

Chapter

Importance of Araucariaceae for Plantation Development in Papua New Guinea

Benson Kumuli Gusamo

Abstract

This article reviews the potential of *Araucaria hunsteinii*, *Araucaria cunninghamii*, and *Agathis robusta* for developing plantations in Papua New Guinea (PNG). The species are propagated from recalcitrant (*A. hunsteinii*) and orthodox (*A. cunninghamii* and *A. robusta*) seeds. The viable seeds are extracted from ripened cones and kept in controlled rooms to maintain seed quality. The seeds are raised in nurseries for seedlings and transplanted in the field. The Bulolo and Wau plantations (PNG) are managed on a 30–40-year cutting cycle. Silviculturally, a 3×4 m spacing ($12 \text{ m}^2/\text{tree}$) is applied with 833 trees/ha as initial stocking. Tending is executed in the initial stages and two medium- to high-intensity thinning operations are employed to boost the growth of residual stands. Also, synthetic fertilizers and termiticides are applied to enhance plant growth and control termite infestation in young plantations, respectively. Next, non-commercial (low) thinning is scheduled at 5–7 years with 416 stems/ha stocking (estimated volume $5.522 \text{ m}^3/\text{ha}$) followed by commercial (crown) thinning conducted at 17–20 years with 208 stems/ha stocking (estimated volume $17.790 \text{ m}^3/\text{ha}$). The 208 stems/ha is maintained as final crops up to 30–40 years with expected 30.206 m^3 volume.

Keywords: evergreen coniferous species, *Araucaria hunsteinii*, *Araucaria cunninghamii*, *Agathis robusta*, recalcitrant seeds, orthodox seeds, plantation silviculture, reforestation/afforestation

1. Introduction

The Araucariaceae is a member of evergreen coniferous trees (softwoods). There are several species of importance belonging to this family, which are confined to Asia and the Southern Hemisphere [1, 2]. Some members of Araucariaceae and their natural distributions in Asia and the Southern Hemisphere are given (Table 1). In New Guinea (Papua New Guinea (PNG) and West Papua of Indonesia), the three species (*Araucaria hunsteinii* K. Schum., *A. cunninghamii* Ait. ex D. Don and *Agathis robusta* F.M. Bailey var. *nesophylla* Whitmore) of Araucariaceae are found in the natural forests [1, 2, 15–17]. According to Havel [2], these conifers are mostly found in the lower and mid-montane rain forests between 660 and 2300 m above sea level. The species occur on the mountains of mainland New Guinea commonly in softer

Scientific name	Common name	Natural distribution	Source(s)
<i>Araucaria hunsteinii</i> K.Schum.	Klinkii pine	New Guinea*	[2]
<i>Araucaria cunninghamii</i> Ait.	Hoop pine	New Guinea*	[2–4]
<i>Araucaria angustifolia</i> (Bertol.) Kuntze.	Parana pine	Brazil, Chile	[5, 6]
<i>Araucaria bidwillii</i> Hook	Bunya pine	North Queensland, Australia	[3, 7, 8]
<i>Araucaria heterophylla</i> (Salisb.) Franco	Unknown	Norfolk Island	[3]
<i>Araucaria araucana</i> (Molina) K.Koch	Araucaria	Argentina, Chile	[9]
<i>Agathis robusta</i> (F.Muell.) F.M. Bailey	Kauri pine	New Guinea*, Fraser Island, Australia	[1, 4, 10]
<i>Agathis microstachya</i> J.F.Bailey & C.T.White	Bull kauri	Australia	[10]
<i>Agathis atropurpurea</i> B. Hyland	Blue kauri	North Queensland, Australia	[7]
<i>Agathis alba</i> (Lam.) Foxw.	Dammar pine/Kauri pine	Moluccas, Philippines, Sulawesi	[2, 6]
<i>Agathis macrophylla</i> (Lindl.) Mast.	Pacific kauri	Solomon Island, Vanuatu, Fiji	[3, 11]
<i>Agathis borneensis</i> Warb.	Borneo kauri	Indo-China, Sarawak, Malaysia, Borneo	[12]
<i>Agathis australis</i> (D.Don) Lindl.	New Zealand kauri	New Zealand	[1, 13]
<i>Agathis montana</i> de Laub.	Mt. Panie kauri	New Caledonia	[5, 14]
*PNG and West Papua of Indonesia.			
The scientific names, common names, and synonyms are checked and confirmed with International Plant Names Index [6].			

Table 1.

Some members of *Araucariaceae* and their natural distributions in Asia and The Southern Hemisphere.

slopes and ridges in their natural habitat. These conifers have excellent wood properties and are among the top-listed timbers with other tropical broad-leaved species (hardwoods). Due to wood properties and economical value of the *Araucaria* spp. and *Agathis robusta*, the species are highly sought by the timber industries. Thus, the government via the PNG Forest Authority (PNGFA) restricted the export of round logs of these timbers since 1980 unless logs are converted into semi-finished or finished wood products [18].

