EFFECT OF DIFFERENT LEAF LITTERS ON CARBON, NITROGEN AND MICROBIAL ACTIVITIES OF SODIC SOILS

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Received: 28 December 2013; Revised: 22 July 2014; Accepted: 25 July 2014

ABSTRACT

This study investigates the effect of single leaf litter of Terminalia arjuna (Ta) and Prosopis juliflora (Pj), mixed leaf litters [Ta, Pj, Azadirachta indica (Ai) and Albizia procera (Ap)] and paddy straw (Ps) on chemical properties and microbial activities of slightly sodic (SS), moderately sodic (MS) and highly sodic (HS) soils during 1 year in vitro decomposition process. For this purpose, equal amount (600 g) of single leaf litter [Ta (C:N = 43) and Pj (C:N = 38)], mixed leaf litters [1/4 of Ta, Pj, Ai and Ap (C:N = 30)] and Ps (C:N = 107) was added to equal amount (600 g) of SS, MS and HS soils. After addition of litters, changes in soil organic carbon (SOC), available nitrogen (Nav), microbial biomass carbon, nitrogen, soil respiration, microbial quotient (Cmic:Corg) and metabolic quotient (qCO2) were observed at 2 months intervals for the whole year in greenhouse at constant soil moisture. The respective annual increase, at the end of the experiment, in SOC and Nav was highest in MS soil (40% and 45%), whereas soil microbial biomass and soil respiration showed decreasing trend from HS soil (39% and 29%) to SS soil (28% and 21%). The highest SOC was mineralized in the MS (42%) and HS (32%) soils containing litter of Ta; although greater (20%) accumulation of SOC in SS soil was noticed with mixed leaf litters. The study reveals that MS and HS soils comparatively showed fast decomposition of litters and significant increase in carbon, nitrogen and microbial activities. Copyright © 2014 John Wiley & Sons, Ltd.

KEY WORDS: litter decomposition; microbial biomass; Prosopis juliflora; restoration; soil respiration

INTRODUCTION

Soil sodication and salinization are the abiotic threats to soil fertility of arable lands (Wong et al., 2010). Sodic soils, resultant of sodication, are widespread (436 Gha) in semi-arid subtropical regions of the world (Singh, 2009; Wong et al., 2009; Ivits et al., 2013). Leaf litters with lower C:N ratio tend to leaf litter decomposition and associated release of inorganic nutrients from litter through the combined activity of microbes and other organisms in the detritus food web (Muhammad et al., 2008; Yao et al., 2009; Mukhopadhyay & Joy, 2010). Nitrogen content in the plant residue is important for the assimilation of decomposer microorganisms, and the C:N ratio often controls litter biodegradation/mineralization, microbial biomass and CO2 evolution. The C:N ratio and chemistry of leaf litters influence their mineralization/biodegradation by microbial communities (Taylor & Middleton, 2004; Gul et al., 2012). Leaf litters with lower C:N ratio tend to decompose faster, increase in N mineralization and increase in microbial biomass (Gul et al., 2012). Litter quantity

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significantly affects the soil microbial activity and resilience of soil fertility. Other edaphic factors, such as soil texture (especially clay minerals) and its intrinsic chemical properties (pH, ESP, sodium adsorption ratio and cation exchange capacity), are also expected to modulate biodegradation rate through loose physical protection of residues and feedback on microbial communities.

Soil microbial activity is the driving force in the transformation of litters to soil organic matter and development and maintenance of soil fertility. A huge literature supports that soil microbial biomass (SMB), soil respiration (SR; emission carbon dioxide as a result of microbial activity), microbial quotients ($C_{mic}/C_{org}$; the ratio SMB carbon to soil organic carbon) and metabolic quotients [$\rho$CO$_2$; the ratio SR to microbial biomass carbon (MBC)] are sensitive indicators of changes in soil quality (Anderson & Domsch, 1989; Anderson & Joergensen, 1997; Nannipieri et al., 2003; Xue et al., 2006; Wong et al., 2008). Therefore, it is important to study how soil carbon, nitrogen dynamics and soil microbial activities are affected after addition of different leaf litters in a range of sodic soils.

