A Review and Evaluation of the Biological Effects of Coarse Woody Debris in Forested Ecosystems

by
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ABSTRACT

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Coarse Woody Debris (CWD) is considered any woody decay that has fallen on the forest floor. This important piece of forest ecology has a large influence on a variety of forest characteristics. This thesis first evaluates CWD's effectiveness on soil, water, plants and animals through literature review. The second section of this thesis focuses on policies produced by four countries (Canada, USA, Finland and Iran) that regard CWD management. Lastly, this study will test the ability of these policies to account for each of the biological factors CWD holds within the forest. Where lacking, this study connects the gaps in order to form best practice suggestions throughout the study. This study found that there is much to be desired in policy as the countries studied fail to accurately account for all the main forest characteristics. In addition, allowing CWD to be considered at the beginning of the planning process is optimal in ensuring long-term health and protection of biodiversity.

CONTENTS

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1.0 INTRODUCTION

Conservation of biodiversity has been at the centre of many scientists' conversations worldwide over the past few years (Dudley 2009). Sandbrook (2015) defined conservation as a set of "actions that are intended to establish, improve or maintain good relations with nature". In addition, biodiversity is a term that envelops the "extent of nature's variety or variation within the natural system; both in number and frequency" (Rawat *et al*. 2015). Therefore, when both definitions are coupled, the conservation of biodiversity is defined as the "protection, upliftment and scientific management of biodiversity in order to maintain it at its threshold level and derive sustainable benefits for the present and future generation" (Velmurugan *et al*. 2008). Government entities, local communities, schools, and individuals have all taken the conservation of biodiversity as a serious objective in ensuring a healthy future for our forests (Redford *et al*. 1999).

Coarse Woody Debris (CWD), known to many as sticks and snags, plays a fundamental role in forest characteristics (BC Environment 1995). Although CWD has been studied for extensive periods of time by scientists and foresters around the world, there remains insufficient data on CWD's full impact on the forested ecosystem (Stevens 1997). Although CWD has been defined in many ways, the most agreed upon definition for CWD used in the literature has been given by Yan *et al*. (2006):

"*Coarse woody debris (CWD) is generally considered as dead woody materials in various stages of decomposition, including sound and rotting logs, snags and large branches.*"

As this definition suggests, CWD is fallen wood, and fallen wood may land in water, thus impacting water quality; or it may fall on the soil which gives way for habitat of soil organisms and other ground dependent animals (Stevens 1997; BC Environment 1995). Hence, when viewed from a broad perspective, CWD is decomposing wood that has an impact on a forest's soil, water, plants, or animals.

Given that most research conducted on CWD focuses on particular impacts of CWD in forests, a broader perspective of the role of CWD and its influence upon the conservation of forests is desirable. Such a perspective would require a synthesis of the key scientific research conducted on CWD in forests and evaluating the effects of CWD on the conservation of the following elements of a forest:

i. soil;
ii. water;
iii. plants; and
iv. animals.

The first objective of this thesis is to evaluate, from a broad perspective, the effects that CWD can have upon meeting the goal of conserving biodiversity in our managed forests. In order to meet this objective, a review paper on this topic will be written which;

a. summarizes the current state of understanding of CWD by surveying published studies on the impacts of CWD upon the above 4 parts of a forest. This survey will, of course, explore the many sub-categories within the above 4 parts.
b. identifies recent major advances and discoveries;
c. identifies significant gaps in the literature;

d. explains currently debated topics in CWD; and

e. shares ideas on where research might go next.

The second objective of this thesis is to evaluate a variety of management strategies for CWD found in different countries. This thesis calls upon studies from Iran, the United States, Canada and Finland. This section builds understanding of the complexity and ability of the various policies to account for the variety of biological factors CWD has on the forest community.

2.0 METHODS

The methods are comprised of three major parts;

i. A comprehensive review of the literature on the biological nature of CWD.
ii. A review of management strategies for CWD used in different countries.
iii. An evaluation of these management strategies, based on the current understanding of the biological nature of CWD established in part i.

First, a review of the biological nature of CWD is based on a comprehensive review of the current literature on this topic. This review is presented in the Results, and is broken down into four parts. Each of these parts explains the impact of CWD on the goal of conserving that part of the forest. These parts listed are based on a review of the impacts of CWD upon a forest's:

1. Soils;
2. Water;
3. Plants; and
4. Animals

Each of these sections have corresponding subsections that help to evaluate the impact of CWD on even more specific characteristics.

Second, an examination of different management strategies for CWD is conducted by reviewing literature on different management strategies used in four different countries: Canada, USA, Finland, and Iran. This review of management strategies comprises the second part of the Results.

Finally, in the Discussion section of this thesis, an evaluation of different management strategies for CWD is presented. This evaluation is based on the current knowledge of the biological nature of CWD, established in the first part part of the Results. The evaluation is intended to allow for a broad understanding of the role of CWD in forests. This broad understanding is necessary because the goal of conserving biodiversity in managed forests is also broad. Hence, this thesis is designed to facilitate an understanding of the contribution that CWD can make toward achieving the broad goal of conserving biodiversity in managed forests. Additionally, the discussion ties together the initial parts of this thesis and uses the basis of knowledge of CWD in science to answer questions of policy and programs that may be implemented to better future biodiversity. Four countries have been chosen for this part of the thesis (Canada, USA, Finland and Iran) in order to build global understanding of the needs for management of CWD. Each of the policies are then assessed and evaluated based on, as previously mentioned, scripted scientific knowledge.

3.0 Results

The first section of the Results is comprised of a comprehensive review of current literature on the biological nature of CWD in forests. This review examines the biological impact of CWD on 4 parts of the forest: soil, water, plants, and animals.

3.1 IMPACT OF CWD ON SOIL

3.1.1 Decomposition of CWD

Understanding the decomposition of CWD is a necessary first step in understanding the impact of CWD upon forest soils (Li *et al.* 2007). The process of decomposition, whereby a live tree becomes organic matter (OM) has best been explained by Li *et al.* (2007) as follows: the moment a tree has reached mortality, sapwood is consumed by wood-boring beetles which allow for fungi and bark beetles to become the first group of colonizers to attend to the dead tree. These first colonists use the cambium and the sapwood to survive, and their work entices organisms such as spiders, species of ichneumons' wasps, false scorpions and various groups of fungi to gather (Li *et al.* 2007).

Fungi act as a catalyst in the process of heartwood decay which helps to facilitate the entry of various organisms. Threadlike mycelia allow this entry and help the tree to be led to the final stage. At this point the tree is beginning to be taken up by soil organisms such as Nematoda, Acarina, Collembola, Myriapod, and Oligchaeta. At this stage, due to the soil organisms beginning to eat away the woody debris, the majority of the woody material becomes humus and lays on the top layer of the soil, which allows for the nutrients, that have been long feeding the tree through the soil, to return to their origins (Li *et al.* 2007).

As CWD decomposes in the soil, it becomes a very important contributor to nutrient cycling (Woldendorp *et al*. 2005). Understanding the dynamics of CWD and its position in forest health is an important piece in forest management. In addition to forest health, CWD offers many species of birds, insects, small mammals, *etc*. a place to live (Riffell *et al.* 2010).

Decomposition is a process in soil dynamics defined by the changing of the organic structure in biological material, in this case wood, to its more broken-down organic matter form (Li *et al.* 2007). CWD may be broken down into three organic processes that achieve the goal of decomposition:

i. respiration,

ii. fragmentation, and

iii. leaching.

The respiration process occurs when a sum of microbes and invertebrates break down about 50% of the total organic carbon which makes way for a release of gas.

The leaching process stems from the impact of the physical forces exhibited by water, temperature and gravity. Through such physical forces, vital nutrients are transported to become part of the soil which causes the main woody material to slowly decay and become the final product: organic matter. Although leaching tends to be an over-looked factor in wood decomposition, the benefits to CWD decomposition are existent.