The *Araucaria* spp. and *Agathis* spp. are propagated solely from seeds. The seeds from ripened cones are dispersed by wind and animals in the natural habitat [3]. The only threat to seeds on the forest floor or during storage are rodents who feed on them for food [17, 19]. The seeds of these coniferous species (*Araucaria* spp. and *Agathis robusta*) have low dormancy and can lose their viability quickly in natural conditions. For example, seeds of *A. hunsteinii* are dead within 8 weeks if left in the open and allowed to dry [19]. Also, seedling survivals are low in prolonged shadings under the forest canopy [3]. However, if there is no damage by rodents or infestations from insect pests and diseases on the fertile seeds, the species have good natural regeneration capabilities when exposed to environmental conditions (moisture, light, and temperature) conducive for germination. The species can easily be domesticated from their wildings either from seeds or from seedlings plucked

up from the forest floor. Thus, these species are widely domesticated and cultivated on monoculture or mixed plantations and as ornamentals in the tropical environments of PNG and northern Australia. For silvicultural trials and plantation establishments, the seeds are selectively sourced from healthy parent trees with good vigor and stem forms. The seeds are stored in a controlled storage shed and raised in nurseries for seedling production until they reach a transplantable size for out-planting in the field. As far as timber processing and utilization are concerned, the softwoods are non-porous with desirable wood characteristics, that is, physical, mechanical, and working properties in terms of strength-to-weight ratio, sawing, peeling, gluing, seasoning, machining, and permeability to treatment with chemical solutions [16, 20].

The PNG government has developed a policy on reforestation for sustainable forest management due to depletion of forest resources as a result of industrial logging, forest clearance (deforestation) for agri industries, and shifting cultivations [21, 22]. The envisaged target is to achieve 800,000 ha of planted forest by 2050 via reforestation and afforestation activities of logged-over concessions and anthropogenic grasslands or degraded lands, respectively [23]. In the reforestation and afforestation programs, the softwoods *Araucaria* spp. and *Agathis* spp. (as well as other indigenous hardwoods of commercial value) are identified as prime candidate species for increasing the plantation capacity in the country. Apart from the production of a forest through plantation establishment, the reforestation and afforestation practices should address other sustainable development goals such as carbon sequestration and climate change mitigation.

This work provides a review on the three native coniferous species (*Araucaria hunsteinii*, *A. cunninghamii* and *Agathis robusta*) of *Araucariaceae* of PNG. Specifically, the article highlights the species' natural distributions, flowering and seed characteristics, seed storage and viability, nursery techniques for seedling production, basic silvicultural practices applied in Bulolo and Wau plantations (PNG), and the importance (potential) of the species for developing plantations.

2. Botanical description and natural distribution of *Araucaria* spp. and *Agathis robusta* in Papua New Guinea

The *Araucaria* spp. and *Agathis* spp. come from the *Araucariaceae* family in the order *Araucariales*. The *Araucariaceae* is classified as seed-bearing (vascular) conifers belonging to Phylum *Gymnospermae* [24]. Unlike the angiosperms, the gymnosperms bear arborescent seeds with no enclosing carpellary structure [25]. The *Araucaria* spp. and *Agathis* spp. have male and female flowers (unisexual) in the crown and bear naked seeds in cone-shaped fruits [2]. Whitmore [4] said that the species have characteristics of growing huge in size (50–90 m tall and 2.0–2.5 m diameter) with straight and cylindrical bole as emergent trees in the natural forest canopy (**Figure 1**). The descriptions of tree taxonomy (based on natural stands) and natural distributions of *Araucaria* spp. and *Agathis robusta* in PNG (**Table 2**) are summarized from various literature sources [2, 15–17].

The genus *Araucaria* composes of 19 species and occurs along the eastern coast of Queensland (Australia), eastern half of New Guinea, New Caledonia, Norfolk Island, southern and eastern Chile, Argentina, and southern Brazil [3, 26]. On the other hand, the *Agathis* genus comprise about 20 huge timber trees [27] that have natural distributions in the Philippines, Malaysia, New Guinea, Australia, and New Zealand



Figure 1.
Emergent trees of Araucaria hunsteinii with monopodial crown in a mixed forest of Bulolo.

Taxonomical descriptions	<i>Araucaria hunsteinii</i> (Klinki pine)	<i>Araucaria cunninghamii</i> (Hoop pine)	<i>Agathis robusta</i> (Kauri pine)
Habit/ Characteristics	A very tall tree (93 m height & 2 m diameter) with straight cylindrical bole, which continues to the tip. Branches whorled, horizontal, slender, with long leaf-bearing twigs crowded at the end. Young trees have a pyramidal crown but may change to round or flat tops in older trees.	Tall tree (66 m tall & 2 m diameter) with a straight cylindrical bole, which continues to the tip. Branches whorled, slender, horizontal, with leaf-bearing twigs along the whole length. Crown mostly irregular & sharply pointed in young trees.	A large tree (50 m tall & 2.5 m diameter) with a huge cylindrical bole & broad crown. Young trees with narrow pointed crowns.
Bark	Thickness: 3 cm. Outer bark: dark brown with large pustules & fissures, peeling off in thick corky flakes. Inner bark: red to pink, fibrous near the wood tissue, with thick, white resinous exudate.	Thickness: 3 cm. Outer bark: dark red-brown, rough, peeling off in papery layers, which often cling to the bole. Inner bark: brown & white, mottled, with thick, white resinous exudate.	Thickness: 2 cm. Outer bark: rusty brown, craterous & pustular, peeling off in rounded flakes. Inner bark: pink with thick, white exudate, corky, non-fibrous.
Wood	Straw colored with pink tinge, soft & light, non-porous with fine rays.	Straw colored, fairly soft & light, non-porous with fine rays & uniform texture.	Pink to light brown, soft & light, non-porous with narrow rays & fine texture.