The tree species selected in this study are most commonly used for afforestation on wastelands globally, and therefore, their litters are easily available residues in semiarid regions. Their application in sodic soils can be practiced to maintain soil carbon, nitrogen and microbial activities in slightly sodic soil with addition of litter with lowest C:N ratio. Leaf litter with low C:N ratio will mineralize faster in highly sodic soils in comparison to litter with high C:N ratio even in slightly sodic soils.

**MATERIALS AND METHODS**

### Sampling of Soils and Litters Used in the Experiment

Soil was sampled randomly from abandoned sodic land [pH = 10.5, electrical conductivity (EC) = 1.83 dS m$^{-1}$; measured in 1:2 soil–water ratio], monoculture plantations (pH = 8.5, EC = 1.12 dS m$^{-1}$) and the mixed forest (pH = 7.5, EC = 1.06 dS m$^{-1}$) and considered as highly sodic (HS), moderately sodic (MS) and slightly sodic (SS), respectively, on the basis of descending soil pH, EC and ESP (Table I) (Singh et al., 2012a, 2012b). These soils, used in the experiment, were collected from the upper 10-cm soil depth of each land after removing litter layer, in case of vegetated lands. Before the establishment of experiment, the replicated soil samples were mixed thoroughly and sieved (2 mm mesh) to make its uniform structure. Sampling was carried out in May 2010.

### Litter Sampling and Analysis

Litter collection was carried out in late February 2010, which is the main period of litter fall in this region. The

<table>
<thead>
<tr>
<th>Soil properties</th>
<th>SSS</th>
<th>MSS</th>
<th>HSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil classification</td>
<td>Typic Natrustalfs</td>
<td>Typic Natrustalfs</td>
<td>Clay loam</td>
</tr>
<tr>
<td>Soil texture</td>
<td>Silty loam</td>
<td>Silty loam</td>
<td>Silty loam</td>
</tr>
<tr>
<td>Bulk density (g cm$^{-3}$)</td>
<td>1.20 ± 0.06</td>
<td>1.42 ± 0.03</td>
<td>1.62 ± 0.08</td>
</tr>
<tr>
<td>pH</td>
<td>7.50 ± 0.00</td>
<td>8.60 ± 0.06</td>
<td>10.5 ± 0.06</td>
</tr>
<tr>
<td>Electrical conductivity (dS m$^{-1}$)</td>
<td>1.06 ± 0.15</td>
<td>1.12 ± 0.17</td>
<td>1.83 ± 0.30</td>
</tr>
<tr>
<td>Organic carbon (g kg$^{-1}$)</td>
<td>9.47 ± 0.36</td>
<td>4.50 ± 0.54</td>
<td>2.04 ± 0.27</td>
</tr>
<tr>
<td>Total nitrogen (g kg$^{-1}$)</td>
<td>0.76 ± 0.39</td>
<td>0.28 ± 0.62</td>
<td>0.17 ± 1.40</td>
</tr>
<tr>
<td>Microbial biomass-C (µg g$^{-1}$)</td>
<td>36.8 ± 9.08</td>
<td>22.8 ± 4.05</td>
<td>61.0 ± 4.58</td>
</tr>
<tr>
<td>Microbial biomass-N (µg g$^{-1}$)</td>
<td>35.0 ± 3.22</td>
<td>27.0 ± 2.89</td>
<td>4.67 ± 0.67</td>
</tr>
</tbody>
</table>
recently senesced leaf litter was collected from representative vegetation; that is, T. arjuna (Roxb.) Wight & Arn. (Ta), P. juliflora (Sw.) DC. (Pj), A. indica A. Juss. (Ai) and A. procera (Roxb.) Benth. (Ap) plantations.

At this study site, different tree species were planted as plantation cropping under biomass research project in 1980–1982 to meet substantial requirement of fuel wood for domestic and industrial purposes as well as rehabilitation of degraded sodic lands (Garg, 1992, 1998; Srivastava et al., 1999; Goel & Behl, 2001, 2004). Sodic soil rehabilitation efficiency of P. juliflora (Garg, 1999), T. arjuna (Singh, 1996; Singh et al., 2012), A. procera and A. indica (Goel & Behl, 2001) plantations has been investigated, but decomposition of its leaf litters in sodic soil was unknown. Therefore, we have tested effect of leaf litter of these species on sodic soil properties. The paddy straw was used because one patch of land is being rehabilitated under rice-wheat-cropping systems (Singh et al., 2012).