Lastly, the physical and chemical compounds that cause such specific decay are termed fragmentation. The physical causes that induce fragmentation are identified as any process that causes the exterior characteristics of CWD to be affected. Such processes may include, the falling of a tree, freezing or thawing, snow, swelling, formation of cracks, *etc*.

Decomposition rates in CWD may be attributed to the types of organisms inhabiting the wood. This idea was advanced by Harmon *et al.* (1986). Small organisms play a large role in the actions of decomposition in tree species and depending on which species of decay organisms the tree harbours, the time taken to decompose is greatly affected. Yuan *et al.* (2017) mention that beyond the impacts of the inhabiting organisms, the density of the wood also has a large impact on the rate at which decomposition occurs.

3.1.2 Soil-Carbon and CWD

CWD acts as an important factor in the reservoir of organic carbon in forest soils. (Gonzalez-Polo *et al.* 2013). Quantitatively, it is said that carbon budgets can be underestimated by nearly 50% in forests that have not experienced recent disturbance. Spears *et al.* (2004) state that CWD can be considered as “recalcitrant carbon islands”. This means that CWD causes variations in carbon quality which may classify various microsites on the forest floor (Spears et al. 2004).

3.1.3 Soil Nutrients and CWD

In a case-study conducted by Maranon-Jimenez *et al.* (2013), CWD was identified as a member of the forest ecosystem that releases many nutrients in the post-fire stage. Identified as a key connection between nutrient availability and the growth and development of recently established vegetation, CWD tends to release its nutrients through the process of decomposition allowing increases in soil fertility, which in effect, accelerates microbiological processes. Logs recently affected by fire, identified as semi-charred, are an important part of the ecosystem since they provide soil nutrient sustainability and have a large impact on the regeneration success of such forests (Maranon-Jimenez *et al.* 2013). The research done by Maranon-Jimenez *et al.* (2013) suggests that there is a large release of nutrients from the dead wood in the first four years of its decomposition.

Herrmann *et al.* (2018) propose that the impact of CWD on specific sites depends on the species and stage of decomposition. Results of their study indicate that Spruce CWD tends towards a net sink of nutrients such as nitrogen, sulfur, calcium and phosphorous whereas beech and pine species were constant. It appears that, generally, there is no high level of nutrient release until CWD has lost around two thirds of its net mass (Hermann *et al.* 2018).

3.1.4 Slope Stability and CWD

A study published by Kim *et al*. (2006) identifies CWD as key in slope dynamics. Rather than being washed downslope, soil, organic matter, and water are retained when CWD is present as it rests on the forest floor. As CWD retains this down-slope movement, it helps to increase the quantity of mineral soils and organic material in that area (Kim *et al.* 2006).

3.1.5 Soil Bacteria and Fungi and CWD

Regarding the biological factors that influence CWD decomposition, which in turn affects the soil, Johnston *et al.* (2016) observed that both fungi and bacteria are large influencers in the decay process and that conserving the diversity of these organisms in a forest is dependent on the presence of CWD.

Fungi and bacteria tend to live in a cooperative state. Both fungi and bacteria work to accomplish the same goal of reducing the woody debris down to its state as part of the organic matter (Johnston *et al.* 2016).

A study by Kwak *et al.* (2015) tested the impact of CWD on oil sands soils and found that CWD increases the microbial community, causing a more diverse ecosystem. In addition, their work indicates that CWD is said to regulate the temperature of soils and water content and create areas for the establishment of vegetation in upland sites. For a regenerating forest to quicken its process, Kwak *et al.* (2015) suggest that CWD be used in order to increase biomass content and speed up the regeneration process, thus allowing for increased nutrient cycling and decomposition rates in the soil.

3.1.6 Nitrogen Cycling and CWD

Hafner *et al.* (2005) evaluated CWD's impact on nitrogen cycling. Post-assessment, researchers found that CWD may be the determinant factor of future forest cover (Hafner *et al.* 2005). The negative side to CWD and its relation to nitrogen cycling showed that CWD reduces potential nutrient availability in some areas of the forest floor, reducing nitrogen availability in some areas, which in turn decreases the potential persistence and establishment of species with specific nutrient requirements (Hafner *et al.* 2005).

3.2 Impact of CWD on Water

3.2.1 Lakes and Streams

A paper published by Triska *et al.* (N.D.) shows the importance of CWD in streams and other water ecosystems. It is mentioned that CWD has a major influence on the community of those aquatic organisms. The removal of CWD from streams may change the stream channel, and streamside riparian habitat. Sass (2009) observed that CWD plays an integral role in the stabilization of shorelines and riparian zones from erosion. In addition, Sass mentions that

CWD tends to promote sediment burial, retention, and alternate flows in lotic systems. An example brought out by Sass (2009) is that a lake in Wisconsin experienced an increase by threefold of waterborne methyl mercury concentrations once an entire lake was removed of CWD. In order to understand better the positive impact CWD has on water ecosystems, Sass (2009) broke the impacts down to three integral points. Firstly, CWD tends to have a major impact on the rates of erosion found in banks. Secondly, CWD tends to create pools and allows for specific organisms to live off such material. Lastly, CWD tends to initiate deposition of sediment and helps in the formation of bars.

Haga *et al.* (2002) observed that CWD has the power to influence the ecology and morphology of streams. In moments where streams have considerably high flow rates, it becomes apparent that some woody material in the water may be washed away, therefore causing significant changes in the ecosystem.

Overall, although CWD is often overlooked in water ecosystems, it tends to be integral for the long-term health of water ecosystems.

3.2.2 Fish and Invertebrates

O'Connor *et al.* (1989) addressed CWD as a major player in the aquatic ecosystem and mentioned that CWD found to be 10 centimeters in diameter or larger contributes to high quality habitat for anadromous fish (*i.e.*, species that migrate from freshwater rivers to the ocean and back to spawn in their natural streams). CWD abundance tends to have a major impact on the dynamics of the stream, and the presence of CWD or absence thereof may determine the differences within the ecosystem.

In New Zealand, Wagenhoff *et al.* (2014) observed that the presence of Large Woody Debris (LWD) has no significant impact on the hyporheic invertebrate communities at the site studies. However, the authors acknowledge that adding wood to an aquatic system has been proven to be effective in the process of rehabilitation in hyporheic (*i.e.*, region of sediment and porous space beneath and alongside a stream bed, where there is mixing of shallow groundwater and surface water.) invertebrates. Therefore, the impact of LWD varies based on the area it is found in, the situation of each ecosystem is set case-by-case.

The City of Rochester Hills, in Michigan, reviewed the impacts of CWD on streams in their LWD Management Guide (2007). It is stated that large coarse woody debris plays a large role in the survival of many small organisms, and that it also causes a ripple effect that leads to local populations of organisms tending to help in the overall health of the ecosystem. In addition, CWD provides food to specialized organisms and helps in conserving habitat for such populations. In order for abundant macro-invertebrate and fish populations to be present, it is said that CWD must provide adequate food resources that may be moved by way of the food-web.

Overall, CWD plays a role in the dynamics of streams and in essential communities found within the aquatic ecosystem. As stated earlier, water quality is certainly higher when there is presence of CWD in the ecosystem; and therefore, it may be said that CWD has an impact on the wider range of community dynamics. CWD may be considered integral to the aquatic community, but there still is a call for proper management of CWD in streams to slowly prevent the possible occurrence of extensive floods (JFNew 2007).

3.3 Impact of CWD on Plants

3.3.1 CWD and Trees

CWD tends to play a major role in the succession of trees in any type of canopy forest (Santiago 2000). In order for a woody plant to succeed, aerial roots are typically formed over the nurse logs in order to obtain establishment. Nurse logs with moss have higher success rates (Santiago 2000). As nurse logs tend to harbour significant masses of moss, this allows for higher success rates for species as the moss works as a water retention system and provides water to the germinating seeds. Sanchez *et al.* (2009) observed that large CWD fragments, such as nurse log,s play an important ecological role in tree recruitment in temperate forests. The researchers found that, despite no noticeable difference between the density of seedlings on a given nurse log and the number of seedlings found on regular soil, nurse logs acquired a wider variety of trees than the soil that had no nurse logs. The fragments of large CWD were primarily colonized by a set of smaller-seeded and wind-dispersed species (Sanchez *et al.* 2009). Large CWD has a significant impact on the diversity within the canopy since it acquires species of trees that perhaps soil alone would not have allowed to succeed.