Taxonomical descriptions	<i>Araucaria hunstenii</i> (Klinki pine)	<i>Araucaria cunninghamii</i> (Hoop pine)	<i>Agathis robusta</i> (Kauri pine)
Leaves	On shaded young trees: distichous, 3 cm long, relatively thin & lanceolate. On matured trees: crowded around the branches, thick, coriaceous, broadly lanceolate & 10 cm long. Both surfaces are glossy, medium to dark green.	On shaded young trees: spreading almost distichous, 2 cm long, sharp & pointed. On matured trees: shorter (1 cm) crowded, overlapping & awl shaped.	Sub-opposite. Almost without petioles, narrowly elliptical (8 × 2 cm) thick coriaceous, parallel venation, glabrous light green. The terminal bud is rounded & has pointed buds.
Flowers	Male flowers on lower branches, in pendulous spikes (15 cm long), consists of papery scales covering anthers; light green in color. Female flowers on upper branches, in short spikes & consists of pointed scales covering the ovules.	Male flowers on thin hanging branches in the lower part of the crown, in spikes (5 cm long). Cylindrical, composed of scales & anthers. Female flowers erect on the uppermost branches in small (2 cm long) spikes, consists of sharp pointed scales & ovules.	Male flowers in axillary spikes. Spikes ovoidal to cylindrical, consists of papery scales & anthers. Female flowers in short spikes, consists of blunt scales & ovules.
Fruit	A large cone, broadly ovoid (20 cm long & 12 cm broad), consists of numerous leathery, winged scales, with sharp points. Seeds (2 cm long) are contained in scale, with broad tip & pointed base, starchy.	An ovoid cone (7 cm diameter) composed of woody, winged scales, with sharp points, which contain the seeds.	A near-globose cone, which consists of spirally arranged woody scales & seeds. Scales blunt, seeds separate from scales, thin, with coat extended into 1 or 2 wings.
Habitat	In the mountains of Eastern New Guinea, especially on softer slopes of lower montane rain forests. Mostly occurs between 660 and 1650 m above sea level.	Throughout the mainland New Guinea & islands of Milne Bay Province, mainly on the ridges of upper (mid) montane rain forests. Mostly occurs between 1000 and 2300 m above sea level.	In the mountains of mainland New Guinea & New Britain island (Pomio). Occurs mostly between 660 and 1980 m above sea level.
Natural distribution (PNG)	It is found in Bulolo, Watut, and Waria Districts (Morobe Province); border valleys of Whagi (Western Highlands) & Jimi (Jiwaka); and borders of Eastern Highlands & Morobe Provinces.	Heads of Sepik River (Ambunti, East Sepik Province).	Inland Pomio (East New Britain Province). Occurs at 2000 m altitude in Watut, Morobe Province.

Table 2.
Taxonomical/botanical descriptions and natural distributions in PNG.

[3, 17, 26]. According to Whitmore [27], the genus *Araucaria* (18 species) and *Agathis* (13 species) compose the *Araucariaceae*, whereby the *Agathis* spp. has wide distributions than the *Araucaria* spp. In the tropical rain forest of the Far East (**Table 1**).

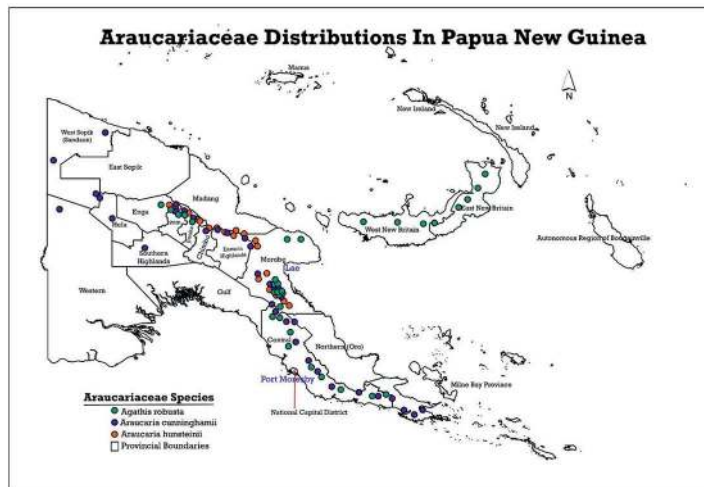


Figure 2.
Map showing the distribution of three species of Araucariaceae in Papua New Guinea.



