CHINESE FIR (*CUNNINGHAMIA LANCEOLATA*) A GREEN GOLD OF CHINA WITH CONTINUES DECLINE IN ITS PRODUCTIVITY OVER THE SUCCESSIVE ROTATIONS: A REVIEW

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(Received 1st Apr 2019; accepted 19th Jun 2019)

Abstract. Chinese fir (*Cunninghamia lanceolata*) is a prized timber species, which is grown in China from more than a thousand years. According to 8th national forest inventory data, Chinese fir plantations area expanded over an area of 11 million hectares, which occupies almost 18.2% area of all plantations in China principally in southern China. Successive rotations with clear cutting have become a common practice for Chinese fir plantations. These management practices on continues bases have led to a declining in yield production. Therefore, a serious concern has been raised on the Chinese fir plantations less yield and long-term productivity decline, particularly about the current rotation regime. In this review, we discussed the general causes of Chinese fir productivity decline and their effective solution. In forest conservation, the decline in soil quality is a serious ecological problem and recalcitrant litter, monoculture planting has aggravated the mechanism of soil degradation in Chinese fir plantations. The deteriorated soil properties in Chinese fir plantations were well mirrored in the reduction of plantation growth. Traditional plantation method of successive rotation without the period of fallow and management system of clear cutting, complete ploughing, burning of site and residues removal could be blamed for site degradation resulting in the poor growth and productivity decline of Chinese fir plantations. Complete burning and clear-cutting can lead to soil degradation by the loss of nutrients and organic matter. Therefore, a comprehensive knowledge of Chinese fir in terms of low productivity causes and solutions will allow us better forest management strategies and better development of plantation and afforestation throughout China.
Keywords: *productivity, soil quality, soil degradation, forest conservation, Chinese fir, China*

Introduction

Plantation forests are the significant part of the forest ecosystems of China (*Fig. 1*), and Chinese fir (*Cunninghamia lanceolata* (Lamb) Hook) is one of most planted species in these plantation forests. It is a typical evergreen sub-tropical conifer with high timber yield, excellent timber quality, and fast growth. It is the third most commonly planted species in plantation forests worldwide (State Forestry Administration, 2010). Chinese fir is often used in the provision of the ecosystem as well as inorganic matter storage. It

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/1705_1105511067

is characterized by its fast growth rate when grown in a monoculture plantation, producing volumes of up to 450 m^3/ha after 25 years (Wang et al., 2014). Its timber accounts for 24% of China's national commercial timber production (FAO, 2007). Fast growing species, along with the quick economic returns also provide the opportunity to mitigate the climate change by sucking the big carbon emissions, which had a significant impact on global climate (Yang et al., 2005). Since 1949, due to afforestation policies area under Chinese fir plantations increased nearly tripled (Li et al., 2013).

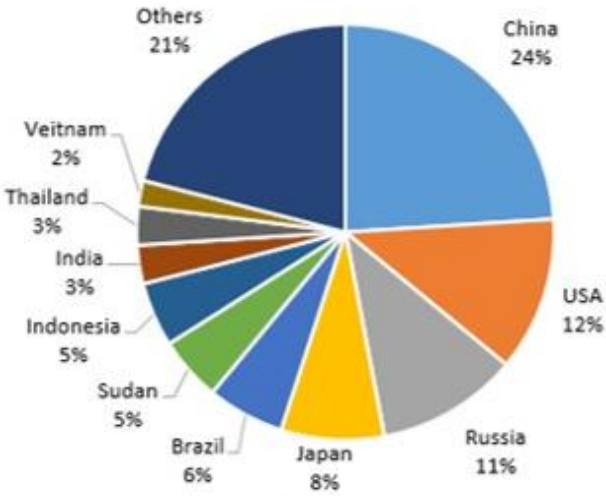

Figure 1. *Distribution of plantations forests worldwide (FAO, 2007)*

As one of the most important subtropical coniferous species, Chinese fir plantations have been using across China for more than one thousand years, especially in southern China (Wu, 1984). China gradually increased its area under plantations since the 1970s (Yu, 1997) and southern China have the highest percentage (54.3%) of forests primarily the plantations (Wang et al., 2014). According to 8th national forest inventory, data indicates that Chinese fir plantations expand over an area of 11 million hectares which occupies almost 18.2% area of all plantations in China and 6% worldwide (FAO, 2015; State Forestry Administration, 2014).

