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EUCALYPTUS IN MALAYSIA: REVIEW ON ENVIRONMENTAL IMPACTS

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ABSTRACT

Development of forest plantation is mainly intended to provide income opportunity and to ensure the improvement of the socioeconomics of society. Sabah Softwood Berhad (SSB) is one of the private companies that pioneered the development and commercialization of fast growing timber species and forest plantation. The *Eucalyptus* plantation in SSB was initiated in response to the emergence of fungal disease that implicated the environment. Nevertheless, the impacts of plantation to the environment regarding water use, soil erosion, nutrient loss, pest and disease, biodiversity, soil quality and hydrology are reviewed. The disputes among various scientists over the physiological and plantation aspects of *Eucalyptus*, especially their implication towards the environment are also discussed. This paper aims to present information on the impacts posed by the *Eucalyptus* plantation that will guide the planters and policy makers in facilitating a management plan to mitigate the impacts of this species to the environment.

Keywords: *Eucalyptus*, Soil erosion, Water consumption, Soil quality, Biodiversity, Hydrology.

INTRODUCTION

The development of forest plantation is vital to the economy, social and ecology especially in the Southeast Asia region (Duan *et al*., 2010). In countries such as Malaysia, Laos, Indonesia, Vietnam and Thailand, sustainable plantation forestry is adopted as a plantation scheme that has proven to benefit economically (Harwood & Nambiar, 2014). In Cambodia, the increase in number of forest plantations contributed significantly towards the dynamics of supply and demand of wood in the region (The Forestry Administration (FA), 2010). *Eucalyptus* is one of the important species for forest plantation and is typically managed on short rotation to enhance economy with the production of timber, pulpwood, charcoal, and fire-wood (Zhou *et al*., 2018). In Malaysia, the plantation program of *Eucalyptus spp*. in the state of Sabah commenced in 1970s as part of an effort to promote forest conservation. As a result, larger forest coverage was created with the advent of remote sensing technology.

Sabah Forest Industries Sdn. Bhd. (SFI) is Malaysia's one of the largest timber growers and wood processors that manages forest estate totalling 288,000 hectares, pulp and paper manufacturing facilities, and an integrated timber complex consisting of a sawmill and a veneer and plywood factory. Acacia Forest Industries Sdn. Bhd. (AFI) is another example of company also located in Sabah that planted *Acacia* and *Eucalyptus* as the major species. According to the company, it is their mission to increase the value of forestry assets under their control through systematic conversion of the existing *Acacia* plantation to a genetically improved *Eucalyptus* plantation using superior silviculture practices (Janssen *et al*., 2016). Sabah Softwood Berhad (SSB) is one of the private companies that pioneered the development and commercialization of fast-growing timber species and forest plantation since 1970s. Among the eucalypt species, *E. deglupta* was initially introduced during the early plantation development but was soon replaced by other superior species due to poor growth characteristics and less economical (Enters *et al*., 2002).

Zaiton *et al*. (2018) indicated the potential of planting *Eucalyptus* in Sabah, Malaysia as relatively new venture that has yet to be undertaken by the government or private sector extensively. However, since the discovery of fungal disease exposure in *Eucalyptus spp.* (Salleh *et al*., 1995), researchers have begun to highlight the environmental impacts of *Eucalyptus* plantation. These include water consumption (Hubbard *et al*., 2010), soil erosion (Sun *et al*., 2018), nutrient loss (Wang *et al*., 2019), pest and disease (Wingfield *et al*., 2008), biodiversity (Goded *et al*., 2019), soil quality (Blanco-Moure *et al*., 2016) and hydrology (Ferraz *et al*., 2019). Currently, there is still a lack of research on the issue possibly due to insufficient fund to conduct studies or even lack of interest. Therefore, it is pertinent to assess the environmental impacts attributed by the *Eucalyptus* plantation.