Figure 3.
A stand of Araucaria cunninghamii at Bulolo University College.

The three coniferous species *Araucaria hunsteinii*, *A. cunninghamii*, and *Agathis robusta* are endemic in PNG, and their distributions are indicated on the map (**Figure 2**). *A. hunsteinii* grows at altitudes between 500 and 2100 m in primary forests and are distributed mainly in Bulolo, Wau, Watut, and Waria (Morobe Province); Jimi Valleys (Jiwaka Province); and Central and Western Highlands Provinces (**Figure 1**). Meanwhile, *A. cunninghamii* is scattered along the eastern coast of Australia (northern New South Wales to north-eastern Queensland) and New Guinea (**Figure 3**). In PNG, *A. cunninghamii* occurs at altitudes between 600 and 1500 m often in sub-montane forests on leached soils in association with *Podocarpus neriifolius*, *Prumnopitys amara*, and *Castanopsis acuminatissima*. On the other hand, *Agathis robusta* occurs at altitudes between 700 and 2000 m in mainland New Guinea, for example, Watut in Morobe Province, and in New Britain Island, for example, Pomio in East New Britain Province [2, 15, 17]. The cultivated stands of *A. robusta* are shown (**Figures 4 and 5**).



Figure 4.
A stand of *Agathis robusta* at Bulolo University College.



Figure 5.
An unthinned plot of Agathis robusta at Bulolo plantation.

3. Flowering and fruiting

The flowering and fruiting seasons and the characteristics of the three pines (*Araucaria hunsteinii*, *A. cunninghamii* and *Agathis robusta*) differ between the species and between different geographical localities. The species are reproduced sexually via pollination mainly by the wind. For instance, in *Araucaria hunsteinii*, the pollen from the male flowers on lower branches in pendulous spikes are carried by the wind to the ovules of the female flowers on the upper branches on short spikes [16]. In Bulolo and Wau, flowering begins from January to March, and the cones mature at the end of dry season (September to October) per year. On average, a single cone weighs *ca.* 850 g with 117 viable seeds, which produces approximately 5000–6000 seeds per kilogram (**Figure 6B**). Meanwhile in *A. cunninghamii*, flowering occurs between March and June every year. The fruit, in a single cone, matures from October to December for



Figure 6.
Clean viable seeds: (A) *Araucaria cunninghamii* and (B) *Araucaria hunsteinii*.

collection. The mature cone weighs *ca.* 200 g with 260 seeds, which yields between 4000 and 5000 seeds per kilogram [17]. In addition, Laufenfels [3] noted that individual trees of *Araucaria* spp. can produce >500 cones per year. Later in the year, the cones become ready (ripen), and winged seeds are dispersed early in wet seasons (**Figure 6A**). In contrast to 260 seeds produced per mature cone [17], Laufenfels [3] reported 800 seeds contained in a cone. The difference in the number of seeds produced per cone is suggested to be due to the size of cones from which seeds were extracted during the time of seed collection. In this case, the 800 seeds may have been extracted from larger cones sourced from the natural forest (old-growth) stands in the 1950s [3] compared to 260 seeds derived from the cones of plantation stands [17].



Figure 7.
Clean viable seeds of *Agathis robusta*.

There is insufficient information available on the flowering and fruiting seasons of *Agathis robusta* in PNG. Whitmore [27] described *Agathis* spp. As monoecious, but female cones are produced before the males. The male strobili are more or less sessile and comprised of a number of bracts that produce the microsporophylls. The female cones are heavily globose and borne on shoot tips with blunt scales, each having a single ovule. At maturity, the cones are shattered where flattened ovoid seeds with wings are dispersed (**Figure 7**).

4. Seed collection, storage, and viability

In PNG, seeds of Araucariaceae are collected from seed trees of natural stands marked out in the field. Often these trees lose their vigor and health, and the ability for seed production declines over time. In order to maintain improved and quality seed sources, the best individual stands (healthy and defect-free) of *Araucaria* spp. and *Agathis robusta* are marked and selected as seed trees in few compartments of the plantations. Usually, thinning is conducted to remove the inferior layer of the stand and allow the superior layer of the stand to grow as seed trees for improving seed production and sourcing quality seeds. These seed trees in the compartment are not managed as part of a seed orchard as the seed trees are harvested during clear-cut operations. And, new seed trees are marked in established compartments. This is unlike other countries where seed orchards are permanently established and managed from genetically improved stands for the mass production of quality seeds [28].