The litter was separated from green and standing dead materials (twigs, fruits and so on) to include only recently senesced leaf litter. Decolorized and physically damaged leaf litters were also removed. The litter samples were brought to the laboratory and spread on newspapers in thin layer and subjected to air drying for a week. Some part of each litter was kept in oven (70 °C, 72 h) for carbon and nitrogen analysis. The dried samples were crushed and grinded roughly to increase the surface area of detritus. In case of paddy straw, stubs of paddy rice (O. sativa) were collected from the paddy field and processed similarly as tree litter. We have selected paddy straw because cultivation of paddy rice on sodic soil is possible to some extent and retention of its residue may play important role in sodic soil reclamation (Singh et al., 2013a in press). The analysis of leaf litter carbon and nitrogen was carried out using standard protocols (Piper, 1950). Litter samples were ground, oven-dried and analysed for total N using the macro Kjeldahl method with a Tecator Kjeltec Auto 1030 Analyser (Tecator, Höganäs, Sweden). The carbon, nitrogen and their ratio (C : N) are shown in Table II.

**Experimental Design and Treatments**

This *in vitro* aerobic incubation study was conducted in 270 [270 = 5 (litters + control) × 3 (three soils: SS, MS and HS soils) × 3 (replicates) × 6 (time intervals)] perforated PVC pots (8 × 8 × 9 cm³) in net house, to protect from extreme conditions. Each pot was filled with processed and homogenized soils (600 g) and litter (60 g), including one no added soil considered as control for each soil type and time interval. The experiment was established using a full factorial design with three factors, treatments (four leaf litters and one control), soil types (three) and time intervals (six); and each factor was further divided into three replicates. The litter was not added in the first treatment (control). The experiment was planned for bimonthly soil sampling and analysis in twelve months (15 January 2011 to 15 November 2011). The experiment was established on 15 November 2010. The soil (with and without leaf litter) of each pot was moistened to field capacity thoroughly with deionized water; thereafter, moisture was uniformly maintained with three sprinkles in a week.

**Soil Sampling and Processing**

A set of 45 (5 litter + control × 3 soils × 3 replicates) PVC pots, out of 270 PVC pots, were taken to the laboratory for soil analysis at each time interval (after 2 months). First of all, a glass beaker of 100-ml volume was used for soil sampling from each PVC pot for the measurement of soil respiration. Remaining soil was processed for chemical (oven dry, 100 °C 24 h) and microbial analysis (stored at 4 °C for 6 days to stabilize microbial activity disturbed during sampling). This was repeated throughout the study undertaken for a period of 12 months (15 January 2010 to 15 November 2010). All the parameters were estimated using soils of three replicated PVC pots.

**Soil Analysis**

The water holding capacity, bulk density and soil particles (silt, clay and sand) of selected soils (for bulk soil only) were determined following the standardized methods published by Kalra & Maynard (1991). Soil pH and EC was determined in a soil–water suspension of 1:2.5 (weight/volume) ratios. Soil organic carbon was estimated using Walkley–Black’s rapid titration method (Jackson, 1967). Available nitrogen of soil samples was estimated by extraction in KMnO₄ solution followed by steam distillation method with the help of Kjeltac Auto 1030 Analyser (Kalra & Maynard, 1991). Microbial biomass carbon and nitrogen were estimated with chloroform fumigation extraction method (Brookes et al., 1982, 1985; Vance et al., 1987). Three portions of fresh soil stored at 4 °C were weighed out separately. One part was used for moisture content, and remaining two portions were kept into 50-mL glass beakers. One of these two portions of soil sample was kept as unfumigated. The

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**Table II. Carbon (%) and nitrogen (%) of leaf litters and crop residue selected for the experiment**