Cooper (2012) observed that core purpose plants grow on CWD. Such a study was conducted in a temperate forest located in the United States. They showed that there are two factors that influence the success of a plant on a large mass of decaying wood, that is the decay class and chance. In order for a decayed log to be available for rooting and success of a plant, it must reach a late stage of decomposition since the material must have the ability to enclose the seed in its debris.

Kumar *et al.* (2017) showed that there is a significant difference in the composition of a forest with changing decay classes and substrate species. Species such as jack pine (*P. banksiana* Lamb.) were found to have significant changes in composition when in stage classes 2-3 (decay process has recently begun) and 4-5 (material more broken down). On this basis, the researchers suggest that due to the great influence of CWD on understorey species, diversity in CWD must be considered at both the decay class and species level.

Arsenault (2002) lists the set of species that are dependent on CWD and there are several hundred. Wide varieties of hepatic (perrenials) and lichen species indicate that CWD plays a heavy role in the survival of many ground species around the B.C. region. The impact of harvesting on CWD dependent species is truly a problem in the conservation of these species. Foresters in the future will need to accommodate for the foreseen decline in such species world-wide with increasing removal of CWD from the forest floor (Arsenault 2002).

3.4 Impact of CWD on Animalia

3.4.1 CWD and Birds

Riffell *et al.* (2010) provide a meta-analysis of biofuel harvests, CWD, and biodiversity. In their paper, they show the various degrees of impact CWD has on wildlife abundance. Their paper also shows that primary and secondary cavity nesters are dependent on dead wood for various uses. Hence, CWD plays a large role in both the long-term and short-term survival of certain bird species.

Lohr *et al.* (2002) claim that the impact of CWD on birds is dependent on the season. During the winter, CWD has less of an impact on bird species than in the summer. There are two main reasons reasons that may cause such a phenomenon. The first is indicated by bird foraging area during the winter months. The data collected by Lohr *et al.* (2002) indicate that bird species that cover larger areas have a larger selection of areas to feed on. This, in turn, decreases their dependence on the density of CWD per unit area. The second is that forest canopies, that have experienced an overall decrease in CWD, allow for higher populations of winter flocking. Lower levels of CWD increases the likelihood of predators persisting in a forest. This allows for habitats of invertebrates to continue to persist in the forest ecosystem (Lohr *et al.* 2002).

3.4.2 CWD and Small Mammals

Loeb (1999) argue, in general, that that there is no significant impact of CWD on the diversity of mammals. Rather, the abundance of CWD impacts specific species of small mammals; *e.g.*, the cotton rat, short-tailed shrew and cotton mice flourished in areas of higher CWD. Coarse woody debris tends to be key in the long-term survival of small mammals since CWD provides an area for nesting, travel routes, roosting sites, *etc.* (Loeb 1999). Despite the correlation between small mammals and accumulation of CWD, each situation may be condition dependent. Therefore, there is no broad, simplistic answer, according to Loeb (1999), on whether CWD has a positive or negative impact on the abundance of small mammals.

Bowman *et al.* (2000) shed light on the impact of woody debris, in various stages of decomposition, on small mammals. Although data revealed that that there was no significant correlation between the level of decay and the frequency rate of the small mammals, it was suggested by Bowman *et al.* (2000) that various small mammals will utilize woody debris at various stages of decay for different purposes. For example, the red-backed vole only nests in rotted logs and utilizes the hardiness of early fallen woody debris as runways (Bowman *et al.* 2000).

3.4.3 CWD on Amphibians and Reptiles

Ground species, such as amphibians and reptiles, that are temperature and moisture sensitive, tend to find CWD as a habitat that is key to their survival (Owens *et al.* 2008). Greenberg (2001) collected data which show that there was no significant difference in amphibian and reptile population sizes between the areas that were logged and those of which were not. In order to supplement such a study, Owens *et al.* (2008) observed that, in general, species of reptiles do not have a response to changes in CWD, but many studies suggest that certain species of snake tend to rely on CWD as refugia and for feed (Owens *et al.* 2008).

3.4.4 CWD and Insects

In a study conducted over three years (Lindgren *et al.* 2006) at the University of Northern British Columbia, researchers focused on the responses of ant and ground beetle communities to variations in coarse woody debris quality. Their results suggest that, in general, ant populations do not have specific requirements regarding CWD since they tend to be generalists and are quite versatile in their area of residence, feeding, *etc.* The only exception to this rule, as suggested by the researchers, is the carpenter ant, *Camponotus herculeanus,* who's requirements tend to be more specific.

The study conducted by Stevens (1997) advanced the idea that CWD plays an integral role in the housing of ant communities. This is because, for the ant community to be established, woody material is used as a colonizing substrate. In addition, Stevens (1997) observed that colonies of ants tend to help in the wood decay process, are predators of spruce budworm, and are prey to pileated woodpeckers. This implies that CWD has an impact that goes beyond just the colony.

Torgersen *et al.* (1995) found, in Oregon, that there is one established colony of ants per 3 downed logs which each contained budworm-foraging ants. Lindgren *et al.* (2006) found that ground beetles were more affected by the population of ants in the community than by the type of woody material found on the forest floor. Therefore, although CWD tends to be revered in the beetle community (Li et al. 2007), it seems that beetles are more critical to the decay process and have increased presence in areas that already consist of populations of ants.

3.4.5 CWD and Earthworms

Hendrix (1996) found that different earthworms utilize CWD in different ways. Although earthworms are commonly considered detritivores, they only have limited biological mechanisms that allow them to digest plant residue living on CWD. Although their actions may not be seen in the early stages of decomposition, it has been found that earthworms will tend to exercise their affect in the second stage of wood decomposition. In addition, earthworms play a very strategic role in the transport of essential nutrients, soil particles, and morsels of the microbial community that are brought into the wood as they move across the forest floor.

3.4.6 CWD and Snails

Caldwell (1996) found that CWD is a very important to many land snail communities in the Southeastern United States. He found that 98 species of land snails are dependent upon log habitats in the Southeastern part of the United States alone (Caldwell 1996). In addition, land snails tend to play a large role in the inoculation process, since they ingest fungal spores.

The Table 1 represents a summary of the results found through the literature review on the biological nature of CWD. Each of the sections are listed as categories and the trends that were found are included on the right column indicating the role of CWD in that category.

Table 1. Summary of all the literature review section of this paper

Category	Role of CWD
Soil	• Helps in the process of decomposition (Li *et al.* 2007) • Retains soils, and increases minerals in soils on a slope (Kim *et al.* 2006) • Increases the fungal and microbial community (Johnston *et al.* 2016; Kwak *et al.* 2015) • Decomposition of CWD in soil helps to predict future forests (Hafner *et al.* 2005) • Holds important contributions to Nitrogen cycling (Woldendorp *et al.* 2005)
Water	• Helps fish and invertebrate populations, provides feed and shelter (Triska *et al.* N.D.; O'Connor *et al.* 1989) • Reduces/slows the process of erosion (Sass 2009) • Invites good organisms to the community (Sass 2009) • Aids in the long-term survival of smaller organisms (JFNew 2007)
Plants	• Promotes a more diverse community • Ensures the success of early-stage trees (Santiago 2000) • Help in tree recruitment (Sanchez *et al.* 2009) • Provides hepatic and lichen species life on the forest floor (Arsenault 2002)
Animals	• Provides feed for birds and other small animals (Riffell *et al.* 2010) • Holds shelter to small mammals, as well as funnels for quick

	transport (Loeb 1999) • Many organisms depend on the process of its decomposition (Bowman *et al.* 2000) • Harbours feed for land snails (Caldwell 1996)

3.6 Management Practices for CWD

This section of the thesis reviews the managerial strategies for CWD across various landscapes. The first section reaches understanding of CWD's positive impacts on biodiversity and how management practices that focus on CWD may help to conserve the biological community. In order to understand the various impacts of CWD management on the conservation of biodiverse communities, various studies across three continents have been identified and used to broaden our understanding of the subject. Countries of the following three continents were used: North America (Canada and the USA), Europe (Finland), and Asia (Iran).