4.1 Preparation of *Araucaria hunsteinii* seeds

The time for cone maturity and seed shedding is usually short; thus, it is important to understand cone maturity and plan seed collection promptly on time. The following methods are used to determine cone maturity: (1) the embryo should be 16 cm long with a well-developed and hard endosperm; (2) cut the tip of the cone to observe the brown color on the cone's scale; and (3) use weight, as mature cones are usually lighter than immature cones. Cones are collected immediately using hooks attached to a bamboo pole, or use ladders to climb and collect cones from orchards or parent trees. Cones are transported in copra sack bags to an extraction shed and dried for 2–3 weeks on open racks or stored in bags for a week (note: longer storage in bags can result in fungal infestations). As the cone dries, it disintegrates into individual scales, making it easy for hand separation. The seed is de-winged by hand and dried for a week before storage. The matured seeds are recalcitrant with >53% moisture content (MC) and can tolerate desiccation below 32% MC during storage (**Figure 6B**). Seed viability reduces to zero after 4 weeks when stored at 25°C; however, viability can be maintained for 6–18 months if seeds are kept in air-tight containers at a constant temperature of 3–6°C [17]. For example, Evans [19] reported seed viability up to 8 weeks, while Havel [29] observed 50% seed survival for 18 months when stored in moist conditions in a sealed container. Next, McKinty [11] added that the seeds of *A. hunsteinii* lose viability at a rate of 10–12% per week.

4.2 Preparation of *Araucaria cunninghamii* seeds

The matured cones are collected before they open while on the trees. A hook is attached to a pole to dislodge the cones. Cone maturity is determined by cutting

slightly the tip of the sample cone with a sharp knife where a dark gray–brown color indicates maturity. Also, full-sized dark green cones are considered mature and are collected. The cones are then air-dried by spreading on trays for 2–3 weeks under a heavy shade. The wings are moved with hands using gloves and a wire screen. Other cleaning techniques are winnowing or the use of domestic electric fans to separate light materials from the seeds. The seeds are orthodox unlike their counterpart *Araucaria hunsteinii* (**Figure 6A**). The matured seeds have 23% MC at the initial stage and can dry to 2% MC without damage. Seeds are stored best in a refrigerator (-18°C) where they can be stored for up to 6 years. Meanwhile, seeds placed in copra sack bags or in air-tight containers can be stored at -10°C for up to 3 years. Additionally, the fresh seeds have 75–80% viability [11, 17, 29].

4.3 Preparation *Agathis robusta* seeds

There is little information available on its flowering/fruiting phenology, seed preparation, and viability in PNG. According to PNGFA's National Tree Seed Centre (Bulolo, Morobe Province), *A. robusta* flowers every 6 months per year, and fruits are harvested from January to March in the same year. Tree climbers use ladders to climb the parent tree and use hooks to dislodge the cones. The collected fruits are dried in the open where cone scales are disintegrated, and seeds fall off (**Figure 7**). The seeds are separated by hand and winnowed before storage. The orthodox seeds are best stored in a refrigerator at a temperature of 3.5°C immediately as the seeds lose viability rapidly at ambient temperatures. Elsewhere in New Zealand, there could be documentation on the *Agathis australis* with regard to seed collection, preparation, and storage techniques as well as tests for viability [3, 5, 12, 27].

5. Plantation development and management with reference to Bulolo and Wau projects

Iverson et al. [30] reported that the plantation of *Araucaria* spp. began in Bulolo and Wau districts of Morobe Province after the gold discovery and extraction in the 1960s in Bulolo Valley during the Australian colonial administration of the Territory of New Guinea. As the gold deposit was depleting, a Canadian gold mining company (Bulolo Gold Dredging Ltd), which was renamed Commonwealth New Guinea Timbers Ltd. (CNGT), ventured into the timber-processing industry. The pure stands of *Araucaria* spp. in the Bulolo Valley were harvested for veneer production for plywood manufacture in the 1950s. The plantations of *Araucaria* spp. in Bulolo and Wau districts began in the 1950s, and the plantation capacity increased in the 1960s in order to maintain the raw material supply and sustain the plywood-making industry. CNGT was later changed to PNG Forest Products Ltd. in the 1970s and established as a sawmill complex (alongside the existing plymill) where plantation raw materials (*Araucaria* spp.) were fed for sawn boards and pole productions while maintaining plywood making [30].

Presently, the state through the PNGFA owns and manages 12,000 ha of pine plantations at Bulolo and Wau districts of Morobe Province. The plantations are composed of three major species: *Araucaria cunninghamii*, *A. hunsteinii* and *Agathis robusta* (including exotic *Pinus caribaea*). A few area (ha) is planted with *Agathis robusta* within the plantations due to inadequate knowledge about its silviculture and longer cutting cycle as compared to *Araucaria* spp. However, *A. robusta* has huge potential

for commercial cultivation on a plantation scale for veneer and lumber production given the favorable environmental conditions in PNG. Apart from Bulolo and Wau plantations, a few compartments of *Araucaria cunninghamii* can be found in Lapegu and Kainantu state-owned plantations in the Eastern Highlands Province (PNG). According to the PNGFA's Corporate Plan 2021–2030, the annual target of the plantation management is to raise 500,000 seedlings of *Araucaria* spp., reforest 330 ha, and harvest 100,000 m³ volume of raw materials [23]. The PNGFA regards Bulolo and Wau monoculture plantations as a model project, and the project anticipates to achieve sustainable yield and high economic return on investment with prudent management and application of appropriate silvicultural practices.