Since the 1980s, the cultivated area under Chinese fir plantations has been expanded from disconnected patches to large plantations (hills to high mountains) to meet the growing need (Ma et al., 2002). Majority of the Chinese fir plantations are monoculture and increasing timber demand resulted in shorter rotations (15 years) without the period of fallow (Bi et al., 2007; Tian et al., 2011). Successive rotations with clear cutting have become a common practice (Hu et al., 2014; Ma et al., 2007). These management practices on continues bases have led to declining in yield production along with soil degradation due to below-ground resources loss (nutrient loss) and accumulation of toxic substances (Chen et al., 2013; Hu et al., 2014). Shorter rotations have led to a high nutrient loss in foliage and biomass per tree component decreased as compare to longer rotations especially in the branches per unit biomass (Fang, 1987; Ma et al., 2007; Zhou et al., 2015). Therefore, a serious concern has been raised on the Chinese fir plantations less yield and long-term productivity decline (Bi et al., 2007; Zhao et al., 2013), particularly about the current rotation regime. Therefore, we have reviewed various aspects of Chinese fir related to short rotations regime, which are directly involved in

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
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Chinese fir productivity decline like nutrient availability, nutrient cycling, soil microbes and their biochemical activities etc. We try to uncover the basic problems in the Chinese fir decline over successive rotations and possible effective solutions provided by the various previous studies. This study would provide a reference for future researches.

Chinese fir description

The genus "Cunninghamia" is an evergreen coniferous specie in the cypress family Cupressaceae. Traditionally, it is said that this genus contains two species, Chinese fir (*Cunninghamia lanceolata* Lamb) Hook) and Taiwan fir (*Cunninghamia konishii),* but genetic obedience suggested them as the same species which is usually known as "Chinese fir".

They are native to China, Taiwan, Northern Vietnam, and Laos. Distribution of Chinese fir in China is shown in (*Fig. 2).* They may reach a height of 50 m, generally with the conical shape with tiered and horizontal branches, which often somewhat pendulous toward the tips. Chinese fir has green needle-like leaves, which are softly spun, leathery and stiff (*Fig. 3*). Needles spiral around the stem in an upward arch. Chinese Fir is a valued species in China which is vital because of its fast growth and high-quality timber wood (i.e., straight and decay resistant), along with its historical value and significant culture it is used as an ornamental tree.

