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Woody organic amendments for retaining soil water, improving soil properties and enhancing plant growth in desertified soils of Ningxia, China

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A R T I C L E I N F O

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A B S T R A C T

Extreme soil degradation is one of the most serious problems affecting dryland ecosystem health and agricultural production globally. This study was conducted to investigate the potential for using woody amendments to improve soil moisture availability, soil microbial activity, soil fertility, and plant growth in desertified soils in Ningxia, China. Soil amendments of wood chips derived from tree branches of four readily available tree species (poplar, elm, pagoda tree, and grapevine), were evaluated and compared with more commonly used wheat straw, rice husks, and cow manure, using replicated microcosm experiments. Different types, concentrations, and application techniques of woody and non-woody organic amendments were compared for their impacts on soil moisture, soil chemistry, microbial activity, and plant growth. The treatments with woody organic materials incorporated into the soil consistently demonstrated an improvement in soil water status, increased organic C content, and improved soil fertility, and also resulted in enhanced microbial activity, and wheat growth. Although surface mulch increased soil water storage and enhanced wheat growth, it did not effectively improve soil microbial activity as compared with wood incorporated into the soil. Differences in placement and type of amendment differ markedly in their effects on physical, chemical and biological soil responses. A combination of 5% poplar wood chips incorporated into the soil with a lattice of twigs over the soil was ideal for simultaneously maximizing soil water availability, encouraging microbial activity, and maximizing wheat yield. In conclusion, woody materials from locally available trees can serve as a valuable amendment for desertified soils in Ningxia and other places of Northern China by increasing rainfall capture, reducing irrigation demand, improving soil health and promoting higher crop yields.

1. Introduction

Desertification is one of the most critical types of land degradation and is being widely recognized as a serious threat to arid and semiarid environments worldwide (Veron et al., 2006). In many regions, the cumulative activities of clearing native vegetation for fuel and shelter materials, overgrazing by livestock, and chronic overharvesting with resulting soil erosion have left behind damaged, barren, and unproductive landscapes, contributing to billions of hectares of degraded drylands globally (D'Odorico et al., 2013). In addition to the long-term impacts of human activities, climate-driven changes have exacerbated ecological regime shifts in many regions, further accelerating the conversion of arable lands into degraded and desertified soils. Although a precise definition of desertification can be challenging (Bestelmeyer et al., 2015), the process of desertification in drylands is pervasive, and reversing this trend has become a difficult but urgent mission worldwide.

Some of the main factors that contribute to desertification are limited rainfall, severity and timing of drought, and evapotranspiration deficit (Vicente-Serrano et al., 2015). Thus, both historical and recent changes in precipitation patterns need to be accounted for in efforts to maintain and restore degraded systems. However, desertified soils (i.e., those with > 80% sand and < 10% clay) also have poor water holding capacity (Andry et al., 2009), so that even when it does rain, water is rapidly lost from the surface soil layer. Hence, a possible way to combat desertification in arid and semi-arid areas is to increase capture and retention of water in the soil, especially after rain events. A simple solution to this part of the problem may be to increase soil organic

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matter. In arid and semi-arid areas, most soils contain < 1% organic matter (Karami et al., 2012), so a wide variety of organic amendments have been used to improve soil properties and conditions conducive to a wide range of organisms, from microbes (Bastida et al., 2008) to common crop plants (Fernández-Gálvez et al., 2012). Indeed, in arid and semi-arid areas of China and elsewhere, retaining and returning crop residues to the soil has long been regarded as a practical method to improve general soil conditions (Zeleke et al., 2004; Głąb and Kulig, 2008). Importantly, soil organic matter amendments also can increase water holding capacity, soil porosity, water infiltration and percolation, while decreasing soil crusting and bulk density (Celik et al., 2004; Herencia et al., 2011).

Many amendment types have been used, and tested, with a primary goal of improving soil fertility. Application of manure, straw, or other crop residues into the surface soil can also improve soil texture and increase water capture and retention. However such light residues easily decompose in as little as two years, even in more arid regions. Therefore, although some longer term residual effects have been reported from various compost experiments (Diacono and Montemurro, 2010), most light organic materials will be lost in the short-term, and benefits may be minimal without constant re-application. Some studies have included an analysis of longer-lived, coarse wood amendments, but frequently this is without specific information, subsumed under such headings as “municipal compost wastes”, “green wastes”, and “wood wastes”. It is important to clearly understand how coarse woody materials fit into the tool kit of soil amendments, including comparisons of placement, such as aboveground versus sub-surface incorporation, species of wood, decomposition rate, particle size, and whether the amendment is used alone or in combination with other materials, e.g. fertilizer. To date, there has been no comprehensive research focused on understanding the multiple aspects of woody organic matter amendments.