5.1 Nursery techniques: propagation and management

The Bulolo and Wau plantations' nursery is designed to hold 800,000 plus seedlings of high quality (premium 'A' grade) at any one time per annum (**Figures 8 and 9**). Some specific tasks of the nursery management are to: (1) ensure seed tree locations are well-defined and take necessary measures to protect them (in order to protect gene erosion); (2) supervise collection, extraction, drying, and storage of seeds; (3) plan and implement nursery production of healthy seedlings to meet the target and on schedule; and (4) ensure high quality (disease-free) seedlings are dispatched for reforestation and afforestation activities. The major nursery activities undertaken in order to produce high quality materials for plantation establishments include seed and soil collections, seedling production, and seedling maintenance [17, 28].

Seed collection. Seeds are collected from parent trees marked out in the Bulolo and Wau plantations. The viable seeds are stored at PNGFA's National Seed Centre, Bulolo.

Soil collection. The soils for nursery are usually top layer (humus) collected from the mid-montane forest. The soils are sieved and sterilized using fire to eliminate



Figure 8.
Araucaria cunninghamii seedlings stored under a shed in stand-out beds, Bulolo plantation.



Figure 9.
Saloon cloth is removed for seedlings to undergo hardening or culling. Seedlings are ready for out-planting in the field, Bulolo plantation.

unwanted microorganisms that could infect seeds. The sterilized soils are then tubed using small- and medium-sized polythene bags.

Seedling production. The germination sheds and stand-out beds are prepared in advance to accommodate polythene tubes for germination. The propagation of Araucariaceae is from seeds through direct or broadcast sowing methods. In direct sowing, the seeds are directly sown into the tubes and allowed germination under sheds. Alternatively, the viable seeds are spread on the plastic trays with sterilized soils and allowed for germination under sheds (**Figure 8**). Gunn et al. [17] pointed out that fresh seeds of *Araucaria cunninghamii* take 12–20 days to germinate. The germinated seedlings are then plucked out carefully and transplanted into the polythene tubes. The tubes (with seeds or seedlings) are lightly sprinkled with water to encourage germination.

- **Seedling maintenance.** The following maintenance activities are conducted in the germination sheds (green houses) and stand-out beds for seedling production.
- **Weeding**—light weeding (0–5 months), medium or high weeding (5 months plus)
- **Fertilizer applications**—3–4 g of inorganic fertilizers (NPK and boron) are applied to boost plant growth at the juvenile stage.
- **Shifting seedlings**—after 2–3 months in the germination shed or green house, the seedlings are shifted to stand-out beds for hardening and culling processes.
- **Hardening/Culling/Sorting**—seedlings are allowed to undergo hardening and culling (**Figure 9**). Dead seedlings are removed, seedlings are graded (A, B, and

C), and slow-growing seedlings (B and C) are separated and treated with fertilizer to boost their growths. Seedlings can be in the stand-out beds for 1–2 years until they reach transplantable size.

- Root pruning—tap roots that protrude out at the base of the polythene bags are pruned to avoid root coiling. Coiled root seedlings when out-planted in the field are subject to fall over (or uprooting) due to shallow penetration of the root systems (shallow rooting-habit) to withstand wind-throw incidents.
- Pest and disease control—a synthetic pesticide (from Blitz chemical group) is applied to control snails that feed on young leaves of seedlings. Pesticides are applied to control insect pests (especially leaf chewing or defoliating insects) and fungi that cause blights and root rots.
- Irrigation—continuous sprinkling of water is done on a daily basis. A good time for watering seedlings is in the mornings (7:00–10:00 AM). Watering is also done in the afternoons, particularly during prolonged dry periods [28].

5.2 Establishment of plantations

The current management of Bulolo and Wau plantations applies 3×4 m spacing (12 m^2 per tree) for *Araucaria* spp. and *Agathis robusta* to attain 833 trees per hectare (ha) as initial stocking during establishment (**Figure 10**). Prior to planting,



Figure 10. Three-year-old second rotation *Araucaria cunninghamii* crops, Bulolo plantation. Note the line tending done to control spontaneous vegetation, which will shade the young crops.

site preparatory works such as soil mobilization and brushing of vegetation are not usually conducted. Seedlings are immediately planted after a clear-cut operation when the site is cleared from the regrowth of vegetation for reforestation activity. For afforestation, brushing of spontaneous vegetation and control burning are done as site-preparation activities before planting. Most field plantings are planned and executed during rainy seasons to achieve a high survival rate with low mortality. After 4–5 weeks, tree survival counts are conducted for dead trees (mortality) at planted sites and replaced with new seedlings. Mortality count and subsequent replacement are important for maintaining the initial stocking (833 trees/ha) in the compartments.