It is hopeful that this review could provide a baseline information on reviewing environmental implication of *Eucalyptus* plantation to the companies, especially the small growers. Furthermore, it would be beneficial for larger company such as wood processing industries, and relevant government agencies and institutions in their efforts to plan, manage and promote *Eucalyptus* plantation.

EUCALYPTUS PLANTATION

Eucalyptus belongs to the family of *Myrtaceae* and is closely related to the genus of *Syzygium*. It is native to Australia, South America and Asia. *Eucalyptus* has been introduced into more than 120 countries, and they comprise one-third of the world's total plantation area (Wu *et al*., 2015). *Eucalyptus* plantations started in Australia in the 1980's for service the *Eucalyptus* oil industry. The tree species has a versatile use depending on the country from mining activities and wood production in South Africa to coal production for steel industry in Brazil. The *Eucalyptus* plantation flourished in tropical and subtropical regions owing to its rather high environmental adaptability, however, extreme climate conditions such as sudden and severe frosts especially in the temperate region are important limitations (Stanturf *et al*., 2013). The predominant species for *Eucalyptus* plantation varies with different countries but more than 90 % of the global planted forests of *Eucalyptus* are accounted by the "big nine" species (*E. camaldulensis, E. terreticornis, E. globulus, E. nitens, E. urophylla, E. saligna, E. dunnii, E. pellita*) and their hybrids (Gessesse & Teklu, 2011; Stanturf *et al*., 2013). For instance, *E. grandis* and *E. urophylla* are mostly planted species in the region of Guang Xi in Nanning, China.

In Malaysia, the emergence of *Eucalyptus* plantation in several parts of the country was predominated by *E. deglupta*. However, planting of the species was promptly halted in 1982 due to the substantially slower growth rate compared to other tree species such as *Gmelina arborea, Paraserianthes falcataria* and *Acacia mangium*. Earlier in 1931, seeds of *E. robusta* was imported from Australia as the country attempted to plant *Eucalyptus* in lowland areas. A 40 ha trial plot was established by the Forestry Department of Peninsular Malaysia for timber and fuelwood production (Salleh *et al*., 1995). In 1974, Sabah Softwoods Sdn. Bhd. introduced *E. deglupta* along with other species for afforestation project in Sabah covering 61,000 ha of logged over forest in Tawau Residency of Sabah for pulpwood and timber production. It also reported a total of 7,000 ha was planted with *E. deglupta,* whereas 620 ha of the forest were planted with *E. grandis, E. urophylla, E. globulus* and *E. camaldulensis*. In addition, *E. deglupta* is vulnerable to insect, fungal and pathogens attacks (Salleh *et al*., 1995). Therefore, most investors tend to disfavour the tree performance of *E. deglupta.*

The sudden change of interest towards *Eucalyptus* may have ensued by new interests from other countries, particularly China and Vietnam. In fact, development programme of forest plantation was initiated by the Ministry of Plantation Industries and Commodities (MPIC) as vigorous efforts to reduce the pressure on native forest as a source for raw materials and ensure the sustenance of domestic timber industry. Therefore, the Malaysian government is encouraging the development of large-scale commercial forest plantations through this programme (Malaysian Timber Industry Board, 2005). Since 2008, several private sectors from Sabah and Sarawak such as Rimbunan Hijau Group, Samling Sarawak, Sabah Softwood Berhad, Sabah Forest Industries and Pei Cheong Plywood & Timber Sdn. Bhd. have been involved in developing *Eucalyptus* forest plantation.

ENVIRONMENTAL PERSPECTIVES

Eucalyptus is an effective tree for reforestation due to its rapid growth and adaptability to the environment. The tree species is capable of tolerating severe periodic moisture stress, low soil fertility and even damages of fire and insects (Zegeye *et al*., 2010). Besides dominating in most natural forests with diverse climates and soil types, *Eucalyptus* can also be cultivated as monoculture in forest fields. Currently, *Eucalyptus* is distributed in over 90 countries with more than 22 million hectares worldwide, although only 13 million hectares have a productivity of interest from the industrial stand point (Zalesny *et al*., 2011). Generally, *Eucalyptus* is adaptable to a wide range of soil conditions, but the optimal growth of the plant especially in a managed forest could be limited by nutrition, water, and drainage (Kline & Coleman 2010; Zalesny *et al*., 2011).

