Forest Ecology and Management 377 (2016) 1–15

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Tamm Review: Sequestration of carbon from coarse woody debris in forest soils

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A R T I C L E I N F O

Article history:
Received 2 March 2016
Received in revised form 16 June 2016
Accepted 19 June 2016

Keywords:
Carbon sequestration
Coarse woody debris
Forests
Soil carbon stabilization
Forest management

A B S T R A C T

Worldwide, forests have absorbed around 30% of global anthropogenic emissions of carbon dioxide (CO_2) annually, thereby acting as important carbon (C) sinks. It is proposed that leaving large fragments of dead wood, coarse woody debris (CWD), in forest ecosystems may contribute to the forest C sink strength. CWD may take years to centuries to degrade completely, and non-respired C from CWD may enter the forest soil directly or in the form of dissolved organic C. Although aboveground decomposition of CWD has been studied frequently, little is known about the relative size, composition and fate of different C fluxes from CWD to soils under various substrate-specific and environmental conditions. Thus, the exact contribution of C from CWD to C sequestration within forest soils is poorly understood and quantified, although understanding CWD degradation and stabilization processes is essential for effective forest C sink management. This review aims at providing insight into these processes on the interface of forest ecology and soil science, and identifies knowledge gaps that are critical to our understanding of the effects of CWD on the forest soil C sink. It may be seen as a "call-to-action" crossing disciplinary boundaries, which proposes the use of compound-specific analytical studies and manipulation studies to elucidate C fluxes from CWD. Carbon fluxes from decaying CWD can vary considerably due to interspecific and intraspecific differences in composition and different environmental conditions. These variations in C fluxes need to be studied in detail and related to recent advances in soil C sequestration research. Outcomes of this review show that the presence of CWD may enhance the abundance and diversity of the microbial community and constitute additional fluxes of C into the mineral soil by augmented leaching of dissolved organic carbon (DOC). Leached DOC and residues from organic matter (OM) from later decay stages have been shown to be relatively enriched in complex and microbial-derived compounds, which may also be true for CWD-derived OM. Emerging knowledge on soil C stabilization indicates that such complex compounds may be sorbed preferentially to the mineral soil. Moreover, increased abundance and diversity of decomposer organisms may increase the amount of substrate C being diverted into microbial biomass, which may contribute to stable C pools in the forest soil.

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http://dx.doi.org/10.1016/j.foreco.2016.06.033

1. Introduction

The Kyoto protocol has led to increased attention to the potential of C sequestration in forests in order to mitigate rising levels of atmospheric CO_2. In the past decades, forests have absorbed about 30% of worldwide anthropogenic CO_2 emissions annually (Schulze et al., 2000). However, much uncertainty remains about forest C sink-source dynamics, especially the effects of forest management (Bellassen and Luyssaert, 2014). Naudts et al. (2016) found that despite increases in forest area and in forest management in Europe in the past 250 years, European forests have failed to achieve a net removal of CO_2 from the atmosphere. This was attributed to increased wood extraction which has resulted in a removal of CO_2 from biomass, dead wood and forest soils. Thus, Naudts et al. (2016) demonstrated that not all aspects of forest management will mitigate climate change. This review will discuss the effects of one possible management intervention – retention rather than removal of large dead wood fragments on the forest floor – on sequestration of C in forest soils. It has long been common practice to remove CWD from forests, leading to a global decrease in CWD (Grove, 2002; Moroni et al., 2015). Globally, coarse woody debris (CWD) contains about 36–72 Pg of C (but see Russell et al., 2015 for factors that greatly affect such estimates), and the fate of this C will affect forest C dynamics (Cornwell et al., 2009) as well as global surface C stocks with feedback to climate (Brovkin et al., 2012). In recent literature it has been proposed that leaving dead wood in the form of CWD in forests rather than clearing it, contributes to the system's C sequestration (Luyssaert et al., 2007; Gough et al., 2007; Nave et al., 2010; Cornelissen et al., 2012; Wiebe et al., 2014). Apart from C sequestration, CWD may also provide other ecosystem services such as a habitat, food and nutrients for numerous organisms. For instance, many saprophytic organisms are threatened by extinction due to the global decrease in the presence of CWD (Grove, 2002; Stokland et al., 2012).

Carbon sequestration is defined in different ways within the current literature. It may for instance be defined as the difference between ecosystem C uptake (gross primary production) and C losses (respiration and non-respiratory losses, e.g. export) (Luyssaert et al., 2008), which is roughly analogous to the forest C sink concept (Pan et al., 2011). The IPCC (2007) defined C sequestration as "The process of increasing the C content of a reservoir/pool other than the atmosphere", which will be used as the definition throughout this review. During the past 10 years of research on terrestrial C sequestration the view has emerged that apart from aboveground sequestration of C into biomass, belowground stabilization of C into soil OM pools is an important factor in long term C sequestration (von Lützow et al., 2006; Marschner et al., 2008; Dungait et al., 2012; Ohtsuka et al., 2014). Therefore, it is important to not only consider the aboveground effects on C fluxes resulting from presence of CWD, but also C fluxes from CWD to soil and the fate of this CWD-derived C in forest soils.

Coarse woody debris is an important C pool in forests. Residence times of CWD vary widely based on their size, species and local environment. Half-lives of up to 230 years have been found (Harmon et al., 1986), and Kueppers et al. (2004) reported average residence times of up to 800 years for coniferous species in a subalpine setting. Locally, especially in cases of buried CWD on paludified sites, CWD may persist for over centuries (McFee and Stone, 1966; Triska and Cromack, 1980; Moroni et al., 2015). Although exact definitions may vary, CWD is usually defined as wood fragments with minimum diameters of between 2.5 and 10 cm (Harmon et al., 1986). Distinctions can be made between fine woody debris and intact stems and branches, the latter of which may be downed or still standing. We adhere to the classification proposed by Harmon and Sexton (1996). Fragments smaller than 10 cm in diameter and 1.5 m in length are fine woody debris. Larger fragments can be present as snags (vertical standing fragments resulting from natural processes), stumps (short vertical elements resulting from cutting) and logs (or downed woody debris, DWD). A common distinction between DWD and snags is a lean angle of 45°, larger angles representing snags and lower angles representing DWD. We adhere to Harmon and Sexton's (1996) proposal that also short elements at lean angles >45° be defined as either snags (in case they result from natural processes) or stumps (in case they result from cutting). Belowground elements can be divided into buried wood and coarse roots (Harmon and Sexton, 1996). Although most studies focus on snags and logs, roots and stumps are important constituents of CWD (Palviainen and Finér, 2015), and are included in our definition of CWD.

CWD is structurally and chemically different from leaf litter, and its fate in soils differs from leaf litter (Cotrufo et al., 2013). Extrapolation of results from (far more numerous) studies on non-woody litter would be unjustified. However, this difference has not received prominent attention in ecological research and is underrepresented in terrestrial carbon models. Making such a distinction may greatly enhance modelling of litter decomposition and resulting effects on climate (Brovkin et al., 2012). It is of paramount importance that more scientific attention is dedicated to the effects of CWD on the forest carbon cycle. Various studies have made attempts to identify and quantify pathways of CWD decomposition (Forrester et al., 2012; Herrmann and Bauhus, 2013; Ohtsuka et al., 2014; Bantle et al., 2014), but not of stabilization of CWD-derived C in soils. At the same time, our understanding of principles of stabilization of OM in soils has greatly increased