This section also identifies gaps in the literature to lay the groundwork for future studies in this discipline. Finally, recent topics of discussion related to the management of CWD, as well as the most recent advances and discoveries will be called upon in order to gain greater understanding of the current state of science on this topic.

3.6.1 How CWD management conserves the biological community

The presence of CWD in a biological community promotes a more complex and healthier environment, provides habitat structure, and is a nutrient reservoir which contributes to a community that is more diverse (Huston 1993). As managers seek to promote biodiversity, CWD tends to be recognized as a key component in the long-term preservation of such areas. In order to fully understand how the management of CWD may conserve biodiversity over time, it is first important to analyse the purpose of current practices seen in forest management related to CWD. This section presents studies produced from the Canada, USA, Finland, and Iran in order to build conclusions on various ways the management of CWD can conserve biodiversity.

The complete removal of CWD has long-lasting negative effects on the sustenance of the biological community from which it is removed (Lisle 1995). Habitat complexity has been proven to decrease with the removal of CWD in forests. Therefore, the management of CWD, in order to conserve biodiversity, is highly important. Grove (2001) states that forest management is lacking in concern for downed-woody debris. Elton (1966) mentions that CWD has a major influence on the fauna of the forest floor, that when CWD is removed from the forest more than one fifth of its fauna may perish.

Stokland (2001) attests to the desire for less forest management in areas that wish to conserve species. Studies in Scandinavia prove that forests not receiveing treatment through modern forestry practices have been shown to promote higher biodiversity. Therefore, CWD may be defined as an essential piece in the survival of a high volume of animal species in a natural setting (Lisle 1995). Despite the voluminous studies on biodiversity and research dedicated to CWD, studies on their correlation still leave much to be desired (Stokland 2001).

3.6.2 CWD management in BC and Ontario (Canada)

The standard operation for forest managers in Ontario, Canada as stated by the *Natural Disturbance Pattern Emulation Guidebook* (2001) is that for a case of a clear-cut forest, managers must seek to maintain an average of 25 trees or snags per hectare on site (OMNR 2001). It is stated that field workers are meant to ensure that CWD remaining on site must be spaced and of good quality. In addition, logs deemed unmerchantable must remain on site as CWD. Depending on the site, the OMNR uses various techniques to accommodate the change of land; *e.g.*, when managing for very shallow land, the plan to provide the land with fine CWD is necessitated. If foresters find CWD on roadside, this dead wood is burned.

The idea of preserving a natural landscape through the processes of CWD management is well highlighted in British Columbia (BC) forest government publications. The province of BC holds a different approach to CWD management in that managers are called to include CWD management in the plan prior to any harvesting practices due to its ecological benefits (BC Government 2010). This differs from Ontario's practices as forest management teams across the province of BC must account for CWD in the planning process rather than proceeding by a provincial standard.

The BC government suggests that allowing a wider range of decay classes, species types, diameter classes, are important factors in the management of a site for its long-term benefits in diversity. This suggestion is based on assessments of unmanaged forests, as it is inevitable that such forests will contain a higher level of diversity as naturally, fallen dead wood will remain on the forest floor without anthropogenic interactions (BC Government 2010).

In addition to the diversity it adds to the ecosystem, the BC government pushes to keep CWD as an essential tool to produce bioenergy and other materials. Lastly, the impact of CWD management decisions does not only hold importance at the site level, but also at the landscape level. BC forest officials have identified this also based on the fundamentals of an unmanaged environment where larger masses of CWD remain. In order to mimic the natural landscape, the idea of preserving a wide range of CWD is essential for the natural preservation of a landscape over time (BC Government 2010).

Bunnell *et al.* (2010) have identified the impacts of forest practices on the rate of CWD over time in the Pacific Northwest. It was determined that, as a result of such practices, many species are at risk of extinction. On the topic of these decreasing CWD rates due to various forest management implications, Bunnell *et al.* have identified seven management implications that hold true to country-wide management practices in the conservation of biodiversity through CWD management. The following management suggestions are listed and briefly explained with reason of their relevance.

The first suggestion states that sustaining 50% of the naturally occurring amounts of downed wood at the landscape level is beneficial (Bunnell *et al.* 2010). Due to the large gap of studies that have not indicated the CWD levels to leave for optimal biodiversity, Bunnell *et al.* have calculated that around 40% of case studies have reached optimal species richness when sustaining 50% of CWD. This suggests 50% is a reasonable level for maintenance of optimal biodiversity. This is a target and may be changed depending on the trees species. Despite concerns, this management practice has been executed in British Columbia and has proven benefits.

The second suggestion is that managed stands may be insufficient and that foresters must seek timber in the regular, naturally growing forest (Bunnell *et al.* 2010). There are notable cases where managers have not executed the emulation of natural disturbance, especially in the case of CWD management. Since species are dependent on natural processes, there is a question of whether forests should be left to be managed through natural processes in order to conserve biodiversity.

The third and fourth suggestion is to leave an array of sizes and decay classes and ensure that some of the larger pieces of CWD are retained in the landscape. This is in order to optimize biodiversity in the area over the long term (Bunnell *et al.* 2010). As certain species are specific to a decay class retaining a larger variety of size and decay classes will ensure the optimal level of species being conserved in the area.

The fifth suggestion is that managers consider providing the forest with a selection of aggregated and dispersed downed wood over the landscape (Bunnell *et al.* 2010). The practice of retaining aggregated wood provides shelter for many vertebrate species. Non-vertebrate species depend much more of down woody material dispersed over the landscape, thus, maintaining both dispersed and aggregated CWD benefits both groups. In addition, Bunnell *et al.* (2010) add that, if an unwelcomed species of insect invades the forest floor, having dispersed logs allows for the threat to also be dispersed and thereby decreasing the likelihood of invasion.

The sixth suggestion lies in the retention of wood. Managers are asked to focus not only on the dead wood but also on trees that may soon be CWD (Bunnell *et al.* 2010). Relying on the natural death of a tree ensures that the biological processes set for decomposition are properly activated.

The final suggestion is not to perform the same management processes on each forest unit. Managers are asked to use a case-by-case approach and plan for each unit. Each retention process favours a certain species. The optimal goal is to ensure that the highest level of biodiversity is being conserved in the area. This may be done by ensuring higher levels of diversity at the rate of CWD development. As various species may be needed to conserve a forest area, choosing a management practice that is best coupled with that target is of best practice over the long term, *i.e.*, various practices may be implemented over different forest units. This is done in order to ensure that the highest level of biodiversity is being conserved over the long term (Bunnell *et al.* 2010).

These management suggestions conflict with many of the policies set out by the province of Ontario where a standard is followed and unchanging. Setting rules that focus on the optimal conservation of biodiversity is very important at this time since more and more species become extinct over time. It is a call for managers to further consider the impacts of their actions on the biological level. Perhaps the solution may be to realize a more eco-centric approach where the priority is nature's succession above the monetary merits of man.

3.6.3 CWD management in the United States

Graham *et al.* (1994) has identified CWD as being key to biodiversity in the Rocky Mountains of the United States. Recommendations on the management of CWD under the USDA is determined by the study of ectomycorrhiza's effectiveness in the production of healthy forest soils (Graham *et al.* 1994). In order to maintain the long-term productivity of the forest, Graham *et al.* have determined that specific quantities of CWD in each forest type are required in order to fulfill the needs of a long-term productive forest. This conclusion is largely based on the impact CWD holds on biodiversity. If the quantity of CWD left in the ecosystem is too low, biodiversity decreases, but biodiversity increases if an optimum amount is left for the forest. This strongly signifies that managers must find the optimal point where biodiversity is maximized, as is the presence of CWD. The presence of CWD truly protects the diversity of the ecosystem.