<table>
<thead>
<tr>
<th>Species</th>
<th>Component</th>
<th>C (%)</th>
<th>N (%)</th>
<th>C : N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terminalia arjuna</td>
<td>Leaf litter</td>
<td>40.8 ± 2.12</td>
<td>0.95 ± 0.07</td>
<td>43.0 ± 2.76</td>
</tr>
<tr>
<td>Prosopis juliflora</td>
<td>Leaf litter</td>
<td>41.8 ± 2.45</td>
<td>1.10 ± 0.26</td>
<td>38.0 ± 2.90</td>
</tr>
<tr>
<td><em>Mixed leaf litter</em></td>
<td>Leaf litter</td>
<td>43.5 ± 1.34</td>
<td>1.45 ± 0.34</td>
<td>30.0 ± 3.12</td>
</tr>
<tr>
<td>Rice straw (Oryza sativa)</td>
<td>Stubs</td>
<td>30.0 ± 3.10</td>
<td>0.28 ± 0.05</td>
<td>107.0 ± 7.65</td>
</tr>
</tbody>
</table>

Values are mean of three samples.

*Mixed leaf litter is mixture of leaf litter of T. arjuna, P. juliflora, Acacia indica A. Juss. and Albizia procera (Roxb.) Benth.
second sample was fumigated with alcohol free chloroform (CHCl₃) at 25 °C for 24 h in evacuated desiccator. After fumigation, residual vapour of CHCl₃ was removed from the soil samples by repeated evacuation six times using rotary oil pump. Fumigated as well as unfumigated soil samples were transferred into 250-mL conical flask and added 100 mL (0·5 M) K₂SO₄ solution. The flasks were sealed and shaken on oscillating shaker (180 oscillation min⁻¹) for half hour and filtered the soil suspension through Whatman No.42 filter paper. An 8-mL aliquot of the K₂SO₄ soil extract was taken into 100-mL flask, in which 2 mL K₂Cr₂O₇ (0·4 N), 10 mL concentrated H₂SO₄ and 5 mL H₃PO₄ were added and left for half hour for complete digestion. The excess dichromate was determined by titration with 0·4 M ferrous ammonium sulfate using diphenyl amine indicator. Soil respiration, also known as mineralization quotient that represents the CO₂–C evolved per organic C unit and day (Badía, 2000), of fresh moist soil was determined by alkali absorption method (Yao et al., 2009); 50 g of fresh moist soil samples were place in a 250-mL conical flask. The glass vials with 0·1 N NaOH were introduced in each flask with thread for absorption of CO₂, and cork was placed on mouth of the flask. The flasks were then kept in BOD incubator for 24 h; residual NaOH was titrated with 0·1 N HCl using phenolphthalein indicator after the CO₂ had been stabilized by precipitation with BaCl₂ (Wong et al., 2008; Badía et al., 2013).

**Measurement of Microbial Quotient (Cmic : Corg) and Metabolic Quotient (qCO₂)**

The microbial quotient, Cmic : Corg, a measurement of the carbon produced by soil microorganisms living in a soil thriving on applied leaf litters, was estimated as the ratio of SMB carbon (μg g⁻¹) to organic carbon (μg g⁻¹). The qCO₂ was estimated using the values of CO₂–C produced (mg CO₂·kg⁻¹·24 h⁻¹) by microorganisms and their biomass carbon. The qCO₂ values are presented as mg of CO₂–C mg⁻¹·MB·C day⁻¹ (Moscatelli et al., 2005; Wong et al., 2009).

### Table III. Summary of multivariate statistical analysis (F-distribution)-analysis of variance showing significance of variations in the soil properties in litter decomposition pots with respect to litter types, soil types, time intervals and their interaction

