forest Management Unit (KPH) have the potential for the Sumatran pine sap business. Some of them are included in the Production KPHs in Gorontalo, Central Sulawesi, and West and Southeast Sulawesi, while in the Protected Forest Management Unit (KPHL), pine sap utilization has been cultivated in the provinces of Aceh, West Sumatra, Bengkulu, Bali, Central Sulawesi, Southeast Sulawesi, and West Sulawesi [128]. The tapping of Sumatran pine sap in the KPH/KPHL area is carried out by the community through the social forestry program and by the utilization of license holder companies.

Sumatran pine tapping activities have contributed to the income of the community around the forest. In the area around Gunung Halimun Salak National Park (MHSNP) in West Java, the tapping of Sumatran pine, resin, and rubber sap contribute to 59.18% of the total household incomes [129]. From the socio aspects, the harvesting of Sumatran pine resin employs many people, creating a source of livelihood for the people's welfare. Sumatran pine forest in one of Perhutanai areas in Gombong occupies 463.5 ha with 81,850 trees, contributing to an average household income of pine sap tapping of IDR 765,893.38 per month (55 USD/month) and to household needs by 86.01%. Another example in Pekalongan Regency, which is famous for its batik industry, gum rosin is very useful as a raw material for the batik industry. Furthermore, Fanani and Suliantoro [130] have analyzed the possibility of developing the Sumatran pine forests community into a gum rosin processing business partnership in Pekalongan Regency. The partnership in the gum rosin processing business will encourage the development of small–medium enterprises. It particularly develops the batik industry, which is the foundation of income for the people in Pekalongan city.

5. Sumatran Pine Mitigation and Climate Change

The increase of CO_2 concentration followed by the increasing average temperature of the planet is among the global concern that triggered initiatives for CO_2 emission control worldwide. The tropical Indonesian forest and land use change have been pointed as a significant source of global green house gas (GHG) emissions and removals and might be contributed to the vast tropical forest within the country, coupled with a high rate of deforestation and forest degradation. Related to global initiatives and commitment, Indonesia has submitted its first Nationally Determined Contribution (NDC) targeting the reduction of emissions by 29% with their own efforts and 41% within international cooperation in 2030. Indonesia's NDC commitment to the next period is determined based on a performance review and must show an increase from the next period [131].

The huge area of Sumatran pine plantation that reached almost 1.5 million ha (Figure 1) gives a significant role in carbon sequestration. Referring to the results of Ahmad [132], it was found that the average emission factor for pine forests was 113.2 tonnes C/ha, which was then used as the basis for estimating the carbon stock of pine forests in Indonesia. The results of the estimated carbon stock are ± 41 million tonnes C in natural pine forests and ± 120 million tonnes of C are found in artificial pine forests with a total carbon stock of ± 161 million tonnes C, which is equivalent to ± 590 million CO_2-e. The information generated is very useful as initial information in determining forest management strategies in the context of climate change. In addition, the information from the results of this study shows how great the potential of pine forests, both natural and artificial, is related to the available carbon stock. Furthermore, research activities can be directed to see how much growth and carbon dynamics are occurring in this pine forest.

To mitigate climate change, the availability of accurate data and information will be the main capital in determining policies so that an appropriate strategy can be produced to overcome its impacts. Good management of the forests following the perspective of reduction emission from deforestation and forest degradation (REDD)+ helps to reduce emissions from deforestation and forest degradation. Well-managed forests also help deal with the increasing carbon sequestration or carbon stocks from forests that have been damaged due to forest rehabilitation, planting, and ecosystem restoration activities. The REDD+ scheme (Reducing emissions from deforestation and forest degradation, and the role of conservation, sustainable management of forests, and enhancement of forest carbon) requires an accurate measurement of carbon stocks and emissions. Managing forests to increase carbon sequestration or to reduce carbon emissions and using wood products and bioenergy to store carbon as the substitute for other emission-intensive products and fossil fuel energy have been considered effective to tackle climate change in many countries and regions.

C-woody stock is sensitive to forest management practice, as reported in other studies that compare managed vs. natural forest [133,134]. This is in line with Ruiz-Peinado et al. [135] that reported higher accumulated carbon stock in managed vs. unmanaged forests when the offsite carbon stock (harvested biomass) is included in the balance. Relating to the role of the Sumatra pine forest in mitigating climate change, C-wood stock has a high correlation with the pattern of its management. Growth and yield are among the parameters that are often used for evaluating the effectiveness of the species in mitigating climate change. Of the many problems encountered for Sumatran pine cultivation and management, the lack of availability of its natural wildings is of significance. In more specific conditions, natural regeneration of Sumatran pine of Tapanuli strain is difficult to obtain in their adjacent stands and yet their natural regeneration is often found in open areas such as landslides [136]. Therefore, establishing a well-equipped and well-managed nursery for raising good quality Sumatran pine wildings would be beneficial. To support optimum growth, thinning also plays an important role. The effect of thinning allows reducing the forest canopy, support improvement in the light and water availability for the remaining trees, contributing to the reduction in the natural mortality rate, which is in line with several other works [137,138]. However, the effects of thinning on the accumulation of carbon stock can be very different. Currently, the data on how the different management practices of Sumatran pine stand related to its C-wood stock are still unavailable. However, it is very useful to investigate the different impacts that the classic components of forest management (intensity and frequency of thinning, rotation length) would give on stand productivity [139].

Global climate change has caused several extreme weather conditions around the world. Among them is the prolonged dry season that may trigger fire disaster. The impact of the long-dried season was visible as reported by Hartiningtias et al. [140] that of more than 60% *P. merkusii* trees died by fires, burned natural existing regeneration and reduced their biomass and carbon by about 40%. Continuous land conversion is also a serious threat [3] that caused habitat and population contraction and may alter the future sustainability of the species. Indonesia has its natural distribution of both highland and lowland provenance of Sumatran pines and each would be affected by climate change to a different extent. A study by using climate envelope modeling [141] showed under the scenario of increasing temperature in the planet the Malay Archipelago and the northern part of Australia may become the new suitable habitat of *P. merkusii* outside their natural geographic origin in mainland Southeast Asia and Sumatera. How climate change will shift the Sumatran pine's potential and distribution will be interesting to investigate especially in Indonesia when Sumatran pines have been widely planted all over the country. When a new preferable distribution area is determined, it may be useful for constructing the conservation strategy and sustainable use of the Sumatran pine genetic resources in Indonesia.

6. Conclusions

This review described the management practice of *P. merkusii* in Indonesia. The species has a long history of utilization for its valuable timber as the major product, which later shifted to its resin in recent decades. Efforts on breeding and cultivation have been carried out to gain maximum yield on both timber and resin product. Its wide adaptability on various sites and habitats has made the species to be used intensively both for restoration and production purposes. Sumatran pine plantation has been established commercially by a state-owned company of Perhutani that utilize species for its timber, resin, sap, and environmental services. One distinct characteristic of pine management in Indonesia lies in the practice of agroforestry or social forestry system when Sumatran pines are intercropped with agricultural crops. This system may reflect the successful and a win-win solution between communities and companies or nations where the competition of land use between economy and ecology is high. Through this practice, Sumatran pine trees are nursed while the community can yield the agricultural crops. The huge planting of Sumatran pine may also contribute to the mitigation of climate change by their carbon stocks potential. However, there is still a limited report on how the Sumatran pine forest takes its role in global carbon sequestration.

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