A Review of *Cunninghamia lanceolata* (Lamb.) Hook: A Recent Update and Potential Application in Vietnam

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Abstract

By reviewing worldwide literature, this paper aimed to systematically collate available information about the species *Cunninghamia lanceolata*. Based on the findings of the review, including the species' floral characteristics; updated distribution; historical knowledge and heritage; growth and factors influencing its forests; soil nutrition and microbes; carbon storage; wood; and chemicals and essential oils, we have identified issues for consideration regarding the use of this species for big timber production in Vietnam. We propose that it is suitable for a range of applications: for small or large timber plantations, mono/mixed plantations, and agroforestry. If planted at lower altitudes or warmer temperatures, its growth is likely to be improved, but seed production may be less successful. Cultivation of this species for big timber production should be undertaken according to silviculture best practices, ensuring good seed quality, a suitable stand density, and appropriate fertilization thinning strategies, in support of government policies and in accordance with current science and technology.

Keywords

Introduction

Woody products are always in high demand in worldwide markets and are linked to the forestry sector which exploits timber from both natural and plantation forests. In the context of climate change, sustainable timber production and forest development are increasingly important at both national and global scales. While a recent 'boom' in the wood processing industry in Vietnam is a positive signal for economic development in this sector, it has also highlighted sustainability issues due to the imbalance between timber plantation productivity and processing capacity. Following decades of depletion

of natural forests, the development of big timber plantations has not been sufficient to keep pace with demand. While about 40 million cubic metres of equivalent round wood volume is required by the processing industry annually (Itto, 2019), timber plantation development has not yet met the target of 290,000 ha (Vietnam Gov, 2017), and only 40,000 cubic metres of legal raw timber is being provided annually by domestic forests (VOV, 2017).

Of the fourteen big trees included in legislation (namely *Eucalyptus camaldulensis, Eucalyptus* hybrid, *Eucalyptus urophylla, Dipterocarpus alatus, Acacia mangium, Acacia auriculiformis, Acacia hybrid, Mangletia conifera, Cunninghamia lanceolata, Hopea odorata, Pinus massoniana, Pinus kesiya, Melaleuca leucadendra,* and *Melaleuca cajuputi*), only six are native species *(*MARD, 2018*)*, one of which is *C. lanceolata*. However, the current understanding of *C. lanceolata* and other native species for big timber plantations is seriously limited.

Before the 1990s, a large area of natural *C. lanceolata* was explored for big timber in the Northern regions of Vietnam, but growers and researchers were not interested in this species. As such, research results and published literature regarding *C. lanceolata* are very poor. Therefore, this review has investigated worldwide literature to systematically collate information that will significantly improve the understanding of this species for study, research, and its application for timber production in Vietnam.

Worldwide overview

Classification of C. *lanceolata*

Commonly called Chinese fir in English, this species is currently distributed naturally in the sub-tropical regions of China. Older records indicate that it was previously also naturally occurring in Vietnam and Laos, and refer to it with the scientific names *Cunninghamia lanceolata* (Lamb.) Hook. (Wcsp, 1827), *Cunninghamia konishii* (Wcsp, 1908), and *Cunninghamia lanceolata* var. *konishii* (Wcsp, 1932). Karyotype tests revealed that *Cunninghamia konishii, Cunninghamia lanceolata,* and *Taiwania cryptomerioides* were all members of *Taxodiaceae* (Schlarbaum & Tsuchiya, 1984; Chung *et al.*, 2004). In Vietnam, it is called "Samoc" or "Samu" and currently exists in two varieties, namely *C. lanceolata* (Lamb.) Hook. var. *lanceolata* and *C. lanceolata* (Lamb.) Hook. var. *konishii* (Hayata) Fujita (Pham *et al.*, 2013). Particularly, *C. lanceolata* var. *konishii* was recently reviewed and recorded as one of 33 species, 2 subspecies, and 5 varieties of native conifers belonging to 5 families and 19 genera found in Vietnam (Phan *et al.*, 2017).