Brown *et al.* (2003) identified that, in order to maximize the ecological benefits in the conservation of the biological community and maintenance of biodiversity, managers must optimize the level of CWD on the forest floor. Optimal quantity of CWD on the forest floor means that the quantity of CWD provides the greatest ecological benefits and has low fire hazard. Brown *et al.* (2003) claim that managers must further consider the ecological benefits of CWD in the ecosystem; but that, in order to reach conclusions on such a subject, managers must understand the historical dynamics of CWD in each forest area considered.

The three following pillars (Brown *et al.* 2003) of understanding have been identified as key to the managerial decisions of CWD retention in the ecosystem to conserve biodiversity in the USA:

> 1) understand what levels of CWD will allow for acceptable soil compaction, erosion and sedimentation;
> 2) understand when the expected falldown from fire exceeds optimum CWD;
> 3) understand which forest area has a higher likelihood of being influenced by the landscape scale considerations on the subject of CWD retention.

Huston (1993) states that there is no other ecological factor in the forest that has greater influence on the rate of biodiversity growth than CWD. Due to its premium level of influence on the forest ecosystem's diversity, every management decision about CWD will therefore change the biodiversity of the community. For managers to ensure that biodiversity is conserved and maximized, despite forest practices being executed, ensuring that both high energy input and high structural heterogeneity is key. In addition, by providing the ecosystem with much needed CWD variability in size, stage class, and species, a higher level of biodiversity will be reached. Huston (1993) adds that data suggests when larger trees are removed from the forest floor, CWD energy output and structural benefits drop to zero, therefore amassing a large decrease in biodiversity.

3.6.4 CWD management in Finland

Finland has long understood the variety of decay dependent species that reign on forest floors. The country's forests are known for having very high levels of CWD dependent species. For this reason, Finland is a prime location for understanding CWD management and the impacts it may have on the biological community.

Siitonen (2000) shows that, due to current forest management practices in Finland, approximately 90-98% of all CWD is removed from the forest. This has created many problems for forest managers in the attempt to maintain biodiversity and reap the monetary benefits from the forest. The high rates of CWD removal through management practices in Finland has rendered approximately 50 percent of saproxylic species (invertebrates that are directly or indirectly dependent on dead or decaying wood) in Finland extinct (Siitonen 2000). These numbers continue to grow with the increasing level of managed forests in Finland. Siitonen (2000) states that there are various factors that contribute to the decrease in overall diversity of saproxylic species on the forest floor, such as: the decreasing diversity in size, decay stage, and existing volume of existing CWD on the forest floor.

The absence of these important biological factors has a significant impact on the resulting biodiversity of the forest community. Siitonen (2000) determined that the diversity of CWD on the forest floor is reflected throughout the entire ecosystem. In order for managers to conserve biodiversity, managers must carefully choose management practices that optimize ecological benefits and biodiversity in the forest community to ensure long term health and protection of the ecosystem.

A study presented by Hautala *et al.* (2004) concludes that retention felling has had a significant impact on the volume of CWD existent on the forest floor. In Finland, the process of scarification is a commonly used regeneration method that was predominantly practiced throughout the decade of the 1960's. This method has caused a high volume of CWD to be destroyed in forests across the country. The management of CWD has been accepted as key to obtaining higher levels of biodiversity which has then frothed the idea of retention in felling rather than clear felling (removal of all dead and down trees).

Hautala *et al.* (2004) suggest that better management practices may result in higher levels of biodiversity if the preservation of existing CWD by felling throughout the course of the regeneration phase is practiced. By reducing the use of scarification as a process in the regeneration phase and by lowering frequencies of destruction through other harvesting methods, biodiversity may be conserved. The careful placement of retention tree groups in various patches of high CWD may better preserve the biodiversity at the landscape level.

Rabinowitsch-Jokinen *et al.* (2010) have studied the impact of management on CWD. The study clearly states best practices and their results over the long term on CWD accumulation. They observe that logging and residue harvesting has a significant impact on the remaining CWD on the forest floor; and conclude that this management practice should be avoided if preserving biodiversity is an objective. In addition, although mounding tends to present no impact on the accumulation of CWD in the forest; when mounding is combined with stump harvesting, there are significant decreases in CWD. If managers are expecting to preserve semi-decayed CWD, other management practices are suggested to be sought out and executed (Rabinowitsch-Jokinen *et al.* 2010).

3.6.5 CWD management in Iran

Behjou *et al.* (2018) define CWD as key to supporting biodiversity in the forest system. It is stated in Behjou *et al.* (2018), that the rate of anthropogenic disturbance in Iran is increasing. This type of disturbance is evident in its multiple impacts on the biological community. Results show that, with higher levels of CWD removal, due to anthropogenic disturbance, it is inevitable that the forest-ecosystem is changed (Behjou *et al.* 2018). In Iran, data indicate that, when anthropogenic disturbances increases in a forest area, CWD removal increases. The resulting decrease in CWD leads to lower levels of biodiversity. Therefore, in order to conserve biodiversity, higher retention of CWD is recommended.

A study conducted in the Caspian Hyrcanian mixed hardwood forests of Northern Iran by Sefidi *et al.* (2013) show the need to emulate natural levels of CWD in order to conserve the biological community at large. Sefidi *et al.* (2013) conclude that, in order to properly manage CWD, managers must determine the overall ecosystem and conservation goal of the area and set targets for this goal based on each forest type. Furthermore, in order to conserve or promote a higher level of biodiversity in each forest area, Sefidi *et al.* (2013) observe that the presence of CWD increases both the biological and structural diversity of a younger forest, as well as the habitat potential of any given forest area.

Tavankar *et al.* (2017) have examined, over a 30-year period, the impacts of single-tree selection on the levels of CWD in the Caspian forests of Iran. Using an unmanaged forest to compare the density and size of overall CWD, they showed the long-term effects of such forest practices. The results indicate that forests managed by single-tree selection cutting have caused a significant decrease in the overall size and density of CWD in the forest.

Despite the negative impacts of this technique on CWD and, in turn, biodiversity, Tavankar *et al.* suggest that there are no management techniques that will not have an impact on CWD. This is a call for managers to find alternatives that present the least damaging effects on CWD. This study suggests that managers produce CWD management plans and that they base all management decisions on the plan itself. This would help to conserve biodiversity in the long run and may yield additional benefits.

Tavankar *et al.* (2017) state that "CWD Management Plans" must lay the groundwork for the following decisions: 1) the establishment of cutting cycles that are fit for CWD conservation; and 2) cutting cycles that are appropriate for retention of large-diameter and cavity trees in order to promote the persistence of wildlife populations in the area.

3.6.6 Brief Conclusion on CWD Management Strategies

In order to form conclusions on the managerial aspects of CWD management and the conservation of biodiversity, it may be suggested that the biological framework in a managed forest is determined by the forest managers. Therefore, a chain reaction exists, in which: 1) the decisions of the forest management team impact 2) the amount and type of CWD retained which impacts 3) the resulting biodiversity.

The impact of a forest manager's decisions on biodiversity through CWD management may also be explained as follows:

Decision of manager/s → amount and type of CWD leftover → ecosystem ramifications

Overall, management practices that aim to preserve the accumulation of CWD on the forest floor also conserves the overall biological community and maintains higher levels of biodiversity. Balancing the positives and negatives of CWD's presence is a must for managers.

In order for forest managers to reach their desired levels of biodiversity, it is necessary to first assess which species are aimed at being conserved or promoted; secondly, determine which tree species is of best fit for species survival over the long term, and lastly, to ensure that such a species is available to the biological community and a right percentage is left to guarantee greater health as the forest grows. Table 2 summarizes this section.