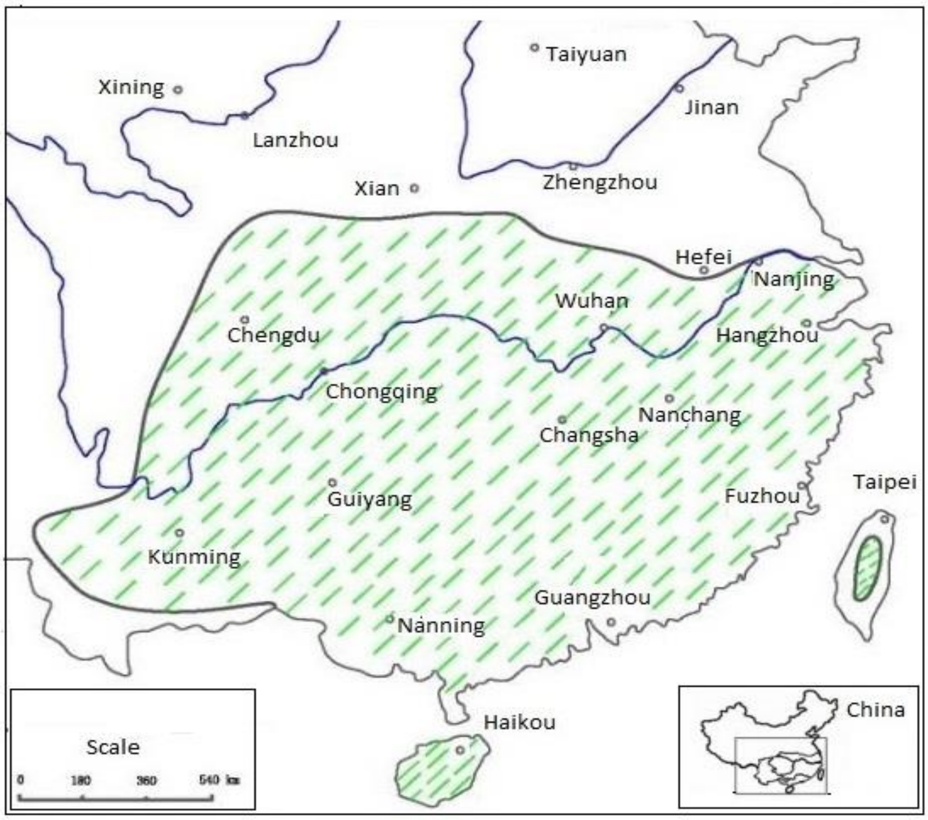

Figure 2. *Distribution of Chinese fir (Cunninghamia lanceolata) in China mainly spread in southern China (Wang et al., 2012)*

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Figure 3. *Description of Chinese fir (Cunninghamia lanceolata (Lamb) Hook) tree*

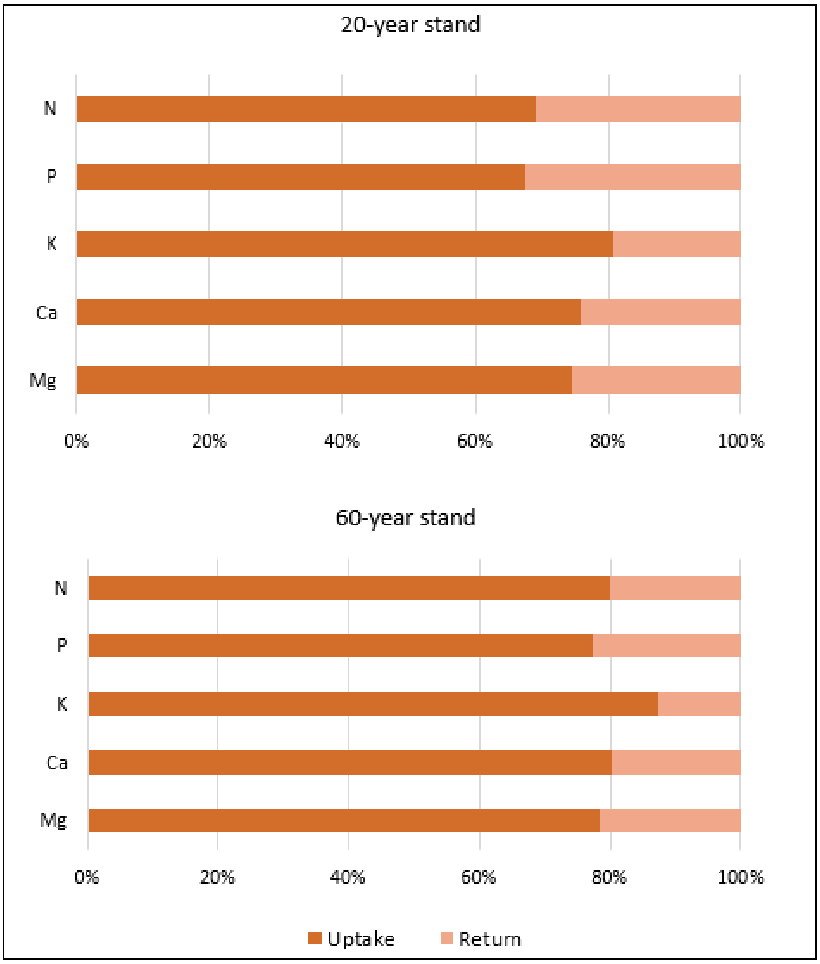

Figure 4. *Nutrient uptake, return and uptake/return ratio Chinese fir plantations of different ages (kg.hm^{-2} a^{-1})*

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Stand development can be the key factors in the nutrient distribution and cycling as well as in biomass production (Li, 1996; Ma et al., 2002, 2007; Zhao et al., 2013). Different factors influence the nutrient absorption of the trees, which include growth rate, nutrient use efficiency and stand nutrient demand (Hobbie, 2015). Climatic as well as physical and chemical factors also affect the nutrient contents and nutrient use efficiency (Piao et al., 2010). According to Ma et al. (2007), annual nutrient uptake and nutrient use efficiency in Chinese fir plantations increased while the nutrient return decreased with stand development. Soil microbes are also the key ingredients in maintaining good soil structure by gas exchange and good drainage, which keeps soil healthy (Bhardwaj et al., 2014).