In Guang Xi, China, the logging activities of *Eucalyptus* (*E. urophylla and E. grandis*) plantation reportedly polluted the river and ponds with black-coloured water runoff due to the increased concentration levels of tannic acid and ammonia in the water (Yang *et al*., 2019). Apparently, high temperature and rainfall condition accelerated the decomposition rate of *Eucalyptus* residues and litter which pose problem as the large amount of tannic acid released into the soil reacts with cations (Fe^{2+}) forming tannic acid iron complex that turns the water colour into black. The water runoff into the stream affects the water quality by intoxicating and lowering the number of dissolved oxygen (DO) that causes anaerobic state of the water, limiting the physiological activities and growth of aquatic organisms which could eventually lead to large number of deaths. (Lappalainen *et al*., 2000; Yang *et al*., 2019).

The suitability of *Eucalyptus* species for planting varies considerably with climates, regions and sites (Whitehead & Beadle, 2004). Genotypes selection for planting is important since there is only a small number of species and hybrids that dominate in commercial plantations (Zalesny *et al*., 2011). Despite the various utilization of *Eucalyptus*, there have been numerous issues associated with *Eucalyptus*, particularly environmental related issues, slow-growth regeneration and properties of the wood.

Water consumption

Eucalyptus is a leafy tree that grows rapidly and produces biomass efficiently (Mekonnen *et al*., 2007). This highly productive ecosystem has created numerous controversies especially the water use efficiency of the plant which may have place the local and regional water supplies at risk (Hubbard *et al*., 2010). This may be attributed to the lack of understanding on the plausible effect and proper forest management towards the growth and water use of these plantation (Forrester *et al*., 2010b; Hubbard *et al*., 2004; Morris *et al*., 2004; Whitehead & Beadle, 2004). The leaves of *Eucalyptus* are thick, tough and highly resilient but with low specific leaf area and low nitrogen and phosphorus content (Whitehead & Beadle, 2004). The transpiration rate of *Eucalyptus* tends to be higher compared to other species with slower growth rate (Hubbard *et al*., 2010). Generally, the rate of transpiration influences the water use efficiency (WUE) of the plant which is defined as the amount of biomass produced per unit of water used (Hubbard *et al*., 2010). This physiological aspect of *Eucalyptus* occurs during the process of photosynthesis where carbon uptake is accommodated by water loss through the stomata (Whitehead & Beadle, 2004).

Eucalyptus generally grows well in a dry environment but their growth and physiological processes can be limited by changes in the plant water status (Whitehead & Beadle, 2004). This can be seen particularly in drought-tolerant clones of *Eucalyptus* when planted under water deficit condition which induces higher water uptake (Silva *et al*., 2004). Therefore, the lower value for water stress is attributable with greater drought-tolerance (Whitehead & Beadle, 2004). Similarly in arid climate and dry season, higher transpiration rate and water uptake of *Eucalyptus* usually occurs from deep soil layer (Whitehead & Beadle, 2004). The tapping of ground water reserves afforded by the plant's deep root architecture could potentially deplete soil water (Jagger & Pender, 2003).

Changes in WUE also can be influenced by species interaction especially where increased photosynthetic capacity resulted in higher nitrogen and phosphorus availability in the plant (Hobbie & Colpaert, 2004). Forrester *et al*. (2010a) demonstrated that mixed cultivation of *Eucalyptus* species (non-nitrogen-fixing) with *Acacia mearnsii sp.* (nitrogen-fixing species) had higher WUE with higher transpiration rate compared to the monoculture. In such circumstance, the increased growth rate is attributed to the expedited cycling of nitrogen and phosphorus by the nitrogen-fixing species of *Acacia sp.* (Forrester *et al*., 2004). Therefore, the proposed hybrid model of cultivating *Eucalyptus* and *Acacia* species was capable of predicting the productivity and water use by *Eucalyptus* on physiological basis (Whitehead & Beadle, 2004).