<table>
<thead>
<tr>
<th>Soil properties</th>
<th>Litter types (LT)</th>
<th>Soil types (ST)</th>
<th>Intervals (ITR)</th>
<th>ST × LT</th>
<th>ST × ITR</th>
<th>LT × ITR</th>
<th>Significance level</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>10689.59</td>
<td>151.98</td>
<td>Ns</td>
<td>15.28</td>
<td>21.82</td>
<td></td>
<td>p &lt; 0·001</td>
</tr>
<tr>
<td>Electrical conductivity (dS m⁻¹)</td>
<td>1182.04</td>
<td>98.42</td>
<td>Ns</td>
<td>1.96*</td>
<td>12.41</td>
<td></td>
<td>p &lt; 0·001</td>
</tr>
<tr>
<td>Organic carbon (g kg⁻¹)</td>
<td>3768.83</td>
<td>1658.99</td>
<td>43·6</td>
<td>15.17</td>
<td>205.71</td>
<td></td>
<td>p &lt; 0·001</td>
</tr>
<tr>
<td>Available nitrogen (μg g⁻¹)</td>
<td>2124.03</td>
<td>1579.96</td>
<td>33·64</td>
<td>6.38</td>
<td>186.85</td>
<td></td>
<td>p &lt; 0·001</td>
</tr>
<tr>
<td>Microbial biomass carbon (μg g⁻¹)</td>
<td>5591.12</td>
<td>4089.77</td>
<td>33·32</td>
<td>16·62</td>
<td>454·71</td>
<td></td>
<td>p &lt; 0·001</td>
</tr>
<tr>
<td>Microbial biomass nitrogen (μg g⁻¹)</td>
<td>1808.06</td>
<td>1613.2</td>
<td>33·22</td>
<td>8·46</td>
<td>187·2</td>
<td></td>
<td>p &lt; 0·001</td>
</tr>
<tr>
<td>Soil respiration (mg CO₂·kg⁻¹·24 h⁻¹)</td>
<td>3575.90</td>
<td>632.82</td>
<td>7·09</td>
<td>6·06</td>
<td>91·2</td>
<td></td>
<td>p &lt; 0·001</td>
</tr>
<tr>
<td>Microbial quotient (Cmic : Corg) (μg g⁻¹)</td>
<td>5268.16</td>
<td>269.52</td>
<td>5·50</td>
<td>3·90</td>
<td>39·0</td>
<td></td>
<td>p &lt; 0·001</td>
</tr>
<tr>
<td>Metabolic quotient (mg CO₂–C d⁻¹·mg MBC⁻¹)</td>
<td>2909.13</td>
<td>719.84</td>
<td>Ns</td>
<td>5·39</td>
<td>78·15</td>
<td></td>
<td>p &lt; 0·001</td>
</tr>
<tr>
<td>Degree of freedom (d.f.)</td>
<td>4</td>
<td>2</td>
<td>5</td>
<td>7</td>
<td>8</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

*Significant at p < 0·05.

### Statistical Analysis

Data of various soil properties were subjected to linear, quadratic, cubic and exponential functions using the SPSS software program, version SYSTAT-9·0 package. Additionally, multivariate repeated analysis of variance was used to analyse whether effects of litter types (main treatment), soil types (subtreatment) and time intervals (subtreatment) on soil nutritional (pH, EC, carbon and nitrogen) and biological (microbial biomass and indices) parameters were significant or not. The F-distribution values were calculated to know significant effect. Interaction effect of soil types with litter types and intervals as well as litter types with intervals were also observed (Table III).

### RESULTS

**Changes in Chemical Properties**

Litter from different sources (leguminous and nonleguminous trees and paddy straw) vary considerably in their C : N ratio, which determines the pattern of C and N mineralization, added in sodic soils has significant effect on soil properties. Sodicity stress inhibits C and N mineralization process irrespective of quality of litter. Litter of low C : N ratio mineralized quickly as compared with that of higher C : N ratio litter. This decomposition and mineralization process affected the properties of incubated soil. The pattern of decrease in soil pH with respect to incubation period was depicted through the best correlation model (linear, logarithmic, exponential and polynomial) for different litters (Figure 1). Consequently, soil pH decreased significantly with respect to incubation period. This decrease was lesser in SS soil in comparison with HS soil. Mixed leaf litter (MLL) was found to be more efficient in reducing soil pH in comparison with other litter types. EC also decreased with the incubation period, moderately in SS soil and MS soil and conspicuously in HS soil (Figure 1). Soil organic carbon (SOC) increased drastically in MS soil in comparison with increase in SS and HS soils with
respect to incubation period (Figure 1). In case of MS soil, litter and paddy straw followed exponential and logarithmic form of decay, respectively. Available nitrogen (N$_{av}$) content also increased significantly with linear or exponential model on addition of TA, PJ, MLL and RS (Figure 2).