Data in the *Table 1* showed fungal population firstly increased from 1-year-old plantation to 20-year-old plantation but decreased in 40-year-old plantations. Bacterial population decreased from 1-year-old plantation to 20-year-old but again increase from 20-year-old to the 40-year-old plantation. Overall, microbial population decreased in 20-year-old plantation due to the decrease in bacterial population.

Table 1. *Soil microbial population in different aged Chinese fir (Cunninghamia lanceolata) plantations ($10^3.g^{-1}$ soil)*

Soil microbes	**Plantation age**		
	1 yr.	**20 yr.**	**40 yr.**
Fungi	74	468	199
Bacteria	16900	13660	15760
Total microbes	16974	14218	15959

Nutrient contents and biochemical activity of soil microbes

Chinese fir plantations consume a large number of nutrients because of its fast growth (Farooq et al., 2019a), and due to short rotation periods, nutrient contents availability decreased significantly over the successive rotations. In Chinese fir plantations, soil nutrient contents decreased drastically as the rotation increased (Fang, 1987; Chen et al., 1990). Data in *Table 2* showed that soil humus carbon (SHC) was 37.6 gkg^{-1}, 33.8 $gkg^{-1,}$ and 32.4 gkg^{-1} in first, second and third rotation respectively during Chinese fir plantation. Soil total nitrogen (TN) was 4.28 gkg^{-1}, 3.91 gkg^{-1} and 3.36 gkg^{-1} in first, second and third rotation respectively while total phosphorous (TP) was 0.27 gkg^{-1}, 0.23 gkg^{-1} and 0.14 gkg^{-1}. In first rotation soil total Potassium (TK) was 19.7 gkg^{-1}, moreover, in the second and third rotation, it was 16.5 gkg^{-1} and 14.3 gkg^{-1} (*Table 2*). SHC decreased up to 15.7% in the second rotation while TN, TP, and TK decreased up to 18.4%, 9.6%, and 2.4%, respectively.

In terms of third rotation, SHC decreased up to 32% from the first to third rotation while the TN, TP, and TK decreased up to 36%, 61.2%, and 11.4%, respectively. As the soil depth got deeper, the contents of all the elements declined over successive rotations (Zhang et al., 2004). Plant available contents also decreased from first to the third rotation. When the Chinese fir plantation was regenerated from the site of first rotation, available nitrogen (N_A), available phosphorous (P_A) and available potassium (K_A) decreased significantly by 42.4%, 44.1%, and 37.5% respectively while on the site of second rotation, N_A, P_A and K_A decreased by 24.2%, and 47.8% and 5.9% (*Table 2*). When the plantations start getting mature (18-20 years), the nutrient content availability

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in the soil surface layer (0-20 cm) was only 50.8%, 14.1% and 36.6% for N, P and K, respectively. In the 20-40 cm and 40-60 cm soil layers' nutrient contents also decreased markedly. Due to the low rate of litter-fall decomposition, this cause imbalance between nutrient uptake and return (Liao et al., 2000). During a study in south China, Yang et al. (2005) described that in surface soil layer (0-20 cm) hydrolysable nitrogen content declined in the second and third rotations by 3% and 18%, respectively, as compared to first rotation while available phosphorus decreased 7% and 20% under Chinese fir stands.