Soil erosion

Soil erosion crisis is one of the major contributor to soil degradation that associate to serious ecological problem worldwide and decreasing of productivity (Alexandridis *et al.*, 2015). Interestingly, both canopy and litter covers are capable of significantly reduce the kinetic force of raindrops onto the soil surface and hence, surface runoff and soil erosion (Sun *et al*., 2018). Besides, soil erosion and surface runoff are associated with the "soil infiltration capacity" under the vegetation and litter (Chu *et al*., 2019). The tree canopy plays a special role as intercepting rainfall that dissipates the kinetic energy of the rainfall upon soil percolation (Gessesse & Teklu, 2011). The interception of rainfall works with vegetation canopy through branches (stemflow), or evaporation into the atmosphere whereas the excess part falls to the ground (throughfall) (Lacombe *et al*., 2018). The size and orientation of the leaves can influence the rain interception which ultimately lands onto the soil surface (FAO, 2009). For instance, narrow-leaved of vegetation structure tend to produce higher raindrops to the ground as a result of lower stemflow and larger throughfall and vice versa (Sun *et al*., 2017). The kinetic theory indicates that broader leaves produced larger size of rain droplets with higher kinetic energy upon falling onto the ground compared to narrow leaves (FAO, 2009).

Study by Sun *et al*. (2018) also demonstrated the impact of different plantation type and age where mature plantation dissipates water that reduce soil loss better than young plantation. Biodiversity has been associated with maturity as well as the increasingly complex canopy structure that contribute to species diversity like herbs on understory vegetation (Goded *et al*., 2019). In another study that compares the surface runoff and soil erosion under the canopy of *Eucalyptus* and oak, thick layer of litter cover under the *Eucalyptus* compared to oak helped offset the splash detachment during the intense rainfall (Thompson *et al*., 2016). Greater litter cover under the *Eucalyptus* canopy also constitutes lower sediment yield which may have helped impede surface runoff and soil erosion. The leaves of *Eucalyptus* contain allelochemicals with notable presence of phenols and terpenoids associated with plant defence mechanism (Zhang *et al*., 2012). The chemicals released by volatilization, leaching, decomposition and excretion (Blum *et al*., 2011) inhibit germination or growth of other species that subsequently create sparse or lack of vegetation cover. This could not only affect the biodiversity in the plantation that reduces species richness of herbaceous plant, thus leaving the ground surface exposed. Under this circumstance, the impact of rainfall can reduce the porosity of the soil, thereby increases surface runoff (Chu *et al*., 2019).

Essentially, canopy cover structure and litter cover play vital roles in reducing surface runoff and hence, soil erosion may evitable. Therefore, several researchers identified the conversion of monoculture into mixed forest with native tree species and *Eucalyptus* as a solution to reduce the surface runoff and soil erosion (Chu *et al*., 2019). Furthermore, soil quality can be retained with appropriate land use and improved soil management (Gessesse & Teklu, 2011). For instance, minimizing ground cover and ground level activities such as cultivation, compaction by foot traffic, livestock grazing and trampling and harvesting or logging damage needs are important for the sake of better soil quality.

Nutrient loss

The fact is *Eucalyptus* is not a nitrogen fixer unlike other tree species such as nitrogen-fixing *Acacia* that is capable of restoring soil health sustainably by recycling nutrient (Forrester *et al*., 2010b). Likewise, the rapid growth of *Eucalyptus* generally demands high nutrient especially in short rotations of forest plantation to afford its large biomass production (Herna´ndez *et al.*, 2009). The considerable productivity may be beneficial for commercial production but could affect the patterns of nutrients absorption and risk nutrient loss under poor soil management. Essentially, the nutrient cycle of *Eucalyptus* includes translocation of mineral elements within the plant, external transfer to the plant via litter production and decomposition, and export via biomass removal (Viera *et al*., 2016). Nutrient export particularly contributes significantly towards the nutrient balance in the system given the potentially high nutrient output from *Eucalyptus* plantation.

