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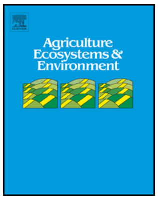

Carbon pool size and stability are affected by trees and grassland cover types within agroforestry systems of western Canada

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ABSTRACT

Agroforestry systems are common land uses across Canada and could play a substantial role in sequestering carbon (C) as part of efforts to combat climate change. We studied the impact of component land cover types (forested vs. adjacent herbland) in three agroforestry systems (hedgerow, shelterbelt and silvopasture) on organic C and nitrogen (N) distribution in three density fractions of soils at the 0–10 and 10–30 cm layers. The study evaluated 36 sites (12 hedgerows, 12 shelterbelts and 12 silvopastures) in central Alberta, Canada, distributed along a soil/climate gradient of increasing moisture availability. At the 0–10 cm layer, soil organic C (SOC) stock in the bulk soil was significantly greater in the silvopasture system (101) than in either the hedgerow (77) or shelterbelt system (67 Mg C ha^{-1}). Soil organic C stock in both soil layers (0–10 and 10–30 cm) was also significantly greater in the forested land cover (89 and 119 Mg C ha^{-1}, respectively) than in adjacent herblands (76 and 77 Mg C ha^{-1}). Across all sites, 31.5, 29.1, and 35.5% of SOC was found in the light fraction (<1.6 g cm^{-3}), occluded fraction (ultrasonic dispersion at 360 W for 5 min, <1.6 g cm^{-3}), and heavy fraction (>1.6 g cm^{-3}) of soils, respectively. The largest pool of SOC in the more labile light fraction of the 0–10 cm layer was in the silvopasture system (50 Mg C ha^{-1}), whereas the smallest labile light fraction component of SOC was in the shelterbelt system (17 Mg C ha^{-1}). The largest pool of SOC in the more stable heavy fraction of both the 0–10 and 10–30 cm depth classes was in the shelterbelt (33 and 35 Mg C ha^{-1}, respectively), while the least SOC was in the silvopasture system (26 and 20 Mg C ha^{-1}, respectively). We conclude that the presence of *Populus* based silvopasture system can increase C storage in surface mineral soils, and that the establishment of *Picea* based shelterbelts in an otherwise annually cropped agricultural landscape enhances the size of the stable SOC pool.

1. Introduction

Soil organic matter (SOM) is a complex mix of plant and animal residues in various degrees of decomposition that affects soil quality, tilth and productivity, and regulates global carbon (C) cycling (Alvarez and Alvarez, 2000; Lal, 2002). Most studies over the past several decades demonstrate that conversion of lands from forest to herbland can significantly decrease SOM levels (Burke et al., 1989; Bonde et al., 1992; Paustian et al., 2000; Sainju et al., 2012). Cultivation alters the amount, timing, and quality of organic residue input into soils (Sollins et al., 1996; Campbell et al., 1999), which in turn, has an effect on the size, rate of recycling and distribution of C among SOM pools (Kang, 1997; Christensen, 2000). In contrast, forested land cover can increase SOM because of the continuous deposition of plant litter (Oelbermann et al., 2004; Paul et al., 2002) and limited removal of biomass because of infrequent harvesting (Six et al., 1998; Ayres et al., 2009; Nascente et al., 2013).

Agroforestry is a unique land use system that intentionally blends perennial vegetation and herbaceous land cover types to enhance crop productivity, profitability, and overall soil quality in agroecosystems. In essence, agroforestry combines trees with either annual crops and/or perennial pastures to increase sustainability of agricultural lands (Montagnini and Nair, 2004; Nair et al., 2009). Further, these systems contribute other ecosystem services such as providing wildlife habitat (Jose, 2009), maintaining biodiversity (Altieri, 1999), reducing erosion (Lenka et al., 2012), and enhancing microbial communities in soil (Banerjee et al., 2015). Trees in agroforestry systems constitute a significant avenue of organic matter (and nutrient) addition to the soil ecosystem (Haile et al., 2008; Takimoto et al., 2008; Isaac et al., 2011). Integrating trees into the agricultural landscape can increase the above- and belowground total productivity of agroecosystems, modify rooting

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depth and root distribution, and enhance organic matter input to the soil from litterfall (Kass et al., 1997; Paul et al., 2002; Partey, 2011; Albrecht and Kandji, 2003). However, increasing SOM accumulation over time through the incorporation of trees is just one step to promoting SOM build-up, as the stability of resulting SOM pools is what ultimately regulates the cycling of C and soil quality (Crow et al., 2007; Dorodnikov et al., 2011; Creamer et al., 2013).

Soil organic C (SOC) is composed of fractions (pools) that differ in stability (Sollins et al., 1996; von Lützow et al., 2006; Strosser, 2010). Organic C may be available in the soil as either: (i) relatively fresh (labile) SOM not protected in soil aggregates, (ii) SOM physically protected through occlusion in aggregates, or (iii) SOM chemically stabilized through association with mineral surfaces (Swanston and Myrold, 1997; Amonette et al., 2004; von Lützow et al., 2007). Land use and management practices can influence SOC and distribution among various pools (Tiessen and Stewart, 1983; Teklay and Chang, 2008; Mujuru et al., 2013). The labile SOC fraction has a significant influence on soil quality and productivity (Chen et al., 2012), and tends to respond the most to management activities (Crow et al., 2007; Duval et al., 2013). As such, labile SOC is a more sensitive indicator of management and land use change compared to other fractions. Therefore, isolation of these functional pools will help to elucidate the net impact of land management systems on C storage, its stability and overall soil quality (Jastrow, 1996; Oades, 1984; Chen et al., 2012).