Much of the research on woody amendments has focused on surface applications, such as mulch in a variety of systems and coarse woody debris in forest settings. Wood chip mulch has added value as a non-herbicidal alternative for weed control (Ingels et al., 2011), and worked better than plastic film or other mulch materials at maintaining higher soil moistures (Splawski et al., 2016). Mulched pallet wood, an under-recognized but extensive resource, increased organic matter, microbial activity, and nutrients in cucumber microcosms (Tiquia et al., 2002). Coarse woody debris laid directly atop forest soils also helped increase soil moisture, along with organic matter, water holding capacity, and reduced bulk density (Bulmer et al., 2007). Used as a management strategy, loose piles of wood latticed above the forest floor achieved similar benefits of cooler temperatures and higher soil moisture contents (Morreale and Sullivan, 2010). Studies directly comparing surface versus incorporated wood chips are scarce. Bulmer et al. (2007) compared placement of woody amendments to restore log landings, and found that the incorporated wood treatments resulted in lower soil bulk density and higher carbon content than surface applications, but surface applications buffered temperatures better. A prairie restoration using untreated urban wood waste similarly resulted in reduced soil bulk density with incorporation, but only at high amounts, and amendment location did not affect soil water availability (Biederman and Whisenant, 2011).

Nevertheless, incorporated wood chips (IWC) provide additional benefits. They yield positive improvements in harvests (Ferrini, 2008; Smith et al., 2000), and can increase yields above fertilizer use alone (Picchioni et al., 2016). They help improve soil aggregates, arguably due to a large increase in microbial and fungal activity (Annabi et al., 2011; Laland et al., 1998). When added to compost, IWC also increased soil organic matter, nutrient availability, and soil microbial action (Scotti et al., 2015; O'Connell et al., 2004; N'dayegamiye and Angers, 1993). A major concern about IWC is that the typically high C:N ratio of the wood can drive nitrogen immobilization. However results are conflicting (Averett et al., 2017; Fang et al., 2011; Tahboub et al., 2007; Holtz et al., 2004; N'dayegamiye and Angers, 1993) and can vary temporally (Laland et al., 1998). Based on microcosm experiments with controlled chemical additions, Qui et al. (2008) concluded that chemical composition of the amendment may drive the rate of availability of both carbon and nitrogen, either encouraging nitrogen mineralization or, alternatively, immobilization. Logically, then, nitrogen availability would depend on how quickly the material decomposes, and the material's properties would be a critical consideration when using coarse wood as a soil amendment.

Recent studies have documented the wide range in decay rates among plant species, from less than a year to over a century (Weedon et al., 2009). Wood from tree branches and boles generally has significantly slower decomposition rates than herbaceous materials, although actual rate will depend on species, source (bark vs. heartwood), and age, summarized as the “stability and maturity” of the organic matter (Larney and Angers, 2012). Once underground, temperature, soil moisture, soil type, and particle size will influence turnover, with rates ranging from less than one year to over 1000 years (Diacono and Montemurro, 2010). At the upper extreme, biochar, or pyrolized wood, can be a valuable, long-lasting amendment for restoration of severely degraded soils (Ohsowski et al., 2012) but it is not always as effective at increasing soil moisture, or microbial activity without other organic matter (Jeffery et al., 2015; Jaafar et al., 2015). Furthermore, biochar production costs and greenhouse gas emissions may also prove prohibitive for use at broader spatial scales (Novak and Watts, 2013). Therefore, there are great potential benefits for consideration of different types of woody material to amend soil, especially from long-lasting recalcitrant species which also could be a valuable tool for carbon sequestration, adding to soil's ability to ameliorate climate change (Lal, 2015).

Another important consideration is the availability of woody materials. In regions with limited forestland, or where harvest residues are less available, there may need to be alternate sources of woody material, such as shrublands, shelterbelts, hedgerows and/or short-rotation cropping of woody plants. For example, as part of broad-scale efforts to reduce erosion, improve croplands, expand livelihood options and increase scenic beauty in northern China, > 2.2 million km^2 of irrigated shelterbelt forests were planted, starting in 2006. In these semiarid and arid regions, and elsewhere in China, shelterbelts are distributed across the landscape and comprise a vast potential source of woody material that could be used in soil amendments, along with crop residues. Moreover, in the driest regions of northern and western China, the tree species most planted are highly productive and fast-growing, and can be readily coppiced. The rapidly growing poplar trees of the genus *Populus,* noted for high productivity and great potential to provide other ecosystem services (Yang et al., 2010), are the most widespread and most available tree throughout China, covering a cumulative area exceeding 10 million km^2. In the degraded and desertified areas of Northern China, three quarters of the poplar trees are planted in irrigated, farmland shelterbelts with 47,000 km^2 in Ningxia province alone. The highly impoverished soil, high rates of desertification, and widely available sources of wood distributed along roadways contribute to making Ningxia, China an ideal site to study the impacts and potential benefits of various soil amendments, especially for ameliorating water scarcity in the rapidly drying soils.

In addition to *Populus*, three other similarly productive woody species are readily available in large quantities in Ningxia and across Northern China, either from intact shelterbelts, or from planted fields: Siberian elm, *Ulmus pumila* (Xu and Chen, 2012); the papilionoid legume pagoda tree, *Styphnolobium japonicum*; and the wine grape, *Vitis vinifera*. The quantity and widespread availability of these woody species, typically discarded or burnt for fuel, across Northern China could make them all practical sources of woody material to use in soil amendment efforts in the region.

We designed related studies to: 1) compare the potential for water capture and retention by woody material from poplar and other species,