Distribution and adaptation to climate change of C. *lanceolata*

Recently, Chinese fir was recorded occurring as an introduced plant in many countries around the world (**Figure 1**), and used mostly for landscaping and horticulture. Outside of China, there are several academic records concerning this species with regard to commercial plantations (e.g. in New Zealand (Fung, 1993b; Fung, 1993a); and in Brazil (Heinsdijk, 1972; Wadsworth, 1997)).

In Vietnam, natural populations of *C. lanceolata* var. *konishii* were previously found at Tay Con Linh in Ha Giang Province, Xuan Lien in Thanh Hoa Province, and Pu Hoat, Phu Huong, and Pu Mat in Nghe An Province (Vietnam Plant Data Center, 2009).

To determine whether the distribution and productivity of *C. lanceolata* is being affected as a result of climate change, the research team of Lu *et al.* (2015) applied process-based growth models to predict its distribution and productivity. The results indicated a northward shift from the tree's current range. The growth model also revealed minor increases in productivity in some of the existing distribution areas, particularly in central China, and attributed this to the warmer climate (Lu *et al.*, 2015). Other similar results also suggest that climate change will lead to a modest increase in long-term stem wood biomass production (6.1% to 12.1% increase after 30 to 60 years). Thus, climate change could have a positive impact because of both a lengthening of the growing season and an

Figure 1. Distribution map of *C. lanceolata* around the world
Source: Farjon (2010)

increase in nutrient-cycling rates, likely contributing to the increasing growth rate of the species' trees (Kang *et al.*, 2017).

History and heritage of C. *lanceolata*

Open-pollinated seeds were tested for allozyme polymorphisms at 24 loci to assess the genetic diversity and multilocus associations in 16 populations of *C. lanceolata*. The results revealed that population subdivision, the founder effect, occurrences across diverse environments, a mating system dominated by inbreeding, and historical events from 2000 years of cultivation in China were likely factors in the generation and maintenance of the multilocus genetic structure in this conifer species (Yeh *et al.*, 1994).

A record indicated that traditional Chinese afforestation and reforestation systems using *C. lanceolata* seedlings grown from rooted cuttings have been widely implemented for at least 800 years. In addition, vast local knowledge of how best to grow this species has been passed down through many generations, establishing successful methods of extensive site preparation, wide spacing, interplanting with crops, planting in mosaics of small-family or clonal blocks, small-block clear-cut harvesting, and

regenerating with cuttings, stecklings, and stump sprouts (Minghe & Ritchie, 1999).

In Vietnam, *C. lanceolata* var. *konishii* grows naturally in Pu Hoat Nature Reserve, Nghe An Province, located at 19o52' N, 104o56' E (Nguyen Danh Hung *et al.*, 2017). Here there are still existing populations with very big trunks, including one Heritage Tree recorded with a diameter at breast height (DBH) of 540cm and a height of 70m, estimated to be about 2000 years old (Nguyen Dinh Vo, 2017).

Growth and factors affecting C. *Lanceolata* forests

Worldwide, dozens of literature articles have been published in English, recording the results of studies on the growth and factors impacting C. *lanceolata* plantations/forests undertaken by Chinese scientists. A study on the early regeneration stages of two major coniferous species (*P. massoniana* and *C. lanceolata*) in a secondary mixed coniferous plantation explained that *C. lanceolata* was likely to deliver better growth of the main stem when it was shaded (Cheng *et al.*, 2011). Furthermore, a report indicated that the germination of *C. lanceolata* seeds is poor in natural regeneration, possibly due to low light and a thick litter layer. Research to investigate how to improve the species' natural

regeneration capacity revealed that seedling emergence was highest at 5-15% sunlight, whereas seedling height, root length, root mass, stem mass, leaf mass, and total mass were greatest at 60% sunlight and that thinning significantly increased the success of natural regeneration (Liu *et al.*, 2018).

