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Total and available soil carbon fractions under the perennial grass *Cynodon dactylon* (L.) Pers and the bioenergy crop *Arundo donax* L.

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ABSTRACT

Understanding and quantifying the impact of bioenergy crops on soil carbon (C) storage is an essential component of crop management. Our objectives were to (i) compare total (TC), organic (OC), and inorganic carbon (IC) storage under *Cynodon dactylon* (L.) Pers and the energy crop *Arundo donax* L. along the soil profile, and (ii) determine the effect of these crops on available soil C (measured as hot water extractable C, HC) as an indirect indicator of soil C changes. The study site was within the Rio Grande floodplain in Quemado, Texas covered by *A. donax* and *C. dactylon*. Soil samples were taken from five soil depths: 0–10, 10–20, 20–30, 30–40, and 40–50 cm at 125 locations in a 34.5 ha field; TC, IC, and HC were measured and OC was derived. In all four C pools, soils under *A. donax* had higher C content (volumetric C or Cv, kg m^{-2}) than soils under *C. dactylon*, except for IC at the top two depths. Larger soil C storage under *A. donax* as compared to *C. dactylon* was consistent throughout the profile. The effect was most pronounced for volumetric HC content (HCv) with 43% higher amount under *A. donax* than *C. dactylon* at 0–10 cm depth. In areas, where *A. donax* is considered an invasive species, the available biomass can be used for bioenergy production and the higher soil carbon under *A. donax* can provide additional economic return in a C economy.

1. Introduction

Efforts to increase soil carbon (C) storage through conservation management have gained momentum in the last few decades, particularly to counter the effects of global warming. Soil C has been a key component of land management for a long time, as it is important for nutrient availability, moisture holding capacity, and soil health as well as several

Abbreviations: OC, organic carbon; TC, total carbon; IC, inorganic carbon; HC, hot water extractable carbon; Cc, carbon concentration in g kg^{-1} of soil; Cv, volumetric carbon or carbon stock in kg m^{-2}.

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ecosystem functions of soil such as filtration of water and contaminants. Therefore, alternative management practices that can enhance soil C sequestration have attracted significant research attention [1–3]. Bioenergy has attracted increasing research and policy support aiming to reduce green house gas emissions and the dependence on fossil fuels. Currently, about 4% of the total energy consumption in the U.S. is derived from biomass energy [4] and it is estimated that up to one third of the transportation fuels can be replaced by biomass energy in the US [5]. Many studies using life cycle assessment technique have reported that biofuels reduced total fossil fuels consumption [6–10]. For example, Schmer et al. [7] reported that switchgrass produced 540% more renewable fuel as compared to nonrenewable fuel used in the process. However, there are various environmental concerns associated with different sources of bioenergy. For example, grain ethanol production is well established in terms of technology and industrial infrastructure, but it is not considered sustainable because it diverts food grains from food and animal feedstock needs. Hill et al. [10] reported that replacing petroleum with either ethanol or biodiesel (from food crops) was not possible without impacting food supplies. Additionally, the energy spent in growing these food grains incurs C cost, while the agronomic chemicals and tillage place further demands on the environment [11,12]. Cellulosic ethanol from crop residues is considered to be a more sustainable alternative for bioenergy production since they do not require additional agronomic inputs. However, crop residues, when left in the field, perform important ecological functions such as erosion control, improvement of soil physical properties and maintenance of soil C levels. Thus, removal of crop residues poses enormous risks for preserving soil health. For example, Anderson-Teixeira et al. [13] reported that removal of as little as 25% corn residues resulted in reduction of soil C stocks. They found that even though perennial grasses accumulated soil C, a period of C payback time was required to restore the soil C lost due to cultivation (e.g., a century for sugarcane). Intensively managed perennial grasses and wood crops are also reported to incur higher C costs due to fossil fuels consumed directly or indirectly during cultivation. For example, Pimentel and Patzek [14] reported that many of the biofuel sources such as corn, soybean, sunflower, switchgrass, and wood biomass actually required 29, 27, 118, 50, and 57% more fossil fuel for production compared to the fossil fuel replaced by the biofuel produced from the feedstocks. Similarly, when other environmental impacts caused by increased tillage, use of chemical fertilizers and pesticides or reduction in biomass input to soil and resultant decrease in soil C and nutrients were considered, the cost outweighed the benefits in case of high input biomass feedstocks such as corn grains or conversion of native lands to cultivated biofuel crops [13]. As a result, in a review of life cycle analyses of bioenergy systems, Cherubini et al. [15] concluded that determination of the C cost of bioenergy is complex and dependent on multiple, highly variable factors. However, the authors also concluded that using waste biomass or crop residues and low input bioenergy crops that offer greater ecosystem services than the systems they replaced, e.g. reforestation of degraded lands, could offer more sustainable and carbon negative solutions for bioenergy.

