Europ. J. Agronomy 73 (2016) 98–106

Contents lists available at ScienceDirect

European Journal of Agronomy

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

Stable isotope technique in the evaluation of tillage and fertilizer effects on soil carbon and nitrogen sequestration and water use efficiency

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ARTICLE INFO

Article history:
Received 28 February 2015
Received in revised form 11 October 2015
Accepted 5 November 2015
Available online 23 November 2015

Keywords:
Intrinsic water use efficiency
Isotopic fractionation
Sequestration
Stable isotope
Tillage

ABSTRACT

Agricultural soil could be made to serve as a sink rather than a source of greenhouse gases by suitable soil management. This study was, therefore, conducted to assess the impact of tillage and fertilizer application on soil and plant carbon and nitrogen fractionation and intrinsic water use efficiency (*i*WUE). The experiment was a split–split-plot factorial design with three replications. The main plot consisted of two tillage treatments: zero tillage (ZT) and conventional tillage (CT). The sub-plot contained four NPK fertilizer treatments (0, 90, 120 and 150 kg N ha^{-1}), while the sub–sub-plot comprised three poultry manure (PM) treatments (0, 10 and 20 Mg ha^{-1}). Soil carbon and nitrogen sequestration were evaluated using stable isotope of carbon (δ^{13}C) and nitrogen (δ^{15}N). The δ^{13}C in maize plant was used to obtain *i*WUE. It was observed that soil δ^{13}C and δ^{15}N were more depleted under ZT than CT and in plots treated with 20 Mg ha^{-1} PM (PM$_{20}$) implying carbon and nitrogen sequestration under ZT and by PM$_{20}$. Relative to the control, application of PM$_{20}$ raised soil δ^{15}N enrichment by 82% and 96% under CT and ZT, respectively. Higher *i*WUE of 25.7% was obtained under CT and was significantly higher than the *i*WUE values under ZT in the second year of the study while the *i*WUE was significantly lower with PM$_{20}$ application than other fertilizer treatments. The significant δ^{13}C depletion and hence lower *i*WUE with combination of NPK fertilizer and PM under CT than the control implied that soil disturbance under tilled plots was mediated by combined nutrient management thereby limiting soil C available for fractionation resulting in lower *i*WUE. This suggests that conservation tillage such as zero tillage and integrated application of organic and inorganic fertilizers are good strategies for reducing soil carbon and nitrogen emission.

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1. Introduction

Quantitative assessment of soil constituents is being enhanced through stable isotopic technique. The basic principle of stable isotope application is that through transition from one phase to another by compounds such as carbon dioxide, the concentration ratio of the isotopic component of the element normally undergoes changes, known as isotope fractionation. During fractionation, discrimination against heavier isotopes (^{13}C/^{15}N) in favor of the lighter ones (^{12}C/^{14}N) is being employed by soil scientists to study soil carbon and nitrogen dynamics in soils, among other applications.

Agricultural soil is generally considered to be a source of greenhouse gases and proper management could make the soil act as a sink (Ogle et al., 2004). Decreasing tillage intensity has been adopted as an option for increasing soil organic carbon (SOC) (Johnson et al., 1995) thereby increasing C sequestration (Yagioka et al., 2015) leading to reduction in greenhouse gas emission. Recent studies on SOC storage and turnover have employed ^{13}C natural abundance as a technique in monitoring the fate of in-situ or applied carbon in the soil. For instance, stable C isotope has been used to understand the mechanisms of litter decomposition, soil organic matter (SOM) formation and turn over (Nadelhoffer and Fry, 1988; Wilts et al., 2004; de Rouw et al., 2015), SOC dynamics (Wedin et al., 1995; Awiti et al., 2008) and water use efficiencies (Ogaya and Penuelas, 2008; Huang et al., 2008). ^{15}N natural abundance (δ^{15}N) technique has also been successfully applied to tracing N in landscapes (Bedard-Haughn et al., 2003) and to gain better understanding of nitrogen dynamics (Awiti et al., 2008). Other applications include nitrogen transformation and mineralization (Hogberg, 1997; Nadelhoffer and Fry, 1994) and processes of

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http://dx.doi.org/10.1016/j.eja.2015.11.002
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nitrogen cycling and fixation (Eshetu, 2004) as well as NO_3^- leaching (Oelmann et al., 2007).

Modification of soil structure, which usually occur following tillage practices, has a major influence on the mineralization or release of C in the soil. Isotopic fractionation of soil organic carbon due to tillage has been identified by Collins et al. (1999) where it was reported that ^{13}C values in mold board-tilled soil were higher than those from non-cultivated soil. Fertilizer application has also, been reported to influence the SOC and $\delta^{13}C$ natural abundance. Wilts et al. (2004) found that SOC declined and natural $\delta^{13}C$ abundance increased during a 29-year investigation. It has also been reported that addition of new carbon source (e.g. organic manure) led to depletion of $\delta^{13}C$ content of the soil (Grieve et al., 2006). Similarly, Awiti et al. (2008) observed higher $\delta^{13}C$ and $\delta^{15}N$ isotope enrichments in low fertility soil classes and depletion patterns in $\delta^{13}C$ and $\delta^{15}N$ isotopes in high fertility soil classes. Vitorello et al. (1989) also found an inverse linear relationship between SOC contents and ^{13}C abundance. Observations by these authors were so, because the isotopic composition of soil organic carbon is not necessarily controlled by the same factors that regulate the amount of carbon in the soil profile (Powers and Schlesinger, 2002) but the main effect is that SOM subjected to increased degrees of microbial processing and decompositions will exhibit ^{15}N and ^{13}C enrichments (Nadelhoffer and Fry 1988; Billings et al., 2002). According to Hogberg (1997), losses of topsoil nitrogen following cultivation usually leads to soils that have higher $\delta^{15}N$ due to microbial discrimination against heavier N isotopes while Nadelhoffer and Fry (1994) observed that increase inorganic fertilizer application brought about decline ^{15}N of soil as a result of increasing nitrification.