Soil nutrients decline over the successive rotations could be reflected in soil microbial population and in their biochemical activities (Bhardwaj et al., 2014). In Chinese fir plantations, when continuous cropping took place over successive rotations biochemical activity of soil microbes decline significantly (Chen et al., 2015; Wu et al., 2017). Nitrogen fixation was 13.2% in the first rotation while it decreased up to 11.4% and 5.9% in second and third rotation respectively. Ammonification also declined by 82%, ranging from 1.6 mg $N.g^{-1}$ soil to 0.4 mg $N.g^{-1}$ soil from first to third rotation. Fiber decomposition was 3.3 CO_2 mg. g^{-1} soil, 0.8 CO_2 mg. g^{-1} soil and 1.4 CO_2 mg. g^{-1} soil in the first, second and third rotation while respiration was 1.6%, 1.1%, and 0.8% respectively. Nitrogen fixation, fiber decomposition, and respiration decreased by 54.1%, 59.2%, and 39.8% when continuous cropping of Chinese fir plantation took place for twice (*Table 3*).

Table 2. *Variation in the soil total nutrient contents, available nutrient contents, soil microbe's biochemical activity, and productivity over the successive rotations in Cunninghamia lanceolata plantations*

Nutrient contents	1st rotation	2nd rotation	3rd rotation
Total nitrogen (gkg^{-1})	4.28	3.91	3.36
Total phosphorus (gkg^{-1})	0.271	0.238	0.14
Total potassium (gkg^{-1})	19.7	16.5	14.3
Humus carbon (gkg^{-1})	37.6	33.8	32.4
Hydrolysable nitrogen ($mgkg^{-1}$)	105.3	95.3	73.2
Available phosphorus ($mgkg^{-1}$)	58.7	52.3	28.7
Available potassium ($mgkg^{-1}$)	101.5	59.6	53.2

Table 3. *Variation in the biochemical activity of soil microbes over the successive rotations in Cunninghamia lanceolata plantations*

Biochemical activity	1st rotation	2nd rotation	3rd rotation
Nitrogen fixation (%)	13.2	11.4	5.9
Ammonification (mg N. g^{-1}soil)	1.6	0.9	0.4
Fiber decomposition (CO_2 mg.g^{-1} soil)	3.3	0.8	1.4
Respiration (%)	1.6	1.1	0.8

Chinese fir growth and productivity

Chinese fir growth and production decreased over the successive rotations (Selvaraj et al., 2017). In productive Chinese fir stands (25-year-old), 280 t ha^{-1} biomass was reported with about 80% of total biomass allocated to the tree stem, which decreased

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over the successive rotations (Zhao and Zhou, 2005). The high soil nutrition consumption due to continuous cropping cause a negative impact on the tree growth of Chinese fir plantations. A decline reported in annual increment in diameter at breast height (DBH) (Farooq et al. (2019b), height and volume in Chinese fir plantations of the same age but with different rotations (Zhou et al., 2016a). Diameter at breast height (DBH) decreased from 14.1 cm to 11.5 cm from first to third rotation (Tang et al., 2016). Plant height also decreased from 15.5 m to 10.8 m from first to the third rotation. Tree volume was 378.5 $m^3.hm^{-2}$, 268.8 $m^3.hm^{-2}$ and 176.4 $m^3.hm^{-2}$ respectively in first, second and third rotation (*Table 4*). The average height, DBH, and volume declined by 14.2%, 12.1%, and 32.3%, respectively in the second rotation and 22.8%, 36.5% and 53.2%, respectively for the third rotation. Higher tree mortality reported in third rotation as compared to the first and second rotation. It was 11.2%, 17.5%, and 21.6% respectively in the first, second and third rotation (*Fig. 5*).

Table 4. *Variation in the growth and productivity over the successive rotations in Cunninghamia lanceolata plantations*

Growth and productivity	1st rotation	2nd rotation	3rd rotation
DBH (cm)	14.1	12.8	11.5
Height (m)	15.4	13.6	10.8
Volume ($m^3.hm^{-2}$)	378.5	268.8	176.4
Tree mortality (%)	11.2	17.5	21.6