5.3 Application of silvicultural treatments and harvesting cycle

The main silvicultural treatments applied in plantations after establishments are tending, pruning, application of fertilizer and pesticide, and thinning operations. These treatments are given in order to improve growth performances of the stands and increase crop yield and productivity. The tending operations (clear and line brushing) are scheduled between 1 and 5 years of planting. The *Araucaria* spp. are often self-pruned; however, low pruning can be conducted together with line brushing at an early age. Occasionally, synthetic fertilizer (N, P, K, Mg or B) is applied when trees in certain compartments indicate symptoms of deficiency (yellowing of leaves, stunted growth) of certain macro nutrients. Likewise, pesticide is applied to young trees that show signs of termite (*Coptotermes elisae*) attack as a chemical control measure.

As per the current Bulolo and Wau plantation management decision, moderate-to heavy-intensity thinning activities are scheduled at the age of 5–20 years for the plantations in which non-commercial (thin-to-waste) thinning is conducted (5–7 years old), followed by commercial thinning (17–20 years old) and final harvest (35–40 years old). In thinning operations, theoretically, 50% is removed at each thinning interval, that is, non-commercial and commercial thinning until retained *ca.* 200 stems/ha for final harvest (**Figures 11 and 12**). Basically, low thinning or thinning from below is employed for non-commercial thinning where suppressed and intermediate trees are removed. While for commercial thinning, crown thinning or thinning from above is implemented where the intensity of thinning is expressed by specifying the number of stems or basal area (m^2) per ha to remain after thinning [19, 28]. The present practice in thinning is that any tree that falls within the vicinity of 5–6 m radius from a residual stand is selected and removed. Types of thinning, age and their schedules, average diameter, residual stock, and estimated volume are provided (**Table 3**). The unthinned plots of *Araucaria hunsteinii* and *Agathis rubusta* are shown in **Figures 5 and 13**, respectively. Under the old management of the 1980s, the rotation age of *Araucaria* spp. was 35–40 years; however, the current management decides to allow one commercial thinning only (after non-commercial thinning) and retain the stocking of 200 stems/ha for the final harvest. The non-commercial and commercial thinning treatments create optimum conditions that stimulate prolific growths in residual stocks to reach harvestable size (*ca.* 55 cm diameter-breast-height on average) at 25–30 years (**Figure 14**).

As per the records of CNGT in the 1970s, the mean annual increment (MAI) for *Araucaria* spp. was $20 \text{ m}^3/\text{ha}/\text{year}$ at 40 years of rotation age [19]. According to present Bulolo and Wau plantation management practices, an average of 1.0 m height and 2.0 cm diameter growth increments are attained annually with prudent silvicultural treatments (nursery techniques, fertilization, brushing of vegetation, vine cutting, pruning, thinning) planned and executed on schedule (**Table 3**).



Figure 11.
Commercial thinned compartment with 208 stems/ha as residual stock for final harvest, Bulolo plantation.



Figure 12.
Commercial thinning materials are stored at a landing awaiting log trucks for hauling, Bulolo plantation.

Treatment	Trees/ha	TTR ¹	Age ²	EAD ³	FSH ⁴	EVH ⁵
Non-commercial thin	833	50	5–7	10–15	416	5.522
Commercial thin	416	50	17–20	30–35	208	17.790
Clear cut	208	100	35–40	40–45	Nil	30.206

¹TTR—Theoretical tree removal (%), ²Age (years), ³EAD—Estimated average diameter (cm), ⁴FSH—Final stocking (trees/ha), ⁵EVH—Estimated volume (m³/ha).

Table 3.
Thinning schedules, stocking and final harvest of Araucaria spp.



Figure 13.
An unthinned plot of Araucaria hunsteinii at Bulolo University College.

5.4 Final harvest and utilization

As far as harvesting and utilization are concerned, the current plantation management allows an annual allowable cut (AAC) of 63,000 m³ and 18,000 m³ from clear-cut (clear-fell) and commercial thinning operations, respectively, from its 12,000 ha forests. These volumes of raw materials (logs) are derived from various compartments of the plantation based on individual compartment history, that



Figure 14.
*A compartment of *Araucaria cunninghamii* due for clear-cut, Bulolo plantation.*

is, compartment scheduled for commercial thinning or clear-fell operations. The clear-cut materials are processed into veneer products for plywood manufacturing, while the thinning materials are converted into lumber products. In particular, the *Araucaria hunsteinii* (Klinkii pine) is managed for specific end uses, for example, core veneer in composing plywood and poles for electricity transmission. The *Araucaria* spp. poles and sawn boards are seasoned, machined, and pressure-impregnated with waterborne copper-based preservatives (copper chromium arsenic and alkaline copper quaternary) prior to marketing and utilization [2, 16, 20, 29]. In clear-cut compartments, immediate reforestation with second-cycle *Araucaria* spp. follows suit, while the regrowth of vegetation is still minimal in order to avoid costs involved in heavy brushing and control burning.