In natural ecosystems, many factors interact to impact individual or/and populations of plants. Dozens of studies have been conducted to investigate the factors influencing *C. lanceolata* forests. First, increased mean temperatures were shown to promote better growth performance of *C. lanceolata* populations, which then exhibited the greatest germination capacity. *C. lanceolata* within the southern population were better adapted to extremely high temperatures than specimens from the northern region population (Zhou *et al.*, 2016). Second, topography influenced the dominant stand height of *C. lanceolata*, with elevation being the most significant factor, followed by soil type, aspect, and slope (Zhu *et al.*, 2019). Third, the structural characteristics of the tree crowns of *C. lanceolata* were such that leaf biomass increased with the crown thickness (Xu *et al.*, 2019), and that related to thinning due to the effects of photosynthesis which is dependent on needle-leaf age (Li *et al.*, 2017). The self-thinning exponents of *C. lanceolata* changed systematically with the mortality rate classes, and −1.5 was a transitory value in the course of self-thinning (Sun *et al.*, 2011). The self-thinning exponent of organs was estimated to be 1.42 for stems, 0.93 for branches, 0.96 for leaves, 1.35 for roots, and 1.28 for shoots, indicating that the thinning exponents of trees, branches, leaves and roots of *C. lanceolata* were significantly lower than 3/2 (Xue *et al.*, 2015). Tree mortality, related to the thinning of trees, is an important process during forest succession, influencing forest structure, composition, and ecosystem services. One study showed that the age and structure variables had a much larger impact on mortality (88.82%) than climate variables (11.18%) (Zhang *et al.*, 2020). However, *C. lanceolata* tree growth rates did not respond to pruning, understory removal, or their interactions. In addition, foliar photosynthesis did not exhibit changes following understory removal in either pruned or unpruned stands (Li *et al.*, 2020). Last, the model results of Bi et al. (2007) suggested that yield decline is caused primarily by a decline in soil fertility, largely as a consequence of slash burning in conjunction with short rotations. Importantly, another study indicated that mixed *C. lanceolata* plantations could improve the soil quality, especially for chemical properties (Zhou *et al.*, 2020)

Regarding growth ring width, *C. lanceolata* is a rapid growth species, therefore, a study of the molecular mechanisms underlying growth alteration due to vascular cambium activity indicated that various cambium-related molecular activities result in alterations in the growth of *C. lanceolata*, particularly during the transition from juvenile to mature stages *(Xu et al.*, 2016). Furthermore, the average growth ring width of *C. lanceolata* was in inverse proportion to the density, modulus of elasticity (MOE), and modulus of rupture (MOR) of the dimension of the lumber (Jiang *et al.*, 2010).

Soil nutrition and microbial of C. *Lanceolata* forests

The results of He *et al.* (2007) showed that after a native broadleaved forest was replaced by a mono-cultured *C. lanceolata* plantation, the soil microbial biomass and nutrient pool decreased significantly due to less litter and a slower decay rate associated with human disturbance. The mean annual litter production of monoculture *C. lanceolata* stands was significantly (24%) lower than mixed stands of *C. lanceolata* and *M. macclurei* (Wang *et al.*, 2008). However, there was no significant difference in litter decomposition rates between these different habitats (Wang *et al.*, 2009). Other results showed that successive rotations of *C. lanceolata* notably decreased the quantity of total soil organic carbon (SOC), recalcitrant fraction, carbohydrates, and microbial properties, especially at the 0-10cm horizon (Zhang *et al.*, 2009). With *C. lanceolata* plantations aged 10, 22, and 34 years, annual litterfall production increased with stand age and was 3.29 ($\pm$ 0.36), 3.73 ($\pm$ 0.21), and 4.88 ($\pm$ 0.21) tons ha^{-1} a^{-1}, respectively.

Generally, the annual total nutrient return to the soil was in the order of 1.12-2.71 tons ha^{-1} a^{-1} for calcium (C), 39.32-62.04 kg ha^{-1} a^{-1} for nitrogen (N), 15.95-22.44 kg ha^{-1} a^{-1} for potassium (K), and 1.30-1.63 kg ha^{-1} a^{-1} for phosphorus (P) (Zhou *et al.*, 2015). In addition, soil nutrition changed from N-limiting to P-limiting conditions, and the nutrient-use strategy changed from "conservative consumption" to "resource spending" of plantations at the ages of 3, 8-11, 16, 20, 25, 29, and 32 years (Wu *et al.*, 2020).