Changes in Microbial Activities

Microbial biomass carbon in the soil increases exponentially when litter undergoes decomposition and mineralization processes (Figure 2). MBC increased linearly in MLL-treated soils with different sodicity stress. Contrary to TA,
PJ and MLL, MBC in the soils added with paddy straw (RS) increased logarithmically. Addition of TA and PJ litters showed an exponential increase in microbial biomass nitrogen (MBN) in soils of different sodicity stresses (Figure 2); this increase was relatively low in HS soil. Increase in SR was apparent with respect to incubation period on addition of various litters in different sodicity stressed soils (Figure 3). Soil respiration increased linearly with TA and PJ litters, and logarithmically with MLL and paddy straw. Microbial quotient \((C_{\text{mic}}:C_{\text{org}})\) varied differently over the year with respect to soil types and litter used in the experiment. The microbial quotient decreased significantly on addition of all litters including paddy straw in MS soil, whereas it increased slightly in SS soil. Thus, the microbial quotients tend to stabilize within a range of fertility status and sodicity stress of the SS and MS soil (Figure 3). In contrast, the \(q_{\text{CO}_2}\) (ratio of SR to...
MBC) of MS soil was almost stable during the incubation period, which decreased in SS and increased in HS soil with litter or paddy straw-treated soils (Figure 3).

Net Annual Change in Soil Properties

Key alterations associated with the reclamation of sodic soils after addition of different litters followed two distinct trends; one decrease in soil pH and EC and increase in SOC, $N_{av}$ and microbial activities. The mean annual decrease in soil pH of SS soil was about 4.4%, 3.8%, 3.2% and 1.4% after addition of MLL, RS, Ta and Pj litters, respectively. When leaf litters of Ta, Pj, MLL and Ps were added to MS and HS soils, decrease in soil pH was 8%, 8%, 7% and 9% as well as 12%, 9%, 9% and 8% in
respective soils; this decrease was significantly higher than in SS soils (Figure 4). The EC of SS soils increased initially after addition of litters of MLL, Pj and Ta but declined later on (1·06 to 0·90 dSm\(^{-1}\)) at the end of the incubation. Least decrease in EC (1·5%) was found in MS soil with PJ litter and maximum decrease (27%) was observed in HS soils with litters of MLL (Figure 4). The average annual increase in SOC and Ne\(_{av}\) was 19·6%, 40% and 26% and 27%, 45% and 43%, respectively in SS, MS and HS soils (Figure 4). The MBC and MBN increased about 23%, 30% and 32% (MBC) and 34%, 34% and 46% (MBN) in SS, MS and HS soils, respectively. The highest increase in soil MBC was observed in Ta-treated HS soils followed by Rs added in MS soil, and MLL added is HS soil; increase in MBN

![Figure 4](https://wileyonlinelibrary.com/journal/ldr)
was highest in Rs (52%) added HS soil, followed by MLL (48%) and Ta (46%) (Figure 4). Soil respiration (CO$_2$–C) increased significantly in SS soils, and highest increase has been observed in MLL-treated soils. The mean annual increase in soil respiration was highest in HS soils (29%), followed by MS (22%) and SS soils (21%).

**DISCUSSION**

Addition of an equal amount of organic matter (leaf litter and paddy straw) with different C:N ratio in the three types of soil mineralized the C and N in different ways with respect to the soil sodicity levels. 