The study by Baah-Acheamfour et al. (2014) in central Alberta, Canada, relied on soil particle size separation to isolate functional SOM pools under three agroforestry systems (hedgerows, shelterbelts, and silvopastures). Soil size fractions obtained by wet-sieving after shaking for 30 min in water are assumed to offer different degrees of SOM stabilization (Hassink, 1997; Moni et al., 2012). However, fractionation by particle size does not allow differentiation of many of the light fraction materials (e.g. incompletely decomposed organic residues–labile organic matter) from the more decomposed and protected mineral-bound organic matter (Moni et al., 2012), thus providing only a rough separation between active, intermediate, and passive SOM pools (von Lützow et al., 2007). A better understanding of SOM storage and dynamics within ecosystems requires more comprehensive separation of the various functional C pools, particularly the labile light fraction of SOM.

The present study expands on the previous work we conducted (Baah-Acheamfour et al., 2014) by examining the effects of three agroforestry systems (hedgerow, shelterbelt, and silvopasture) and their inherent land cover types (forested vs. herbland) on (i) mineral soil organic C and nitrogen (N) in the bulk soil and (ii) the organic C and N distribution among the light, occluded, and heavy fractions in the 0–10 and 10–30 cm soil layers. The distribution of C and N among the different SOM fractions could provide important insight into how agroforestry systems affect the quality and long-term stability of organic matter in soils.

2. Materials and methods

2.1. Site description

This study was conducted in central Alberta, Canada, at 36 study sites distributed across a large geographic range. Study sites were located between 54°43′ and 52°28′ N latitude, and between 113°44′ and 113°17′ W longitude. Elevations of the study sites ranged from 533 to 850 m above mean sea level. Average air temperature based on 30 years of data (1981–2010) collected from 26 Environment Canada climate stations, was 1.9 °C and 2.4 °C, and mean annual precipitation was 463 mm and 448 mm, in the north and south portions of the study area, respectively (Environment Canada, 2012). Landforms in the study area vary markedly from relatively level plains in the south to moderately or strongly rolling hills in the northwest. Historical vegetation in the region includes the Dry Boreal Mixedwood and Aspen Parkland Natural Subregions (Adams et al., 2009). Dominant soil types vary from Luvisols (Soil Classification Working Group, 1998) in the north, to Dark Gray Chernozems in the central portion, and Black Chernozems in the south of the sampling area.

This study examined three dominant agroforestry systems: hedgerow, shelterbelt, and silvopasture systems. Each of these systems consisted of two land cover types: forested (areas with trees) and herbland (areas without trees). Hedgerow systems were made up of naturally regenerating perennial vegetation that included woody species as hedgerows at field edges and adjacent annual cropland. Shelterbelt systems were also comprised of trees and shrubs planted in 1–2 rows as shelterbelts, and were adjacent to annual cropland. Silvopasture systems contained a mosaic of grazed aspen forest and grassland land cover types. Hedgerows are usually 40- to 100-year-old broad-leaved deciduous stands intermixed with *Populus tremuloides* Michx., *Betula papyrifera* Marsh., and *Populus balsamifera* L. Shelterbelts generally consist of one or two rows of trees (3–5 m wide) comprising 20- to 50-year-old coniferous and/or deciduous trees dominated by *Picea glauca* Moench. Croplands in both the hedgerow and shelterbelt system are typically planted to cereal, oilseed or pulse crops such as *Hordeum vulgare* L., *Triticum aestivum* L., *Brassica napus* L., and *Pisum sativum* L., with minimum tillage practices and ample fertilizer applied annually that includes N up to 120 kg ha^{-1} year^{-1}. Silvopastures encompass mostly *Populus tremuloides* forested patches intermixed with grasslands comprised of a variety of species, often including *Bromus inermis* Leyss and *Poa pratensis* L. Tree species composition and ages of the *Populus tremuloides* dominant forest vegetation were similar to the hedgerows; however the hedgerows contained more understory herbs and shrubs species compared to the forest vegetation found in the silvopasture system. Fewer understory herb and shrub species occurred in silvopastures because cattle (*Bos taurus*) grazing tended to simplify the understory by thinning out tall forbs and shrubs.

2.2. Sampling design

The experiment used a split-plot in a completely randomized design (CRD). Whole plots consisted of the three agroforestry systems (i.e. hedgerow, shelterbelt, and silvopasture), each of which was divided into forested and adjacent herbland as sub-plots. Across the study area, 36 sites (12 hedgerows, 12 shelterbelts and 12 silvopastures) were selected along the soil/climate gradient. Within each site (i.e. agroforestry plot), one 30 m long transect was established inside each of the forested and paired herbland sub-plots. Transects in the forested sub-plots were established in the center of the treed zone, whereas those in the herbland land cover type were located at least one tree height (∼30 m) from the edge of the treed zone.

Soil samples were collected in June 2013. Samples were collected from two depths in the mineral soil, 0–10 and 10–30 cm, using a 3.2 cm diameter core, thereby excluding the fresh litter, fibric and humified surficial organic matter (i.e. mulch or LFH) layer. Along each transect, 10 cores were systematically collected, separated into the two depth-classes, combined within a class, and then mixed in the field to form a composite sample from each transect. Additional soil samples were collected at each depth by inserting three metal rings of 106 cm^3 volume into the soil for bulk density measurements. Soil samples were placed in plastic bags and kept cool (∼4 °C) until processed. In the laboratory, fresh soil samples were sieved to pass a 2 mm screen (# 10 U.S. Standard Sieve) and separated into two subsamples. One subsample was stored in a −20 °C freezer for chemical analyzes, while the other subsample