Table 2. Summary of management strategies for CWD, by country.

Country	Management Strategy for CWD
Canada	-Province of Ontario specifies a 25 stem/ha approach (OMNR 2001) -Ontario specifies allowing for higher quality CWD to be left on site, well spaced across the landscape (OMNR 2001) -Province of British Columbia (BC) focuses more on emulating the diversity of an unmanaged forest (BC 2010) -BC includes CWD in the management plan prior to harvest (BC Government 2010) -BC has identified 7 suggestions that concentrate on adaptive management (Bunnell *et al.* 2010)
United States	-Focused on the impact of ectomycorrhiza in the biological community (Graham *et al.* 1994) -Focused on adaptive management, realizing the optimal percentage on the forest floor that impacts, positively, the future forest (Graham *et al*. 1994; Brown *et al.* 2003) -Important rules are: determining the acceptable levels of soil compaction, erosion, and sedimentation, finding the highest tree falldown points, and determining which area will be more likely to be influenced by CWD retention (Brown *et al.* 2003) -Aiming for high structural heterogeneity and energy input is key (Huston 1993)
Finland	-Historically, 90-98% of CWD was removed from the forest floor, meaning there was less focus on biodiversity in the community (Siitonen 2000) -Adaptive management is needed (Siitonen 2000) -Reduction of retention felling in addition to scarification (Hautala *et al.* 2004) -Avoiding other practices such as logging, and residue harvesting may be essential in some areas (Hautala *et al.* 2004)
Iran	-Realizes the impacts of anthropogenic disturbance and calls for higher retention of its CWD on the forest floor (Behjou *et al.* 2018) -Emulate natural rates of CWD to optimize biodiversity (Sefidi *et al.* 2013) -Determine goals of conservation prior to practice, choose for optimal structural and biological diversity of the community (Sefidi *et al.* 2013) -Avoid single tree selection cutting (Tavankar *et al.* 2017)

	-Establish cutting cycles fit for CWD and that are appropriate for retention of large-diameter and cavity trees (Tavankar *et al.* 2017)

4.0 Discussion

The objective of this discussion is to evaluate the management strategies for CWD (that have been reviewed in 4 countries) based on the biological nature of CWD (which was reviewed based on its impact on soil, water, animals, and plants). Hence, in this discussion, each country's strategy for managing CWD will be evaluated by how well their strategies address the impact of CWD on soil, water, animals, and plants.

Part I. Evaluation of Canadian policy on CWD

As seen in the previous section, the management of Canada's CWD tends to be varied across the landscape. Ontario follows a standard operation whereas British Columbia tends toward an adaptive management approach (OMNR 2001; BC Government 2010). Each of these management perspectives result in strategies that relates purely to the amount remaining of CWD on the forest floor.

Ontario states in its policy rules that the CWD on the forest floor must be of good quality and must remain well-spaced (OMNR 2001). This management rule does not state any reason as to the ecological benefits of higher quality CWD and its impact on the forest floor, nor does it state an index as to what is considered high quality CWD. Additionally, given all the benefits CWD holds on the biological community (as discussed previously), it may be of good practice to state the variety of positive impacts CWD holds on biological characteristics such as soil, water, plants and wildlife, in order to form better policies that account for the entire forest community.

Since CWD helps in the process of decomposition and increases organic matter breakdown in the soil when present on a slope, this must be addressed in forest management policy in order to accommodate for the difference in topography (Li *et al.* 2017; Kim *et al.* 2006).

In the review of policy in Ontario and British Columbia, and with supplementing literature from earlier sections, it seems that Ontario and British Columbia must address the positive impacts of CWD in aquatic ecosystems (Triska *et al.* N.D.; O'Connor *et al.* 1989). In addition, as proposed for Ontario, in order to reach optimal benefits to the forest community (and the foresters as well), creating frameworks that address each of the ecological factors may be best for the future of forest policy regarding CWD management and protection of biodiversity.

In addition, providing specific guidelines or frameworks that address various considerations in the planning process may have a variety of benefits to the biological community over time. An example of a guideline may be the following: if managers are striving to reduce the impact of erosion on the biological community, it would be optimal if a guide addresses such a situation. As previously stated, increased CWD reduces the rate of erosion, therefore, managers may be asked within the guidelines to preserve the highest amount of CWD within the area of concern (Sass 2009).

The government of British Columbia suggests adaptive management in order to optimize the positive impacts of CWD on soil, water, plants and animals. The greatest suggestion proposed by Canadian researchers is the seven suggestions of Bunnell *et al.* (2010). These examples, hailing from the Pacific Northwest of Canada and account for the largest types of ecosystem.

The seven suggestions provided by Bunnell *et al.* (2010) account for all factors such as plants, animals, soils, and water prone organisms. These suggested rules should be considered across Canada in order to build better management rules that account for the broadest range of the natural environment. When managers are preparing to begin forest operations, the consideration of the seven suggestions helps to obtain greater knowledge on the topic of CWD and its effectiveness on the forest ecosystem.

In order for the Canadian forest management teams to further equip their heirs to the industry, the prime suggestion is to develop a best practice guide for CWD in each forest ecosystem across the country. This may be included in each of the guides for ecosites across the country. Making this available to forest managers will help to mitigate further problems with biodiversity in the future. Despite this evaluation being a large undertaking, it will help to accomplish the goal of conservation through forest management and build further understanding of CWD's impact on forest characteristics. In addition, the implementation of such rules may bring the conservation of biodiversity to new levels and will certainly act as an important piece in the greater understanding of how other countries may manage for the conservation and preservation of their most vulnerable communities.

Part II. Evaluation of United States policy on CWD

The United States presents adaptive management as being at the forefront of management practices for CWD (Graham *et al.* 1994). As management practices are further focused on the impact that ectomycorrhiza has on the biological community, it is apparent that the USA addresses plants, animals and soil (Graham *et al.* 1994; Brown *et al.* 2003). USA management strategies fail to consider management practices that account for water.

Management practices must be addressed for aquatic ecosystems in order to further fulfill the need for greater diversity, or protection of diversity within aquatic systems.

United States forest management rules on CWD focus primarily on the impacts CWD have on soil. As Brown *et al.* (2003) state, finding acceptable levels of CWD on the forest floor that have optimal benefits for compaction, erosion and sedimentation presents great benefits for the future of forest ecosystems. Such a statement calls for government to state such needs in forest management guides. The United States Department of Agriculture (USDA) is a stronghold in determining valuable benefits CWD holds on American forests. The USDA must continue to provide research in order to deepen knowledge and build management practices that sustain the biological community.

Despite the USDA's efforts to further understand the impacts of CWD on the forest ecosystem, America's forest management guides must continue to strive to implement management rules that clearly state the importance of CWD and its value in conserving the future health of forests.

After a review of the variety of policies centered on CWD management in the forest, the USA presents exemplary management ideas despite lacking in the area of waterways. The USA has determined that the primary focus of management must be set on obtaining high structural heterogeneity and energy input in order to ensure high success rates for the future health of forests (Huston 1993). This suggestion is completely in line with the studies produced by Johnston *et al.* (2016) and Kwak *et al.* (2015) who have suggested an increase in structural diversity through the presence of CWD.

For the USA to fulfill the needs for CWD management of waterways, it would be essential to produce a management guide that clearly states practices that help in the assessment process of CWD management in such areas. If applicable, including water management in the planning process would hold high benefits. In order to build this sustainable future, producing management guides that direct forest managers to a variety of practices that may be executed, under law, would be of great interest. Furthermore, supplementing policies with the works of Brown *et al.* (2003) who clearly state three ways to determine the variety of practices that may help in CWD retention in the ecosystem will yield benefits in the future. Determining acceptable levels that reduce the impacts of erosion is clearly important in waterways. In addition, stating management practices that aid in the life of aquatic organisms such as vertebrates and invertebrates alike, is vital for future conservation efforts in aquatic systems.