The aerial biomass of *Eucalyptus* are valuable source of fuel, charcoal, pulpwood and timber (Bachega *et al*., 2016; Hernández *et al.,* 2016). However, harvest residues from the branches and leaves contain highest nutrient concentration, particularly leaves with high level of calcium that could affect the nutrient balance (González *et al*., 2016). Therefore, removal of harvest residues to facilitate access and soil preparation for subsequent rotation, as well as source for energy production indicates depletion of organic matter that costs soil fertility and thereby, compromise the site productivity (Madeira *et al.*, 2010). In short rotation, the nutrient use by *Eucalyptus* is greater than the contribution through natural means because of the high nutrient demand and its intense utilization of soil nutrition. If the nutrients are not replenished due to poor soil management, this could lead to soil degradation (Spangenberg *et al*., 1996).

Moreover, researchers have demonstrated that nutrient loss is also attributed to surface water runoff (Ferreira *et al*., 2018; Wang *et al*., 2019). For instance, greater vegetation cover and litter contents in red soil region in Southern China were shown to reduce the concentration of nitrogen and phosphorus in surface water, and hence surface runoff (Chu *et al*., 2019; Liu *et al*., 2017; Wu *et al*., 2012). The understory cultivation with native plant enriches the soil that help minimizes huge amount of nutrient losses. Therefore, the conversion into mixed forest resulted in higher nutrient compared to monoculture *Eucalyptus* species as demonstrated by Chu *et al.* (2019).

Pest and disease

Establishing clonal or inter-specific hybrids with high quality yield and favorable growth requires special caution that must consider pest and disease into the account (Old *et al*., 2003). Then, there is also the growing susceptibility to pest attack especially by exotic insects due to the strong competition with endemic insects and herbivores that lack adaptation to feed on *Eucalyptus* (Paine *et al*., 2011). Each disease is attributed to one or more pathogens (Old *et al*., 2003) where the spread and damage usually occur during the early establishment of plantation. At young age, *Eucalyptus* is particularly susceptible to pest attacks and the incidence and occurrence of pests most often happen during the introduction of *Eucalyptus* in a new environment or the early period of planting (Gessesse & Teklu, 2011; Wingfield *et al*., 2008).

The nitrogen-fixing tree species is vulnerable to numbers of diseases with heart rot, root rot and phyllode rust causing the most debilitating damages to the trees (Jung-Tai *et al*., 2017). Disease infection interfere the growth and development of the plant which consequently reduces quality and productivity. The fungal diseases usually attack and spread rapidly when leaf density is high. Other leaf diseases of *Eucalyptus* caused by fungi include *Mycosphaerella spp.* (crinkle leaf disease), *Aulographina eucalypti* (corky leaf spot), *Pseudocercospora eucalyptorum* (leaf spot) and also *Septoria pulcherrima* (leaf blight) (Old *et al*., 2003). On the other hand, insects from the order of Lepidoptera are common pests damaging to *Eucalyptus* with the larvae attacking wood structures that cause the stem to become fragile and broken. The Forestry Department of Sabah documented the presence of treeshrews debarking the tree stem, defoliators by caterpillars and termites as some of the pests damaging on *Eucalyptus* species (*E. pellita, E. grandis and E. hybrid*) in Sabah (Chung *et al.*, 2015).