**Variation in pH and Electrical Conductivity (EC)**

Decomposition of different types of litters reduced the soil pH and EC of sodic soils to various extents. However, this decline in pH and EC was according to their initial levels in the original soils. Because pH and EC values of original soils were highest in HS soils, in most of the cases, maximum decrease was observed in this soil. Decrease in soil pH and EC due to addition of leaf litters or paddy straw in sodic soils was also observed in earlier studies (Singh, 1996, 1998a; Pathak & Rao, 1998; Barbera et al., 2012; Johnston et al., 2013; Singh et al., 2013b, 2013c; Lozano-García & Parras-Alcántara, 2014; Jiaaree et al., 2014). Pathak & Rao (1998) reported significant decrease in initial soil pH 9.8 to 9.0 in 3 months of incubation study on addition of *Sesbania* litter. Similarly, Graham & Haynes (2005) and Badía et al. (2013) reported acidification of soil after addition of organic matter. Such reductions are attributed to various factors. Firstly, it might be due to increased organic matter decomposition in the soil, which release mild organic acids (Amato & Ladd, 1992). Secondly, chemical composition of leaf litters may affect the chemistry of soil thereby acidification takes place (Garg, 1992; Sarıylıdzı & Anderson, 2003; Ganjegunte et al., 2012). Thirdly, the addition of organic matter through litter increases microbial population and decomposition process for higher CO$_2$ emission, and formation of carbonate (HCO$_3^-$) and hydrogen (H$^+$) ions tend to reduce soil pH (Sayer, 2006). Jobbagy & Jackson (2003) postulated three potential mechanisms of soil acidification after litter addition: (i) organic acid inputs, (ii) enhanced soil respiration and (iii) cation redistribution. The highest decrease in pH (alkalinity) was in the HS soils amended with tree litter, whereas the highest decrease in soil pH was when Rs was added in MS soil. It reveals that litter types (C:N ratio of the substrate) interact in different ways with soil sodicity stresses. The paddy straw was more efficient in pH reduction in SS soil and MS soil, whereas in HS soil, leaf litter was more efficient in comparison with paddy straw. As regards to EC, the highest decrease was found in HS soils amended with MLL litter, and lowest was in MS soils amended with Pj litter. Paddy straw did not alter EC of the SS soil in 1 year. This might be due to the initial level of salts in the treated soils, percolation of water through pores in PVC and alteration in soil chemistry because of added litter. These interactions of substrate quality with soil sodicity during decomposition process provide an appropriation protocol for the rehabilitations and restorations of sodic lands under desired land use systems, or we can say it will help in taking the right decision to rehabilitate a particular type of sodic soil under a particular land use system.

**Variation in Organic Carbon and Nitrogen**

In this study, the highest increase in SOC and N$_{tot}$ was observed in MS soils followed by HS and SS soils at the end of the incubation period. Hence, a moderate sodicity (pH=8.5) favours the carbon and nitrogen mineralization over the extreme and almost neutral levels. In field conditions, CO$_2$ efflux is negatively related to soil salinity, which varies seasonally (Badía & Alcañiz, 1993; Badía, 2000). Studies that examined organic matter decomposition in a range of soil pH (saline and sodic) seem to provide contradictory results. One study reported that organic matter decomposition was highest in the soils with neutral pH and reduced with increasing or decreasing pH (DeLaune et al., 1981), whereas another study reported that organic matter decomposition increased from slightly acidic to alkaline soil pH (Amato & Ladd, 1992). van Bergen et al. (1997, 1998) reported that lignin signal was more abundant in less sodic soils than in high sodic soils; they proposed that soil sodicity might affect organic matter decomposition through selective preservation and/or degradation of plant derived biomolecules such as lignocellulose, with these compounds being degraded more in high pH than in low pH soil. Litter addition increases the concentration of carbon and nitrogen in nutrient-poor sodic soils and increases the cation exchange capacity (Singh, 1996). Increase in SOC on litter addition had been reported by others too (Liu et al., 2009). The addition of MLL to SS and MS soils had greatest increase in SOC (20% and 41%, respectively); however, litter of *T. arjuna* (Ta) took the lead (42%) into accumulating SOC in HS soils. This might be due to parallel increase in nitrogen in MLL (30% SS soil and 47% MS soil) and Ta (42% HS soil) in the amended soils. This might also be due to lowest C:N ratio (30) of MLL in comparison with Ta and Pj litters. The lowest increase in net SOC in SS (19%), MS (37%) and HS (24%) sodic soils in which paddy straw was applied, may possibly be due to higher C:N ratio (107) of paddy straw. The results reported here were in line with earlier studies, where dynamics of carbon and nitrogen were observed during litter and fine root decomposition of forested sites developed on sodic soils (Singh, 1996, 1998a; Devevre & Horwath, 2000; Singh et al., 2000).