As the United States presents large topographical diversity across a variety of states, it may be of best practice to allow each state to perform management rules on a case-by-case basis, allowing for state forest managers to speak to their criteria based on their topographical differences.

Regarding wildlife, the United States succeeds in mentioning the impacts of CWD on various organisms such as birds, small mammals, *etc.* The only problem that lies within their policy is that the USA fails to propose management practices that increase wildlife diversity. Despite mentioning the increase in biodiversity throughout the variety of their publications, there lacks reason regarding the preservation of wildlife within the landscape. In order to best address this gap in policy, a review of past studies such as those mentioned previously in this study (example: Riffell *et al.* 2010, Loeb 1999, and Bowman *et al.* 2000) may help in the overall understanding of CWD's variety of impacts on mammalian communities.

Part III. Evaluation of Finnish policy on CWD

After assessing the literature, the author believes that forest management in Finland still leaves much to be desired. As the country continues to lose larger CWD volumes of its naturally occurring species, it becomes a question whether their policies address the variety of other biological characteristics.

The variety of papers reviewed demonstrate that forest management guides in Finland have failed to evaluate the significance of CWD on the forest community. Despite the evidence that CWD has positive impacts on forest characteristics, the country fails to sustain biodiversity in its forests (Siitonen 2000). With decreasing biodiversity across the landscape, forest managers must produce management rules that preserve biodiversity and protect plants, animals, water, and soil. Even though Hautala *et al.* (2004) have mentioned the importance of a reduction in retention felling and scarification, this may take time to reach Finnish policy on the matter of CWD.

Management of CWD in the forest does not seem to be considered of significant importance. In order to preserve biodiversity in the forest communities of Finland it is of best practice to implement policy that restricts the over removal of CWD in the forest area. Creating thresholds that emulate natural disturbance would be optimal. A review of the management suggestions proposed by Bunnell *et al.* (2010) may help to supplement policy on the subject. As Bunnell *et al.* (2010) propose, sustaining around 50% of the naturally occurring amounts of CWD in the landscape would be of great benefit to the biodiversity in the forest ecosystem. Reduction of removal has proven benefits to the biological community, therefore, a serious review of policy in Finland must be enacted.

As commonly stated, Northwestern Ontario and Finland have similar forests; therefore, in order to supplement a new wave of policies that account for biodiversity in addition to the overall health and protection of plants, animals, soil and aquatic communities over time, the suggestions proposed for Canada may be used in Finland as well, although economic stance must inevitably evaluated prior to implementation and planning.

As the goal for Finland is to truly attain richer biodiversity over time, management suggestions must be extracted from studies produced in other countries. More studies must be done on forest operations effects on groundcover, that would supplement reasons for policy to be focused on the preservation of plant communities.

Siitonen (2000) stated that adaptive management is needed in Finland, therefore, a re-evaluation of current practices must be made in order to fulfill overall management needs. Determining the areas of concern, species needed to conserve, and ideal population levels is a valuable suggestion for managers across the country. In order to ensure that all forest characteristics are being accounted for, it is best suggested that clear guides be formed that state each of the forest characteristics, their importance and dependence on CWD, and forest management practices that produce benefits to the associated characteristic. For example, if a managed forest requires less residue harvesting, a forest manager must be able to follow guidelines as suggested by Hautala *et al.* (2004).

Part IV. Evaluation of Iranian Policy on CWD

Iranian forest management strategies account for a variety of forest characteristics. As stated by Sefidi *et al.* (2013), Iran strives to emulate natural rates of CWD in the forest. Despite not mentioning CWD management for aquatic ecosystems, this management rule may be applied to such areas. In addition, Iran strives to implement practices of adaptive management where the conservation of specific species is addressed. Building management guides that state best practices for the conservation of specific species may be of interest for forest managers in Iran.

Iranian forest policy on CWD management fails to account for wildlife; therefore, determining the areas of concern and species targets for managed forest areas may optimize diversity and health of species over time. Including species targets in the conservation plan prior to harvest is optimal.

In order to determine wildlife conservation practices to benefit the long-term survival of Iranian wildlife, it is best to make assessments of the species that live on the forest floor and fend from CWD or use CWD as shelter (Loeb 1999). Once having determined the species, practices may be reviewed and implemented in order to ensure the highest level of biodiversity is being attained every time a forest practice is executed. As Tavankar *et al.* (2017) suggest, in order for managers to perform sustainable forest practices, least impactful practices must be determined and defined within policy measures.

Managers fail to mention the impacts of CWD in aquatic systems and management practices that may benefit the biodiversity of aquatic life. Therefore, building management practices that address the need to conserve aquatic ecosystems may be of great concern at present.

Despite not specifying the immediate actions that may conserve overall biodiversity of aquatic ecosystems, Iran hopes to raise its rates of CWD retention (Behjou *et al.* 2018). Therefore, if this is practiced, Iran will be addressing plants, water, animals and soil equally, yielding high ecological benefits. Iran has addressed its concerns on the overall impacts of selection cutting, as stated by Tavankar *et al.* (2017) by avoiding this forest practice so that higher levels of biodiversity are attained.

Iran must assess the current state of their forests and determine practices that best manage their forest characteristics. Primary studies produced in Iran concern the North Caspian Hyrcanian mixed forest. This area is known to be a temperate broadleaf and mixed forest and, since it is situated near the Caspian Sea, and there may be a question as to the variety of aquatic organisms that depend on CWD providing nutrients.

The primary suggestion for Iranian forest managers is to assess the impacts of CWD on the aquatic systems within forested areas, secondly, to implement policy surrounding the retention of CWD on the forest floor (which may be applied to aquatic communities as well), and lastly, to use past studies executed on the subject of CWD management in other countries in order to form policies that truly account for all forest characteristics and make way for the conservation of biodiversity over time.

Part V. Significant Gaps in the Literature

Despite the voluminous studies conducted on CWD, there remains much to be discussed in order to gain a full understanding of how CWD can have a positive impact on the forest community. Seven significant research gaps have been found within the literature reviewed for this thesis and shall be discussed in this section.

First, the concept of decomposition of CWD into the organic material (OM) truly answers the question of CWD's positive impact on the forest since a large portion of the biota within the forest floor utilizes such decomposition for their survival (Li *et al.* 2007). Despite all that has been said regarding the biological community that depends upon the decomposition of CWD, studies have yet to determine whether the CWD dependent species are specific to tree type.

Second, understanding the dynamics of CWD in the carbon budgets is little studied. Based on the low volume of studies that have been conducted on this subject, a conclusion on the impact of CWD on soil-carbon may not be fully understood. In order to make concrete decisions on whether CWD should be managed for in the context of carbon-soil content and the classification of a microsite, further dedicated studies must strive to include such in assessments.

Third, nutrient cycling, a very important part of the OM does not exhibit a high volume of studies either. There is much to be desired in understanding the correlation between nutrient cycling and CWD. In order to fulfill this desire, researchers who focus on CWD must consider its impacts on soil processes. In order to account for both subjects, a greater study regarding the impact of CWD on forest carbon budgets and nutrient cycling may be best exacted in order to further understand CWD's organic process.

Fourth, within the branch of CWD's impacts on water, CWD has truly been shown to increase the quality of the biological community and help prevent riparian areas from erosion. In addition to what has been previously identified, studies on the impact of CWD on lentic ecosystems should be further considered. Beyond studies focused on the direction of streams due to the presence of CWD, the impact of decomposing CWD within the aquatic environment must be studied in order to: understand the change in water quality over time and gain further comprehension of whether CWD has a positive impact on the quality water. Furthermore, understanding the importance of CWD in predator-prey interactions within an aquatic environment is important and must be considered in order to gain deeper comprehension of CWD's role within the aquatic community.

Fifth, despite the voluminous studies focused on the correlation between CWD and standing live trees, very little has been discussed on the impact of CWD on the plant community. A higher frequency of studies must be dedicated to the impact of CWD on the biodiversity of plants within the forest community. This may strongly supplement the understanding of overstory trees in the forest and in addition the understanding of corresponding animals in the area.