Distribution of *Eucalyptus* plantations have spread from its native in Australia and Indonesia to countries across the globe in different regions owing to its adaptability to different environmental conditions. Accordingly, the complexity and damages of the pests can be brought about by the migration of native and invasive insect herbivores into different environments (Paine *et al.*, 2011). Each disease has its-own pathology, impact, and management control. For instance, *cryptosporiopsis* leaf and shoot blight disease affects the lower crown and coppice shoot that cause the death of shoot in crown. Disease-resistant tree is the most probably the feasible method to prevent the attack of disease. Thus, a sound knowledge of disease is essential in order to deliver proper care and management at the plantation.

Biodiversity Impact

The success of *Eucalyptus* in contributing to wood production and its effectiveness in boosting the development of regional economy depends on the changes made towards ensuring the sustainability of the sector as well as the natural ecosystem (Hartley *et al*., 2002). However, there are also the issues highlighted by several countries regarding the potential implication of *Eucalyptus* to conservation. Several researchers indicated the capability of *Eucalyptus* to protect the native flora and fauna (Barlow *et al*., 2007; Calviño-Cancela *et al*., 2012; Felton *et al*., 2010; Hartley *et al.*, 2002; Hsu *et al*., 2010; Lindenmayer & Hobbs, 2004) while others argued conversely that *Eucalyptus* is capable of retaining the native biodiversity despite their confounding assessment (Brockerhoff *et al*., 2008; Stephens & Wagner, 2007). The aspects used as argument include the age and structure of the stands which influence the ability of plantations to drive biodiversity (Calviño-Cancela *et al*., 2012; Lindenmayer & Hobbs, 2004) where canopy closure affects the species differently (Bunn *et al*., 2010).

The abundance of herb and bird species in *Eucalyptus* plantation is lower compared to mixed and deciduous temperate forests and the plants in *Eucalyptus* mainly belonged to scrublands or mesophilic to wet meadows and pastures (Goded *et al*., 2019). The difference between *Eucalyptus* and native forest can be distinguished in terms of the density of trees where plantation usually comprised of one or two species of tree compared to the diverse species in native forest ranging from herbaceous plants to abundance of bird assemblages (Goded *et al*., 2019). The lack of diversity in forest species as well as the habitat structure in *Eucalyptus* plantation can also be attributed to the limited open spaces in the plantation. This clarifies the disappearance of forest naturalness in *Eucalyptus* that inhibit diversity of forest species compared to native forest (Proença *et al*., 2010).

On top of that, the taxa group in *Eucalyptus* comprised of the smallest number of species in both herbs and bird compared to other tree landscapes such as oak and pine stand (Proença *et al.,* 2010) and native forest (Goded *et al*., 2019). This can be attributed to the structure of monoculture forest stands or the short rotation period of *Eucalyptus* that restricts community bird assemblage (Magura *et al*., 2008) and increasing bird migration during deforestation. In addition, bird assemblage is more attracted to nesting in old trees and large trunks with holes in native forest compared to the plantation. Furthermore, the age of *Eucalyptus* stands that constitutes different shrub structures also influence the composition of bird community where young stand with shrubby structure and open canopy versus mature stand with well-developed and larger canopy but with more flower availability. In fact, flower with copious nectar production is an important source of food for bird as well as for pollination purposes. This explains why mature stands attract more bird assemblages compared to young stand of *Eucalyptus* (Calviño-Cancela *et al.,* 2013). Nonetheless, the paucity of bird assemblages between *Eucalyptus* stand and native forest is evident because of the lack of food such as fleshy-fruited species in plantation (Calviño-Cancela *et al*., 2013; Proença *et al*., 2010). Therefore, the argument that *Eucalyptus* plantation associated with biodiversity aspect, especially in terms of lower plant diversity and bird are indisputable.