Forest biomass was used as a proxy for soil conditions. One study explained the negative relationships between the cyclic dipeptide concentration, microbial community composition, and root biomass (Xia *et al.*, 2015). Similarly, another study showed that the fine root biomass of trees and understory vegetation were significantly and negatively correlated with forest biomass, but the results clearly demonstrated that fine tree root biomass was significantly promoted and increased due to competition from understory vegetation where forest biomass is low (Liao *et al.*, 2019). Furthermore, understory vegetation had more influence on the microbial activities than on the substrate affinities of extracellular hydrolases. Microbes tended to concentrate on maintaining catalytic efficiency when the SOC contents were between 15.8 and 20.3 g kg^{-1} and when the understory vegetation was removed, but the catalytic efficiency could decrease under extremely low soil C content. So, understory vegetation should be maintained to sustain the potential microbial activity in *C. lanceolata* forests (Yang *et al.*, 2019). On the other hand, warming and N deposition were important aspects of environmental change affecting plants, microbes, and soil processes, thus warming, regardless of N addition, significantly decreased arbuscular mycorrhizal (AM) fungal diversity and altered AM fungal community composition, while a N addition alone had only minor effects (Cao *et al.*, 2020).

Carbon storage of C. *Lanceolata* forests

Tree plantations contribute towards balancing global carbon and nitrogen cycles, so large plantations of *C. lanceolata* could have an important role in mitigating climate change. Carbon accumulation and distribution conducted on a 13-year-old mixed plantation of *P. massoniana* and *C. lanceolata* showed that the annual net productivity of the mixed plantation was 11.46 t hm^{-2} a^{-1}, and that of sequestered carbon was 5.96 t hm^{-2} a^{-1}, which was equivalent to fixing carbon dioxide (CO_2) of 21.88 t hm^{-2} a^{-1} (Kang *et al.*, 2006). With a 22-year-old *C. lanceolata* plantation, carbon stored both above- and below-ground was 154.3 tons hm^{-2}, and most of the carbon was in the soil pool (accounting for 55.2%) (Niu *et al.*, 2009). Other results showed about 35-45% of equivalent SOC stocks in the upper soil layer (0-20cm) in stands of all ages, indicating more organic carbon accumulation in the surface layer compared to subsurface layers (> 20cm) (Selvaraj *et al.*, 2017). Comparing *C. lanceolata* plantations (23-32-year-old) with evergreen broadleaved forests (40-100-year-old), soil carbon stocks showed no variation, but in younger *C. lanceolata* plantations carbon stocks were much less (Chen *et al.*, 2017). Annual carbon return to soil was 1.12-2.71 tons ha^{-1} a^{-1} (Zhou *et al.*, 2015). Moreover, other papers' results highlighted that understory removal in thinned stands did not exacerbate soil carbon emission within the plantation (Li *et al.*, 2019a), while the response of heterotrophic (Rh) and autotrophic (Ra) components of soil respiration (Rs) to fertilization was important to evaluate the effects of management practices on soil carbon cycling within young *C. lanceolata* plantations (Wang *et al.*, 2017).

Wood study of C. *lanceolata*

A study of the mechanical and physical wood properties of New Zealand-grown *C. lanceolata* showed the tree's dimensional stability, ease of drying, and reputed durability could allow it to be used in applications such as weatherboarding, paneling, and joinery (Fung, 1993b). Another study on the pattern of variation of wood properties of natural *C. lanceolata* suggested that the results could provide a theoretical scientific basis for wood utilization and early prediction of wood properties (Mnghui, 1996). Using *Postia placenta* and *Trametes*