Therefore, more research is needed for bioenergy feedstocks, which sequester C and require minimal additional inputs. For example, low input - high diversity grasslands and restored prairies have been reported to offer high amounts of bioenergy feedstock without adversely affecting the soil C stocks [16]. *Arundo donax* L. (Giant Reed) is such an excellent bioenergy feedstock with a gross heating value of 17.2 MJ kg^{-1} of dry leaf matter [17]. It is a fast growing plant and can reach up to 8–9 m height and up to 75 t ha^{-1} yield under optimum conditions [17,18]. It is capable of growing under dry conditions and without herbicides [17,19]. *A. donax* has been cultivated in parts of Europe, Africa, Asia, and the Middle East for thousands of years and has been present in the U.S. for more than a century [20]. Researchers have reported the suitability of *A. donax* feedstock for ethanol [21] and net positive energy output when managed for bioenergy production [22]. Angelini et al. [22] reported that when *A. donax* was fertilized, grown without irrigation, and harvested annually it had a mean energy yield of 627 GJ ha^{-1} y^{-1} over 12 years, whereas the mean energy yield for *Miscanthus* was only 467 GJ ha^{-1} y^{-1}. The energy input for both crops was 17 GJ t ha^{-1} in the first year and 12.1 GJ t ha^{-1} every year from second year (average 12.5 GJ t ha^{-1} y^{-1}). These energy yield studies suggest that use of the biomass of *A. donax* for bioenergy can be a sustainable alternative.

In the U.S., *A. donax* has been declared an invasive species in seven states, California, Nevada, Arizona, New Mexico, Texas, Georgia, and Virginia [23] and extensive efforts are expended for control and eradication of this species. Most of the eradication techniques recommended for this species, such as root excavation, mechanical removal, and herbicide treatment of the cut stems, require proper disposal of the *A. donax* debris. The decomposition of *A. donax* canes is slow; chipping requires heavy-duty equipment and C expenditure, while burning is restricted due to air quality considerations. In such cases using the removed biomass for bioenergy can ensure proper disposal of the debris and reduce the net cost of control measures while offering additional environmental benefits. In areas where control measures are not feasible, use of the available biomass for biofuel (as an intermediate measure) can also offer economic returns and reduce the fire hazard, since *A. donax* is highly inflammable. This can be particularly attractive in states such as California and Georgia where commercial cellulosic ethanol plants using waste biomass to produce electricity are already operational or are under construction. Moreover, *A. donax* is an environmental concern only when grown near waterways or in cases of improper disposal [24]. It has multiple uses including fiber, fodder, roofing material, and wind instruments, with existing commercial plantations in California for musical instruments [20]. Therefore, utilization for bioenergy as part of the control strategy of this species can be an ecologically and economically sound alternative.

However, it is necessary to determine the effect of these bioenergy sources on soil C storage. While extensive research has been conducted on soil C in grain ethanol crops [8,25] and cellulosic ethanol from food crops and their residues [16,26], soil C storage under *A. donax* requires further studies. It is also necessary to determine the effects of these crops not only on soil C stock, but also on labile C pools, which predict long-term