Soil Quality

The productivity of *Eucalyptus* must be sustained effectively because of its afforestation role in both tropical and subtropical regions. However, inappropriate or negligence in land management could lead to deterioration of soil quality (FAO, 2009). The plantation of *Eucalyptus* typically rotates approximately 4 to 6 years or even shorter (Xu *et al*., 2020) and hence, the soil organic carbon, nutrient content, microbial biomass and metabolic activity can undergo major changes. Therefore, good quality of soil is the foundation for healthy and productive tree growth. According to (Zaiton *et al*., 2018), *Eucalyptus* grows naturally on low-nutrient soils, they have the potential to adapt on more fertile conditions within their increasing growth rates especially to higher levels of nitrogen and phosphorus. For instance, several *Eucalyptus* species grows well in clay with high organic matter because it is capable of sustaining soil fertility and regulates soil nutrient better (Blanco-Moure *et al*., 2016) while silty clay is not suitable for *Eucalyptus* growth (Xu *et al*., 2020). However, excessive clay content reduces aeration and permeability of the soil which inhibit the root growth (Xu *et al*., 2020). Nitrogen (N) is one of the major nutritive elements that can contribute in plant growth and development (Nacry *et al*., 2013; Thilakarathna *et al*., 2016). Soil functioning changes can be affected by the conversion of nutrient cycling and soil fertility. For instance, the land can only retain so much of nutrients from the conversion to *Eucalyptus* plantation that the excess inputs are transferred to aquatic ecosystems (Hunke *et al*., 2015; Nóbrega *et al*., 2018). One of the study case in Brazil Atlantic Forest conduct on the changes of the soil nutrient stocks indicate that litter leaching, particularly during the lag between harvest and the beginning of the next rotation, or by the deterioration of old stumps and roots after many rotations can affect the rise of nitrogen (N) stocks below 20 cm (McMahon *et al*., 2019). This is also supported by long-term observation on litter yield and decomposition rate in different age stand where 6 year old stand had significantly lower rate of litter decomposition and poor efficiency of nutrient recovery compared to 2 and 10 years stand (Xu *et al*., 2020). Evidently, the organic matter content and nutrient element in the soil could diminished by the harvesting of 6 year stands (Santana *et al*., 2000). Consequently, the soil quality may suffer substantially for long time period.

The temporal dynamic of nutrient in the soil is influenced by nitrogen which also constitute the main composition of soil organic matter (Mendham *et al*., 2003). The breakdown of litter depends mainly on microorganisms that regulate the decomposition and nutrient cycling that subsequently generate more nutrients including nitrogen and phosphorus, and hence, enhance the organic matter content in the soil (Bot *et al*., 2005). Interestingly, increase elevation in altitude has been found to affect the accumulation of soil organic matter due to the decline in decomposition rates (Griffiths *et al*., 2009). Nonetheless, *Eucalyptus* plantation generates a substantial amount of biomass that with potentially massive nutrient. Therefore, inter-rotation period of *Eucalyptus* plantation could provide better regulation of organic matter in the soil that will ensure sustainability and productivity especially during the later rotation (Mendham *et al*., 2003).

In general, the impacts of *Eucalyptus* plantation activities on soil carbon (C) are significant to sustain the forest productivity and to account for possible climate changes. Besides, the rates of litter decomposition that associate in affecting the nutrient and carbon stocks may be altered in both controlled and uncontrolled soils due to changes in temperature, precipitation, or species composition over the 12 years (Brzostek *et al*., 2015; Manzoni *et al*., 2012). Different combination of region, soil order, clay content, seasonal precipitation, and mean annual temperature can affect the changes of sizes and rates in soil C stocks which depend on the cycle modelled (Cook *et al*., 2016). Regional factor reflects land-use history with different levels of disturbance that affect soil C stocks. Based on the type of soil with different physico-chemical properties, clay-rich soil is characterized by medium texture with more than 33 percent of clay content constitute greater soil C (Laganière *et al*., 2010). Understory vegetation is significant for conservation of biodiversity, soil nutrient cycling, and carbon stocks (Wu *et al*., 2011; Zhou *et al*., 2017). Therefore, good management of understory vegetation can contribute on better quality and quantity of soil C stocks and approach sustainable ecosystem.