versicolor as the testing models, the decay of *C. lanceolata* wood showed 34% of mass loss, indicating that it should be classified as slightly durable or non-durable wood and would be classified as moderately resistant (Xing *et al.*, 2005). Testing specimens with different ratios of heartwood thickness to sapwood thickness under radial compression at different compression speeds revealed a consistent tendency of the density distribution and the copper retention along the thickness direction, and showed the layers with higher density having smaller volumes of void areas, and more chemicals absorbed and fixed than in the higher copper retentions (Mao *et al.*, 2009). Using vacuum impregnation and characterizing with x-ray powder diffraction (XRD), scanning electron microscope (SEM), Fourier transform infrared spectroscopy (FTIR), and thermogravimetry-differential termal analysis (TG-DTA) analyses, the XRD analysis of *C. lanceolata* wood indicated that the wood crystallinity of wood/MMT nanocomposites (WMNC) decreased, the montmorillonite (MMT) exfoliated, and some nano silicate layers entered into the non-crystallized microfibrillar region of the wood cell wall (Lü & Zhao, 2008). To establish the method of evaluating wood mechanical properties by acoustic nondestructive testing of standing trees and logs of a *C. lanceolata* plantation, a study concluded that longitudinal vibration may be the most precise and reliable technique to evaluate the mechanical properties of logs among three acoustic nondestructive methods (Yin *et al.*, 2010). Furthermore, literature also has recoded that the red-heart wood ratio of C. lanceolate ranges from 50.5% to 80% in mature forests (Deng *et al.*, 2018; Li *et al.*, 2019b).

Chemicals and essential oils of C. *lanceolata*

Studies of the chemical composition of substances extracted from *C. lanceolata* have been undertaken for several decades (Zhou *et al.*, 1997). A recent study of the chemical composition and olfactory description of the essential oil of *C. lanceolata* showed the main compounds in its oil included cedrol (26.3%), α-terpineol (24.1%), and camphor (7.0%) (Schmidt

et al., 2016). The main constituents of wood essential oil extracted from *C. konishii* Hayata were cedrol (53.03%) and α-pinene (25.57%); and the constituents of leaf essential oil were α-pinene (34.89%), *p*-cymene (16.66%), and γ-muurolene (11.35%) (Cheng *et al.*, 2013). Obtained by steam distillation, the yield of essential oil from *C. konishii* Hayata in Vietnam was 0.18% from leaves and 0.21% from wood, while the major essential constituents of these two samples oils from leaves and wood, respectively, were: α-cedrol (30.6% and 23.5%), β-eudesmol (25.4% and 0.8%), (E)-nerolidol (5.4% and 12.5%), γ-eudesmol (10.9% and 11.2%), and β-caryophyllene (0.5% and 9.5%) (Nguyen Danh Hung *et al.*, 2017).

The essential oil of *C. lanceolata*, even at low concentrations, presented fair antifungal activities against two white-rot fungi, *Trametes versicolor* and *Irpex lacteus*, and two brown-rot fungi, *Postia placenta* and *Gloeophyllum trabeum*. The oil's phenols and antifungal compounds also played a role in resistance to wood decay (Wang *et al.*, 2011).

In addition, crude alcoholic plant extract (APE) from *C. lanceolata* was also tested and showed the presence of proteins (17.7 mg mL^{-1}), flavonoids (2.35 mg mL^{-1}), and phenols (0.19 mg mL^{-1}). This crude APE from C. lanceolata was found to be useful against *Klebsiella pneumoniae* with a maximum observed zone of clearance being 23.6mm, while the MIC (minimum inhibitory concentration) value was 0.36 mg mL^{-1} among the selected bacterial strains. This makes it a potential source of natural antioxidants as well as a strong antimicrobial agent with high protein, flavonoid, and phenolic contents (Jyoti *et al.*, 2018). Essential oils and ethanolic extracts from *C. konishii* Hayata were investigated for use against *A. aegypti* and *A. albopictus*, and the results suggested their effective constituents served as a potential eco-friendly mosquito larvicide against dengue mosquitoes (Cheng *et al.*, 2013).

Discussion for big timber production with Samoc

In 2007, the Vietnamese government issued a strong policy document (Vietnam Gov, 2007),

which was revised and improved in 2011 (Vietnam Gov, 2011), to encourage the planting of trees for big timber production throughout the period 2007-2015. An enhanced policy has since been issued, providing continuous approval of a program for sustainable forestry development during the period 2016-2020 with a target to develop 290,000 ha of big timber plantations (Vietnam Gov, 2017). However, there have been a number of challenges regarding domestic big timber development (e.g. small upland households with small and fragmental land; low household incomes, investment, and credit access; weak collaboration for timber production value chains; poor infrastructure for forestry; and weak technologies of silviculture (Bui, 2018)).