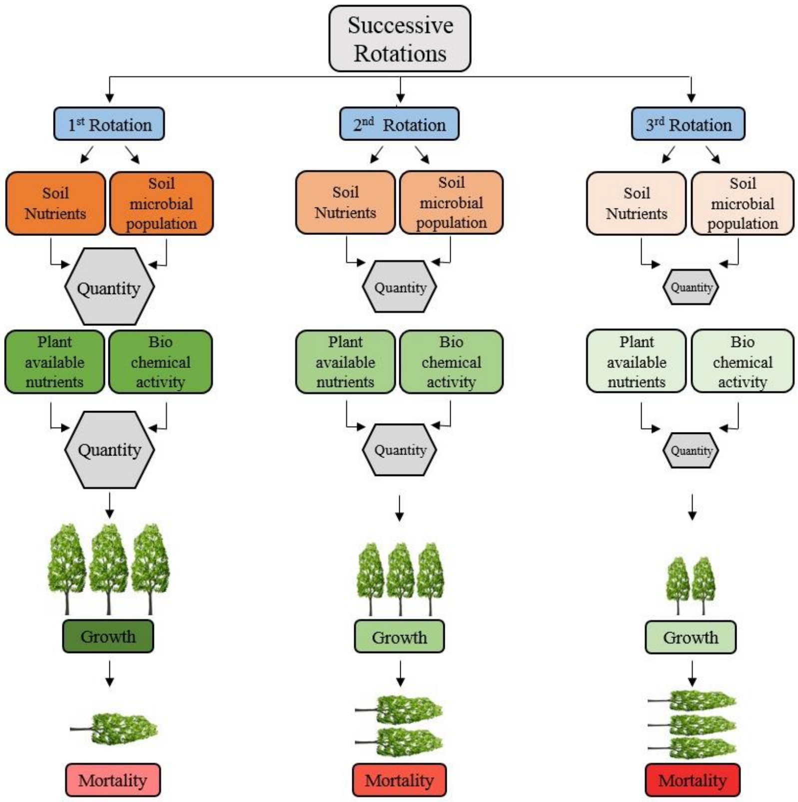

Figure 5. *Graphical summary of soil quality decline affecting the Chinese fir plantations growth and productivity over the successive rotations. (Decrease in the shade of colours of boxes shows decrease in nutrients availability, biochemical activity and growth)*

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Discussion

Due to its soft and adorable timber, Chinese fir is an important species of China, which is in use for manufacturing of buildings, temples, furniture, and coffins, as well as an ornamental tree. Additionally, it also used as biomass energy and pulp production (Ma et al., 2002a, b; Wood et al., 2009). Nutrient cycling and biomass production are the important components of forest productivity (Tian et al., 2011; Farooq et al., 2018) which can vary with stand age, development and different silvicultural techniques (Hou et al., 2009; Zhao et al., 2013). Chinese fir productivity decreased over the years, and current management practices and short rotation policy are highly criticized for being a reason for less productivity (Chen et al., 2004). In Chinese fir plantations, these characteristics have been described in various previous studies in different regions of China (Li, 1996; Liao et al., 2000; Chen et al., 2004; Zhang et al., 2004; Zhao and Zhou, 2005; Ma et al., 2007; Wu et al., 2011; Chen et al., 2013; Zhao et al., 2013; Tang et al., 2016; Zhou et al., 2016b; Selvaraj et al., 2017). From the last one thousand years' traditional plantation method and management system of clear-cutting, complete ploughing, burning of the site and residues removal are under-used which is blamed for site degradation resulting in the poor growth and less production of Chinese fir plantations (Zhou et al., 2016c). Complete burning is the cause of organic matter and some nutrient loss; furthermore, minerals are lost due to rainfall (Wenhua, 2004; You et al., 2015). Soil erosion increased significantly due to complete ploughing while clear cutting resulted in soil and water loss (Dias et al., 2015). Conventional management practice effects tree morphology and biomass production. Morphological characteristics such as survival rate, average diameter at breast height, average height and biomass production were lower in stands where plantations were established with clear cutting and complete burning irrespective of rotation time (Bhardwaj et al., 2014).

Monoculture plantations are also the reason for productivity decline as monoculture system has low resistance and more suspected to pest attack due to the less biodiversity and bad stability (Liu et al., 2018). Non-development of understory vegetation and no proper thinning are the critical issues in the less productivity and poor growth because understory vegetation can markedly improve the soil nutrient and enhanced the biochemical activity (Chen et al., 2004; Zhou et al., 2016b). The decline in productivity is also associated with the non-use of fertilizers as in this era fertilizers are vital for crop development especially in the rotations without a period of fellows (Havlin et al., 2016). However, some experiments by different research teams in different areas showed contradictory results regarding the benefits of fertilizers. In a research on the 5-year old plantation, Li et al. (1991) reported that fertilizer applications of P and K could increase stand growth while Liao et al. (2000) found that P application increased stand growth only at the beginning while N fertilizers showed no effect moreover K fertilizer effects negatively.