Hydrological Impact

Understanding the hydrological impacts of *Eucalyptus* concerned with the water consumption of the plant and its effect on streamflow and water balance in the plantation. This is mostly associated with the high evapotranspiration rate of *Eucalyptus* that drains the water table that subsequently implicate water balance (Richard *et al*., 2013; Salemi *et al*., 2012). There is also the interception that impedes the amount of precipitation upon reaching onto the soil surface (Baillie *et al*., 2015). The age factor is also taken into consideration especially in plantation that involves short rotation length of 6-7 years because the high productivity of the plant can also affect the streamflow (Stape *et al.*, 2010). The water use of the plant is likely to be higher during the period especially at the early age between 1-2 since soil recovery is still slow (Forrester *et al*., 2010b).

Besides local physical factors (soil, topography and forest management), climatic factors such as precipitation and temperature can also affect negatively on the hydrology at the plantation (Evaristo *et al*., 2019; Ferraz *et al*., 2019). Essentially, the capacity of water storage depends on soil texture and depth (Ferraz *et al.*, 2019). Depending on soil texture, the rate of infiltration and percolation depends on the soil texture that also control the water movement and storage by regulating the water flow (Neary *et al*., 2009; Swarowsky *et al*., 2011). In addition, water storage capacity and baseflow control also depends on soil depth (Evaristo *et al*., 2019). This explains the reduced water storage in the soil and water flow control in high slopes plantation because of the dissipating water from the soil (Wichert & Alvares, 2018). On the other hand, the water availability depends on climatic condition, particularly annual precipitation and its seasonality (Potter *et al*., 2005). The hydrological implication by climatological variable is evident especially during the dry season when water scarcity is observed throughout the year (Lara *et al*., 2009; Ning *et al*., 2017). Soil infiltration is another factor to consider on the effect of streamflow, particularly in relation with the amount of precipitation. Hydrophobicity of dry soil can slow down the infiltration and instead stimulate runoff (Ferreira *et al.*, 2000; Dresel *et al*., 2018).

Contrary with streamflow variable, climate influences the stream water in terms of quantity and water quality (Neary *et al*., 2009). Afforestation in New Zealand shows that the stream temperature declined within 6 years of planting which could subsequently affect the aquatic invertebrate (Quinn *et al*., 2009; Baillie *et al*., 2015). Study also shows the effect of litter decomposition of bark and branches from the *Eucalyptus* plantation on the streamflow in hydrology and water quality which lead to changes in the aquatic biota and ecosystem processes. Although microbes and macroinvertebrates are the main agents in litter decomposition, the leaching materials could implicate the stream depending on environmental condition (Ferreira *et al*., 2019).

CONCLUSION

Eucalyptus renders wide range of products (fuelwood, charcoal, timber, poles, posts, mine props, plywood, paper pulp, fibreboard, tannin, essential oil, shade and shelter) and services (ornamental nectary source for honey production). Higher productivity and physiological demand of exotic tree complicate further on the cultivation system. Despite the economic benefits brought by *Eucalyptus*, the implications to environment such as water use, soil erosion, nutrient loss, pest and disease, biodiversity, soil quality and hydrology are evident. Nonetheless, a holistic invalidation of *Eucalyptus* based on literature discussed in this paper is not reasonable. The impacts emphasized in this review depend on the forest location and environmental condition. It is equally important to implement proper land use and soil management to prevent degradation or disturbance to the ecosystem while ensuring the maximum growth of *Eucalyptus*. Decisions must take into account on the physiological characteristics of the site condition towards sustainability of *Eucalyptus* plantation. Intercropping of *Eucalyptus* with other species appears as fine alternative to the conventional approaches to improve soil fertility, control the damage of insect and pests as well as water and soil conservation. Considering the significance of *Eucalyptus* to timber industry, the environmental effects of planting must be carefully evaluated with sustainability as the key priority. Therefore, planters must engage in all sustainability programs such as certification in order to fulfil their environmental obligation.

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