The C isotope fractionation by photosynthesis has made it possible to characterize a plant by its C isotope composition ($\delta^{13}C$) and/or isotope discrimination value (Δ) (Iqbal et al., 2005). The $\delta^{13}C$ has been described by Cui et al. (2009) as a simple, direct and effective method in evaluating the plant intrinsic water use efficiency (*i*WUE). Many authors such as Saranga et al. (1999), Ogaya and Penuelas (2008) and Zhang et al. (2009) have carried out researches on the use of ^{13}C in plant physiology and have found positive relationship between $\delta^{13}C$ and *i*WUE (ratio of net photosynthesis to stomatal conductance). Thus, a less negative (higher) $\delta^{13}C$ value is an indication of more effective water use (Iqbal et al., 2005). Johnson et al. (1990) suggested that Δ is a plant characteristic that integrates the overall metabolic performance during the entire cycle and hence an adequate criterion for selecting plants for their WUE in water-limited environments. Conservation tillage practices have been recommended as a useful measure for water conservation to increase water use efficiency by reducing soil water evaporation (Walley et al., 1999).

Since soil organic carbon and natural abundance $\delta^{13}C$ have been observed to be sensitive to tillage and fertilizer management (Clapp et al., 2000), information on appropriate tillage and fertilizer practices becomes important. Despite the fact that WUE is an important crop physiology parameter in understanding soil-water plant relationship and management, its measurement difficulties on the field is making it of less interest. The use of stable C isotope, however, offers a convenient means of assessing crop water use efficiency. Though, isotopic monitoring of soil carbon and nitrogen fractionations as well as crop WUE has been widely applied in most developed countries of the world, it has found less applicability in Africa and in Nigeria in particular. In this study, we hypothesised that intensive tillage increased stable carbon and nitrogen isotopes fractionation and that combined application of organic and inorganic fertilizers moderated the effect of tillage on stable isotopes fractionation in soil and maize plant. Therefore, the objectives of this study were (i) to determine the effect of tillage and fertilizer application on fractionation of stable isotopes of carbon and nitrogen in soil and plant with a view to evaluating soil carbon and nitrogen sequestration (ii) to assess the effect of tillage and fertilizer application on intrinsic water use efficiency.

2. Materials and methods

2.1. Description of the study site

The study was carried out at the University of Agriculture, Abeokuta, south-western Nigeria in years 2008 and 2009. The study area lies between Latitude 7°14′N and Longitude 3°26′E and is located within a forest-savanna transition zone (Salako et al., 2007) with two distinct seasons—the wet season, which extends from March to October, and the dry season which is usually from November to February. The rainfall is bimodal in distribution—usually Mach to July and September to October, with characteristic August break. Similar to long-term average, the mean monthly temperature ranges from 30 to 37 °C in 2008 and 23.5 to 34 °C in 2009. The mean relative humidity was 68.3%. At the onset of the experiment in 2008 before ploughing, the loamy sand soil used for the study had pH, Organic C and total nitrogen of 5.9, 12.1 g kg^{-1} and 1.0 g kg^{-1}, respectively (Busari and Salako, 2013). The field was under secondary re-growth of shrub dominated by *Adropogon gayanus* prior to the establishment for this study. Further description of the study site and soil classification is available in Busari and Salako (2015).

2.2. Experimental design

The experiment was a split-split-plot factorial design with three replications. The main plot was tillage while inorganic (NPK) and organic fertilizer (poultry manure (PM)) were in the sub-plot and sub–sub-plot, respectively. The main plot involved two tillage treatments: zero and conventional tillage, the sub-plot consisted of four inorganic fertilizer treatments: 0, 90, 120 and 150 kg N ha^{-1} (applied as NPK 20:10:10) while the sub–sub plot included three organic fertilizer treatments (0, 10 and 20 Mg ha^{-1} PM).

Under zero tillage (ZT), no ploughing was done, weeds were controlled using herbicides (paraquat) while conventional tillage (CT) involved ploughing followed by harrowing. Ploughing was done at around 20–25 cm depth using disc plough while disc harrowing was done at the depth of 15–20 cm. The tillage operations were not repeated in year 2009 on the already laid-out plots before imposition of soil amendments but the weeds were cleared manually under CT and with the aid of paraquat under ZT. Further detail on tillage operation procedures is available in Busari and Salako (2015). Each main plot was 11 m × 23 m strip containing 12 plots of 4 m × 5 m with each plot separated by 1 m border. About 4 m margins were left on both sides of each main plot for tractor to maneuver without entering into an adjacent plot.

2.3. Application of soil amendments

The poultry manure (PM) used for the experiment was collected from a poultry house operating a battery cage system at Abeokuta, Nigeria. The PM was applied at 10 Mg ha^{-1} (PM_{10}) and 20 Mg ha^{-1} (PM_{20}) and was incorporated into the soil two weeks before planting under the CT with hand hoe while it was spread evenly on the soil surface under the ZT to ensure less surface disturbance. The stable isotope contents of the poultry manure and its C:N ratio were determined (Table 1). Inorganic fertilizer was applied as NPK 20:10:10 three weeks after planting during each of the two years of cropping at the rate 0, 90, 120 and 150 kg N ha^{-1}

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