The conventional Chinese fir plantation management system has to be replaced with the recently science based and rational management system, which is multi-culturing, includes clear cutting but of small area and mild site preparation. Cutting leftovers should be buried rather than burned. Pure plantation should be avoided and gradually replaced with agroforestry (Chinese fir mixed plantation) such as planting different herbs and shrubs. This could enforce higher productivity with the increase of the timber production and improve the soil physical and chemical properties to certain degrees as herbs and shrubs are easy to decompose and are rich in nutrients. Hence, it will enrich the soil resources. In nutrient-poor soils, direct approach of nutrient inputting should be

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used by applying fertilizers especially the compound fertilizer containing P can have a huge impact on plant growth especially in south china where the sites are mostly P-deficient.

In plantation ecosystem soil microbes are the important decomposers, they are the good indicator of the soil quality and habitat change because they play an important role in nutrient transformations (Chen et al., 2015; Wu et al., 2017). Soil contains a different type of bacteria, algae, fungi, and earthworms. The optimum amount of soil microbial population increases the efficiency of fertilizer and irrigation application (Paul, 2014). Furthermore, it releases essential nutrients N, P, K, and hydrogen back to the soil. On the other hand, excessive soil organic matter can be a problem also as it encourages the growth of unwanted herbs and shrubs, moreover, it also decreases the efficiency of irrigation and fertilizer application (Brevik et al., 2015). These are some of the benefits and disadvantages that soil microbial population can provide to plantation ecosystem (Jacobsen et al., 2014). For soil microbial benefits, an optimum environment that favours soil microbial growth is necessary to build a healthy soil microbial population. Organic based fertilizers can be an excellent way to provide them a healthy environment in which they can thrive in (Hartmann et al., 2015; Hudson, 2015). General causes of productivity decline in Chinese fir plantations and their effective solutions are described in *Table 5*.

Table 5. *Reasons of Chinese fir productivity decline and effective solutions*

General causes of less productivity	Effective solutions	References
Traditional plantation method and management system that creates site degradation	Replacing conventional Chinese fir plantation management system with recently science based multicultural and rational management system	Minghe and Ritchie, 1999; Hu et al., 2006
Short rotation pattern and establishing a plantation on infertile lands	Rotation lengths should be increased and plantation establishment on infertile lands should be discouraged	Ma et al., 2000a; Ma et al. 2007; Slevaraj et al. 2017
Decline in soil fertility due to slash burning and residual removal	Avoid the activities that soil compromise soil fertility. Cutting leftovers should be buried rather than burned	Xiong, 2008; Ma et al., 2000b; Zhijun et al. 2018
Clearcutting and complete plowing before the plantation establishment	Clear cutting but of small area and mild site perpetration	Farooq et al., 2019a; Ma et al., 2002
Introduction of monoculture Chinese fir plantations	Introduction of mixture plantation like agroforestry system should be encouraged and monoculture should be discouraged	Hu et al., 2006; Xiong, 2008; Wang et al., 2008; You et al., 2015
Even aged plantations, non-development of understory vegetation and no proper thinning	Introduction of multi-layering and multi-aged plantations	Lin et al., 2001; Ma et al., 2002; Chen, 2007; Zhou et al., 2015
The decline in the soil microbial population and biochemical activities of soil microbes over the successive rotations	Organic based fertilizers can be an excellent way to provide soil microbes a healthy environment in which they can thrive in	Wang et al., 2008; Zhang et al., 2017
Non-use of fertilizers and organic manure	Essential use of compost and fertilizers	Chen et al., 1990; Liao et al., 2000

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Acknowledgments. This study was financially supported by the National Natural Science Foundation of China (31600502 and 31870614), the Science and Technology Major Project of Fujian Province, China (2018NZ0001-1) and the Special Technology Innovation Foundation of Fujian Agriculture and Forestry University (CXZX2016059).

Conflict of interests. The authors declare no conflict of interests exists.

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