Regarding the market demand for big timber, the wood processing sector of Vietnam has been rapidly expanding and has required substantial imports of primary wood material, especially hardwoods, from over 100 countries. In 2018, about 10 million cubic metres of timber worth 2.34 billion USD market-value was imported by processing industries (Itto, 2019), however, only about 25% or 2.35 million cubic metres of roundwood worth 710.5 million USD was provided to domestic industries (Itto, 2020). Furthermore, UN Comtrade reported that wood sourced for import by Vietnam was always a high risk (Norman, 2016). However, the domestic capacity for the provision of big timber in Vietnam is extremely small, which is a serious problem for sustainable forestry development (e.g. big timber plantations have not yet developed sufficiently to meet the target, with only about 40,000 cubic metres of legal raw timber being provided by domestic forests (VOV, 2017)). In addition, plant species currently available in big timber plantations in Vietnam are mostly *Eucalyptus* and *Acacia*, which are introduced species (MARD, 2018). Many potential native plant species for big timber are still undergoing research, such as the six timber native species legally approved by the Ministry of Agriculture and Rural Development (MARD), namely *Dipterocarpus alatus*, *Magnolia conifera*, *Cunninghamia lanceolata*, *Hopea odorata, Melaleuca cajuputi,* and *Pinus kesiya (*MARD, 2018*), and suggested species*

including Azadirachta exselsa, *Canarium album*, *Cinnamomum bejolghota*, *Cinnamomum parthenoxylon*, *Lithocarpus fissus, Michelia mediocris*, and *Prunus arborea* (Tran Van Con, 2013*).*

Before the 1990s, a large area of natural *C. lanceolata* was explored for big timber in the Northern regions of Vietnam, but this species was not found to be planted widely. Currently, research results and published literature regarding *C. lanceolata* are very poor, with only a few literature mentions of its flora classification and distribution (Thai Van Trung, 1970; Phan *et al.*, 2017), silviculture practices (e.g. standard processes of *C. lanceolata* afforestation) (MARD, 2002), essential oil characteristics (Nguyen Danh Hung *et al.*, 2017), and seedling and nursery techniques (Ho & Tran, 2017 a, b; Nguyen *et al.*, 2017b).

A few existing plantations of *C. lanceolata* have been established in places where *Eucalyptus* and *Acacia* cannot be grown because of low winter temperatures and poor soil fertility. However, the growth of *C. lanceolata* in these places is not as fast as its potential growth rate (e.g. the DHB of 20-year-old trees of *C. lanceolata* planted in household plots ranges from 15-20 cm (personal record)). However, the evidence reviewed above shows that *C. lanceolata* could be utilized in a range of applications, for small or large timber plantations, mixed plantations, and agroforestry. Therefore, the cultivation of this species for big timber production should be based on best silviculture practices, which ensure good seed quality, suitable stand density, appropriate fertilization, and a thinning strategy. It could also be planted at lower altitudes or in warmer regions, with consideration given to the possible trade-off between likely better growth conditions, and possibly poorer seed production.

Conclusions

Based on the above reviewed evidence regarding *C. lanceolata*, there are many advantages in using this tree for timber production. *C. lanceolata* is a naturally big-

stemmed tree with a wide distribution, especially when its introduced distribution is considered. While it tolerates infertile soil, strong wind, and cold temperatures, it also grows better in warmer temperatures. It is good at naturally self-thinning and tolerates shade, making it appropriate to grow in high density and/or in mixed plantations. Its growth seems not strongly dependent on altitude (excepting for seed production). It is a potentially multi-purpose plant for big/small timbers, and for essential oils - a natural and safe non-timber forest product for human usage. However, similar to other native species, there has not yet been much interest in *C. lanceolata* as a plantation species in Vietnam.

Acknowledgments

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