Sixth, it has been shown that CWD's relationship with land snails is of high importance in key ecological processes; yet there are few studies conducted on its relationship (Caldwell 1996). There is much to be desired in studies observing the specific contribution of land snails to CWD decomposition, and the positive impact CWD holds on the survival of land snails. In order to fulfill this requirement, field assessments may account for the existence of land snails, or a dedicated study indicating the relationship of CWD and land snails is optimal.

Seventh, even though earthworms reside under CWD, rocks, and other such areas, in addition to the strategic role earthworms play in the decomposition process identified by Hendrix (1996), there still exists only one dedicated study to the subject. Earthworms play a fundamental role in the ecosystem. To understand their specific role in the process of CWD decomposition is an area requiring further study..

Part VI. Persistent Problems and Breakthroughs Observed in Research on CWD

Five persistent problems were observed in the review of CWD and its management. In addition, two highly significant breakthroughs in CWD research have also been observed.

First, as Yan *et al.* (2006) suggest, is how ecologists will come to an agreement on the definition of CWD. It is proven that there are numerous factors that influence the definition (*e.g*., topography, forest type, species type, *etc*.), and are all therefore an impediment to the agreement. The question is whether there will be a world standard definition brought out by forest ecologists. This discussion is a long way from being solved. Due to the various factors influencing CWD's definition, it may be concluded that there is no universal definition to be discussed and that the definition remains in the hands of multiple and diverse planning foresters.

Second, the largest topic of discussion is the question of: 1) CWD's impact on forest characteristics; and 2) management practices required to preserve the long-term health and diversity of the biological community. This discussion has been ongoing for the past decade and although the subject holds considerable impact on the future biodiversity of forest ecosystems worldwide, it has not been of paid the attention it is due and an integrated topic (Yan *et al.* 2006).

Third, regarding CWD management focused on the preservation of biodiversity over time, Canadian management requirements have perhaps never been brought to discussion and have bewildering disagreements in policy and management suggestions. The seven management suggestions previously mentioned by Bunnell *et al.* clearly stated that, in order to ensure high future levels of biodiversity, management considerations must accommodate the various forest conditions at the landscape level. This is completely opposed to the management requirements thought out by Ontario's Ministry of Natural Resources and Forestry, who have clearly stated a standard and that managers must adhere to this management rule universally, regardless of site-specific conditions (Bunnell *et al.* 2010; OMNR 2001).

Fourth, from an operational scale of forest management, subjects of discussion may perhaps be brought to light on policy for CWD management and the preservation of biodiversity over time in the forest despite current practices. In order to ensure future biodiversity, forest managers must consider their impacts on the bio-community through forest operations. Detailed operational best practices are needed to reduce the impact to the area attended to, in order that biodiversity may be optimized over time.

Fifth, as most of the groundwork has been covered on the topic of CWD over the last 75-90 years, the current discussion lies in policy making. It was Hagan *et al.* (1999) who stated, forest managers would much rather begin with a clean slate of forest floor at the end of their array of forest management practices. Given that the resulting biodiversity is at the hands of forest managers, this creates a conflict since biodiversity must be conserved. Furthermore, as managers prefer "cleaner" forest floors, this has a major impact on the discussion of CWD in spite of the current declines in biodiversity.

A recent breakthrough on CWD research has occurred in the work of Gorgolewski *et al.* (2020). Gorgolewski *et al.* (2020) have developed a matrix transition model that predicts nutrient dynamics of CWD over a long-term period. The idea was brought to light by using CWD density, volume, and nutrient concentrations through a decay class transition model in order to obtain the future nutrient dynamics. This gives managers the opportunity to dive deeper in their assessments of CWD management, in order to determine optimal conditions for the forest floor, through the providence of CWD. Despite all data that has been acquired on the subject of CWD, this is the first decay class transition model that predicts nutrients other than carbon rates over time. In addition, Gorgolewski *et al.* (2020) have determined that other nutrients in the soil may be predicted based on this model, indicating that the future on this subject is bright.

From a managerial perspective, the demonstration of the model presented by Gorgolewski *et al.* (2020) suggests there will be great advancements in the aspect of both policy making and forest management. If utilized, CWD standards set by provinces may be revisited and compared to the actual results of the model in order to create standards that ensure the highest level of biodiversity conservation over time.

A second recent breakthrough in CWD research was made in Alberta, Canada Queiroz *et al.* (2020) mention that managers are struggling to assess CWD abundance over a landscape. and who claim that foresters can predict future CWD volumes by way of image analysis of multispectral LiDAR. Despite the discovery being at its early stages, there is strong evidence that this method may be the path for future foresters in assessing CWD volume over large forest landscapes. Through optical imagery and infra-canopy vegetation-index layer data used from multispectral aerial LiDAR, managers will be able to obtain more accurate data. It is said that the maps can provide additional alternative benefits such as fire-hazard assessment and seismic line restoration.

5.0 CONCLUSION

In this thesis, it has been shown that specific species are more inclined than others to rely on CWD as feed, habitat, refugia, *etc*. Coarse Woody Debris plays a very important role in the future success of a forest ecosystem. Dead woody material aids in the succession of more diverse species and is a very important component that should be further considered in management practices that aim to conserve biodiversity.

This thesis has also shown that, in order to apply such knowledge into the forestry sector, it may be of significant use for forestry professionals to consider the impacts of CWD and its need to be conserved. For those practicing wildlife assessments, or tree inventory practices, it may be best to take the following precautions reviewed in this thesis prior to deciding whether to remove higher levels of CWD. First, for wildlife assessors, consider which species are present in the forested area and find whether they are dependent on CWD as refugia, for feed, or even for its fungal communities. Second, for those practicing tree inventory, assess which trees are in the canopy and select to remove the trees wisely as each morsel of CWD that is left to become part of the OM has an impact on the forest cover of the future.

Through the findings of this thesis, it may be concluded that it is best to conserve CWD because of its positive impact on forest characteristics and its protective actions for small mammals and other such members of the forest community. Additionally, CWD must be considered in the management process for increased protection of biodiversity over time. The management of CWD is vital for the forest community and forest managers have the power to determine the future of biodiversity in forest communities worldwide.

Future research can be made about CWD's biology. The continuation of studies that focus on its specific actions in helping to conserve species is highly important. Despite the high volume of studies that have been focused on the key biological benefits of CWD, researchers must be called to produce studies about CWD in order to gain attention from forest managers.

In order to supplement current studies, long period assessments of CWD's impact on specific forest characteristics will highly benefit the study of CWD and its value to the ecosystem. In addition, considering CWD an important forest indicator may supplement studies in management in order to help in the prediction of the future forest conditions of specific areas.

In the future, there is hope for larger scale, more intensive and dedicated study to this subject. Despite the studies that have been presented in the literature, gaps remain in the relationship between epixylic species and CWD. In addition, studies regarding CWD's relationship with lichen and hepatic species should be conducted in forest regions that have higher levels of lichen. And finally, further studies in the relationship of CWD with land snails should be conducted over a long-term period in order to fully understand the relationship found in CWD and land snail communities.

Regarding forest management, despite current discussions and the models that have recently been discovered, there remains much to be desired. The goal of forest managers must be to implement policies that are strong, non-debatable, and ensure higher biodiversity over time in order to counteract the current declines worldwide. The implementation of management rules per ecosite (forest type) may be of best interest, this may ensure the greatest outcome for forest biodiversity.

Since this thesis is not part of a larger field assessment, the findings in this review of research papers may be used to spark ideas in further research or experiments that may allow for greater discoveries regarding this vital subject.

Overall, CWD is proven to be highly important in the overall ecosystem and is proven to be key to overall biodiversity. The preservation of CWD on the forest floor ensures higher levels of biodiversity over time and therefore, CWD should never be ignored in the management process. This study suggests that CWD harbours communities and protects their dynamic relationships which further aids in the wider forest community. In addition, CWD plays an integral role in sheltering such community interactions.

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