**Variation in Soil Microbial Biomass (MB) and Quotients**

Microbial activities are likely to play key roles biodegradation of organic matter, biogeochemical cycling and soil structure formation and hence in restoration of degraded sodic lands (Wong et al., 2008). Generally, litter addition to soils leads to an increase in microbial communities, which
affects the microbial biomass (Sayer, 2006; Samahadhthai et al., 2010; Prevost-Boure et al., 2011). In this study, increase in MB in different levels of sodic soils, after addition of different leaf litters, have been observed to various extents. Increase in MBC and MBN showed significant difference across soil and litter types; exceptional case was MBN in MS and HS soils treated with Pj litter. On an average, HS soil had the highest increase in MBC (32%) and MBN (46%) at the end of the incubation period. The HS soil treated with Ta had comparatively higher MBC, likewise organic carbon. The results further obtain support from higher increase soil respiration (CO₂ emission) in HS soils when leaf litter as well as paddy straw were added. An increase in MBC was also reported after addition of shoot and root litters of C₃ and C₄ plants in semiarid soils (Jin et al., 2010). It is attributed to increase in microbial activity resulting in an acceleration of mineralization as substrate and energy source (Kuz yakov et al., 2000). Higher increase of microbial activities in soils with least nutrient availability (HS soils) is expected to be induced by the addition of complex organic matter (Allison & Vitousek, 2005). Furthermore, it can be explained that when nutrients are less available, microbial activities enhanced during short-term incubation in nutrient-poor soils, called priming effect (Blagodatskaya & Kuz yakov, 2008). Application of paddy straw to different levels of sodic soils reduced highest soil pH in MS soils along with high organic carbon, MBC and qCO₂. It indicates a strong and positive influence of paddy straw on these chemical and microbial properties of MS soil (Chodak & Niklinska, 2010). The alterations in the amount of available organic substrate may alter SMB. The pattern of MBC and MBN was almost reverse to that of SOC and Nₐᵥ across different litter types in MS and HS soils. Correlation of increase in SOC and N with MBC and MBN was insignificantly negative (data not presented). It is likely due to nutritional status and pH (alkaline) level of the sodic soils.

The lowest range (2.72–3.32) of microbial quotient (Cmic:Corg) in HS soils in comparison with that of SS (3.89–4.74) and MS (3.29–5.63) soils also indicates nutritional deficit in these soils (Anderson, 2003). SR is often measured for the assessment of microbial activity (production of carbon dioxide when soil organisms respire) that releases carbon from the soil in the form of CO₂ and release energy for metabolic processes. In this incubation study, addition of different litters to sodic soils has positive effect on soil respiration. Increase in soil respiration indicates various microbial efficiencies for organic matter decomposition. Soil respiration increased significantly in all soils treated with different litter types throughout the incubation period. It is attributed that microbial activity increases because of acceleration of mineralization as substrate and energy source (Kuz yakov et al., 2000). This consistent increase in soil respiration might be due to (i) decreasing pH and EC (Badía, 2000; Yao et al., 2009); (ii) increasing carbon and nitrogen, microbial size is typically dependent on nitrogen, (Mukhopadhyay & Joy, 2010; Bradley et al., 2011); (iii) constant moisture and temperature regime (Aka & Darici, 2005; McIntyre et al., 2009); and (iv) enhanced litter inputs (Liu et al., 2009). The microbial quotient is the ratio of the MBC to SOC (Cmic:Corg) and indicates the ratio of the living fraction of organic carbon relative to total organic carbon. The microbial as well as qCO₂ showed various trends throughout the incubation period in SS, MS and HS soils. Average increase in qCO₂ was 2% in SS soil, 4% in HS soil and 11% in MS soil. It appears that the soil with sodicity stress induced microorganisms to release more CO₂ per unit microbial biomass per unit time and hence results in increase in qCO₂ (Wong et al., 2007).

CONCLUSIONS

Soil organic carbon, nitrogen and microbial activities showed litter-soil-specific trends. Litter decomposition is actively being affected by (i) types of substrate (soil) to which various leaf litter types are added and (ii) types of leaf litters being applied to various types of substrates.

ACKNOWLEDGEMENTS

Kripal Singh expresses his sincere thanks to Council of Scientific and Industrial Research (CSIR), Government of India, New Delhi, for financial assistance (31/8/233/2009/EMR-I and HRDG/CSIR-Nehru PDF/LS/EMR-I/03/2013). K.S. is very thankful to Professor Artemi Cerdà for his comments and suggestions on each version of this paper. We are also grateful to the reviewers for their useful comments on this paper.

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