5.5 Fire, pests, and disease infestations

The *Araucaria* spp. And *Agathis robusta* are highly susceptible to fire incidents in Bulolo and Wau monoculture plantations. The species are intolerant to fire, with 100% mortality in any fire incidents particularly during the dry season, which falls between the months of June and September per year in PNG. The plantation management is fully equipped with fire-fighting equipment and tools, and the fire-fighting team is always on alert to combat fire. There are three fire lookouts (towers) built at higher locations within the plantations to monitor fire incidents. Any fire incidents are immediately reported to the fire-fighting crews to respond and suppress fire from spreading in the plantations. Huge losses of plantation crops were experienced in 1997 and 1998 El Nino-Southern Oscillation (ENSO) events in PNG [11].

Typical of any monoculture cropping systems, Bulolo and Wau plantations of *Araucaria* spp. are subject to the outbreak of pests and diseases with devastating effects on the crop productivity and economic value. Laufenfels [3] first reported the susceptibility of *Araucaria* spp. from a host of insect pests such as leaf branchlet-mining scolytid, wood-boring weevils, and termites. The major threat to the plantation crops at present is infestations from insect pests, namely *Hylurdreconus araucariae* Schedl. (Coleoptera: Scolitidae) and subterranean termite (*Coptotermes elisae*) Desneux (Isoptera: Rhinotermitidae). Also, Gray and Lamb [31] reported infestation of the leaves of *Araucaria cunninghamii* by *H. araucariae*. According to Schneider [32], the larvae of *H. araucariae* bores into the leaves of *A. cunninghamii* and mines the cortex between the healthy green and wilt yellow or brown area of branchlets. The prime targets are 4–11-year-old crops that are confined to compartments located at cooler climatic conditions. The insect pest gradually kills the hosts (*A. cunninghamii*) over a period of time. On the other hand, subterranean termite (*C. elisae*) enters the hosts (*Araucaria* spp.) via injured roots or bark and bore (tunnel) into the cambium and heartwood (**Figure 15**). Once inside the wood, the termite intensifies its boring activity until killing the hosts. The symptoms on the termite-infested trees include yellowing or browning of tips of branchlets, defoliation at the upper crown, and mud galleries constructed at the base of the trees [32]. Often the main targets are young *A. cunninghamii* crops of 4–10 years old, while *A. hunsteinii* and *Agathis robusta* are unaffected by the termite. Usually, young trees growing under stress or weak trees as a result of disease and wound infliction release a volatile allelochemical (kairomone), which is sensed by the termite to initiate its attack [32]. At the moment, the plantation management applies a termiticide (trade name: Termido) as a chemical control



Figure 15.
Subterranean termite (*Coptotermes elisae*) attack on young *Araucaria cunninghamii* stem, Bulolo plantation.

measure with limited success. The application of Termido is an expensive exercise, and the control of the subterranean termite is difficult due to the fact that the termite colony lives underground and in most cases are unaffected by the termiticide [32]. A biological control measure undertaken now is the burning of tree residues (debris such as branches, tops, and stumps) after log extraction from clear-fell operations, which become a food source for the termite. The biological control measure looks promising, and further research works are required to substantiate the effectiveness of the technique.

6. Conclusion

The three species *Araucaria hunsteinii*, *A. cunninghamii*, and *Agathis robusta* of *Araucariaceae* flowers all year round in the PNG's environmental conditions. The seeds of these conifers have low viabilities and should be kept dry (avoid moisture uptake) during extraction from mature cones and refrigerated immediately at recommended temperatures to maintain the quality. The seeds have good dormancy in cool storage as long as they are kept dry and protected from rodents. The conifers are easily propagated from seeds with low mortality in nurseries if proper nursery techniques are applied to raise seedlings for plantation establishment purposes. The conifers have the ability to adapt well and grow prolifically (with 25–30 years cutting cycle) in Bulolo and Wau environmental conditions, except for *Agathis robusta* where its silviculture and cutting cycle are unknown. This opens up research opportunities for silviculture of *A. robusta* in order to promote the species for plantation cultivation. The species of *Araucariaceae* have excellent working characteristics for lumber, treated poles, and plywood products. In PNG, the importance of the species as plantation crops will be maintained with timely application of silvicultural practices. The only threats to plantation of *Araucaria* spp. are fire and termite attack. Burning of forest biomass left behind after log extraction from clear-cut operations is a promising biological control measure for pest (subterranean termite). The global climate change phenomenon will influence the tree physiological processes (photosynthesis, respiration, phenology of flowering and fruiting characteristics) as well as outbreaks of fire, pests, and diseases in the plantations. For instance, climate change potentially affects biotic and abiotic factors, which in turn causes imbalances in macro/micro climatic conditions, ecological functions, soil properties, and forest hydrology that have direct bearing on tree growth and productivity. For sustainable plantation management in the future, one must have a fair understanding of the effects of climate change so that mitigating strategies can be adopted to address the potential impacts to tree crops.

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Author details

Benson Kumuli Gusamo
Forestry Department, Bulolo University College, PNG University of Technology,
Papua New Guinea

*Address all correspondence to: benson.gusamo@pnguot.ac.pg

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